Invited paper

Frequency modulated fiber optic electronic speckle pattern interferometry and its applications. Part I: Hardware and software design

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Electronic Speckle Pattern Interferometry (ESPI) is an important tool used in non-destructive testing, experimental mechanics, material properties studies, medicine, etc. In the first part of our paper we present a system with extended measurement capabilities using fiber optics and frequency modulated semiconductor laser. Several design improvements enabled to integrate several experimental configurations in one device for measuring in-plane and out-of-plane displacements, their partial derivatives, vibration analysis and surface contouring. A novel full-featured fringe image analysis software is also described.

1. Introduction

Electronic Speckle Pattern Interferometry (ESPI) is already known for 26 years [1, 2, 3]. Nowadays ESPI encompasses a set of optical techniques used in experimental mechanics, material sciences, medicine, non-destructive testing and other scientific and engineering fields. Its popularity is due to the fact that it has eliminated most of the drawbacks of the conventional holography – wet processing, long measurement times and the need for extreme environmental stability. Electronic or TV-holography, as it is sometimes called, can produce high accuracy results in time of a few seconds, can measure the displacements as low as nanometers of the objects of dimensions in the range from tenths of micrometers up to large structures such as cars. However, the price paid for the speed and versatility is a relatively low spatial resolution, smaller dynamical range, high noise content and complicated data processing. However, these disadvantages do not overbalance the positive features of ESPI.

ESPI is one of the optical techniques particularly suited for industrial applications. Lower environmental stability requirements, high degree of automation of data acquisition and processing, and full-field analysis make it an attractive alternative to other methods. The adaptivity to industrial needs can be amplified by the use of optical fibers and semiconductor laser sources. Most of the comercially available systems use gas lasers and bulk optic components being characterized by a substantial weight, big dimensions and limited configuration versatility to investigate only a few physical quantities.

Systems based on bulk optics are quite big and difficult to assemble, they are also susceptible to environmental conditions because the laser beam travels in a free space. Such systems must be shielded from air movements and temperature changes. The laser beams need to be spatially filtered because of dust specks and other artifacts on optical elements reducing the quality of images. All optics must be rigidly fixed to the optical bench to avoid the influence of environmental vibrations. These systems occupy quite a big space and

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are hardly portable unless mounted on special breadboards. In this case their weight is counted in tenths of kilograms. Also the systems need to be reconfigured each time when different quantity is to be measured. These restrictions are acceptable in optical laboratories but measurements *in situ* and in industrial conditions are subject to much more stringent requirements.

The technology development has allowed several improvements to the original design extending the system measurement capabilities to provide better solutions to the problems met in daily use. The newest advances leading to the interferometer designed in Optical Engineering Group of the Institute of Micromechanics and Photonics are discussed in the following sections.

2. Principle

The common principle of all ESPI systems is the comparison of two TV frames to extract the information about the correlation of speckle patterns. The type and order of processing depends on the method used. However, a general schematic of electronic ESPI processing can be assumed as shown in Fig. 1.

Digitized intensity values of the reference frame are

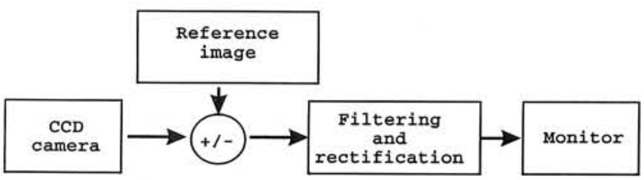

Fig. 1. Schematic of electronic processing in ESPI systems.

stored in the frame grabber memory. Subsequent images acquired from the CCD camera after object changes are subtracted or added to the reference frame in real time. The resulting signal is then filtered, rectified and displayed on the TV monitor.

In mostly used subtraction mode ESPI the two images I_0 and I_1 are recorded before and after the change of the measured object parameter. Assuming that the registered signal is proportional to the irradiance at the detector the two images can be written in the form

$$I_0 = I_0 + I_r + 2\sqrt{I_0 I_r}\cos\psi , \qquad (1)$$

$$I_0 = I_0 + I_r + 2\sqrt{I_0 I_r}\cos(\psi + \phi) , \qquad (2)$$

where I_0 and I_r are intensities of the object and reference beams, respectively, ψ is the phase term responsible for the speckle background, and ϕ is the phase corresponding to the measured quantity change.

The image I_0 recorded before the change is stored in the video memory of the frame grabber. The image I_1 is then subtracted from the image I_0. The resulting intensity profile takes the form

$$I_1 - I_0 = 4\sqrt{I_0 I_r}\sin\left(\psi + \frac{1}{2}\Delta\phi\right)\sin\frac{1}{2}\Delta\psi . \qquad (3)$$

Obtained expression assumes negative and positive values. To avoid displaying the negative values as black areas the signal must be rectified. Assuming that the brightness B on the monitor screen is proportional to the video signal, the most common rectification process taking the absolute value of the differential intensity results in the expression

$$B = 4K\sqrt{I_0 I_r}\left|\sin\left(\psi + \frac{1}{2}\Delta\phi\right)\right|\left|\sin\frac{1}{2}\Delta\psi\right| , \qquad (4)$$

where K is the proportionality factor.

The brightness on the monitor screen is modulated by dark fringes on the speckle background. Dark fringes with zero intensity are found at the locations where the phase term $\frac{1}{2}\Delta\phi$ is a multiple of 2π. The bright fringes with maximum intensity of $4K\sqrt{I_0 I_r}$ show the locations where the change is an odd multiple of π. This operation is usually followed by high-pass filtering to remove the low frequency noise and enhance the contrast of fringes.

Generally the subtraction mode ESPI gives correlation fringes with better visibility than the speckle pattern addition approach since minima have zero intensity. Moreover, the processing of additive images is somewhat more complicated. However, the addition method can be sometimes advantageous because there is no need to store the separate reference frame.

3. Hardware considerations

3.1. Fiber optics

Single mode optical fiber is a very convenient means for the delivery of light, particularly suited for interferometric applications. Inside the fiber the light propagates in the lowest mode (LP_{01}), therefore maintaining its coherence state. On the other hand, birefringent properties of glass subjected to stress introduce changes to the state of polarization of the light propagating in the fiber.

Another disadvantage of optical fibers is their high sensitivity to environmental changes. Typical optical phase change coefficient is of the order of $100\,\frac{rad}{m \cdot K}$. In an interferometer with several meters of fiber, the change of temperature by 0.1K produces phase variations of several tenths of radians. This influence can be reduced to acceptable level by insulating the fiber in special coatings and shortening the data acquisition time. In the setup described in this paper the fibers were isolated by putting them in a thin insulating sleeve and no influence of temperature variations on the measurement accuracy was observed. Several methods based on active fringe stabilization have been also proposed in the literature. Most of them are based on monitoring of the intensity changes in the fourth, not used port of the directional coupler [4, 5, 6]. These systems allow long-term supervision of the optical phase with high degree of accuracy but sometimes can slightly slow down the maximal image acquisition rate [7]. Some more advanced schemes were also presented incorporating a laser velocimeter for stabilization of zeroth order fringe in vibration measurements [8], or using an additional interferometric system for monitoring the object motion [9].

In spite of the disadvantages mentioned above, optical fibers are a very attractive alternative to bulk optics providing flexibility and compactness difficult to achieve by other means. Designs based on fiber optic components are characterized by reduced number of elements in comparison with "conventional" systems. Such systems can be designed to be easily reconfigurable for investigations of different phenomena or the objects with difficult access without the need to rebuild the system [10]. Fiber optics facilitates the implementation of convenient phase shifting methods by using PZT based devices.

At an early stage of the development of fiber optic ESPI fibers were used only as convenient means for delivery of a smooth reference wave [11, 12]. In some setups another piece of fiber was used to deliver the light for object illumination [13]. The optics used for dividing the laser beam into the reference and object beams was built using conventional beam splitters. The evolution of ESPI systems from bulk optics to all fiber arrangement was presented in [14]. Complete ESPI systems employing the directional coupler, phase shifting device and beam delivery system were reported thereafter by several authors (e.g. [15, 16, 17]).

For dividing the light beam usually a directional coupler with fixed split ratio is employed. For the out-of-plane displacement sensitive configuration typically the split ratio is 90:10 (object:reference beam) whereas for the in-plane displacement measurements the split ratio of 50:50 is used. Because of the fixed value of the beam division ratio for a particular directional coupler, the system can be used only for the measurement of one type of displacement. A different system configuration is required for each sensitivity vector direction (e.g. in-plane and out-of-plane displacement measurements). This is a serious disadvantage in laboratory practice. The optimization of the fringe contrast is done by fine adjustments of the reference to object beam intensity ratio using a set of filters introduced in the reference beam. In this paper an interferometer employing variable ratio directional coupler is presented which can greatly improve the situation by allowing in-plane and out-of-plane displacement sensitive configurations in one device. So far, except for the system designed by the authors [10], no literature reports are available.

Least but not last advantage to use the fiber optics is its compatibility with the semiconductor laser technology. Commercially available "pig-tailed" laser diodes are very convenient light sources and are discussed in the following section.

3.2. Laser light sources

The most often used laser light sources in ESPI are gas lasers such as helium-neon (632.8 nm) or argon-ion (514.5 nm) [18, 19, 20]. The argon-ion laser can deliver several watts of optical power, being capable of illuminating objects as large as a car body [21]. Helium laser is usually used for smaller object studies due to its lower power output, up to few tenths of milliwatts. Solid state lasers such as frequency doubled YAG (532 nm) were also reported working in ESPI systems [22]. However, all these light sources have some disadvantages limiting the total performance of speckle interferometry. They are usually quite large, require complicated powering and cooling systems and their efficiency is very low. An attractive alternative represent semiconductor lasers, which are small and efficient, they can be powered from portable sources, and have unique spectral properties that can extend the range of applications of ESPI. Laser diodes emit linearly polarized light at wavelengths corresponding to the peak sensitivity of CCD cameras, therefore increasing the light efficiency of the whole system. Coherence properties of the laser diode light are very good, typical coherence length is of the order of several meters. Semiconductor lasers were reported working successfully in ESPI in different configurations, e.g. [23, 24, 25, 26].

Semiconductor lasers, unlike other laser types used in ESPI, possess the unique capability of tuning of the emitted wavelength and power level. By injecting the current into the lasing region the refractive index can be controlled (it increases with the increase of the concentration of free carriers). These changes cause

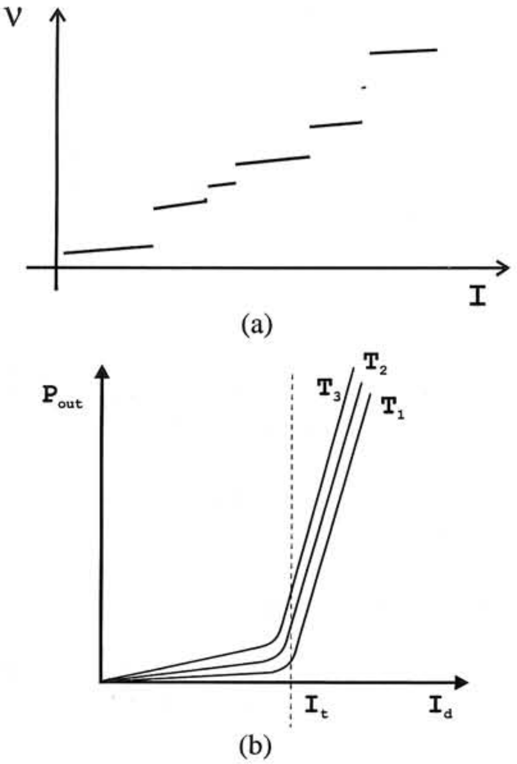

Fig. 2. Typical frequency (a) and output power (b) characteristics of a semiconductor laser as a function of the injection current.

the change of the optical length of laser cavity, therefore altering the emitted wavelength of light (Fig. 2).

The bandwidth is limited only by the carrier recombination time, so modulations in GHz region are possible.

The wavelength of the laser depends on the junction temperature as well. These changes are associated mainly with the temperature dependent cavity length changes and, therefore, are quite slow. The junction temperature must be controlled with the accuracy of 0,01° to avoid fluctuations of the output wavelength.

The changes of the output optical frequency are related to the driving current changes through factor k_ν

$$d\nu = k_\nu di, \tag{5}$$

where $d\nu$ is the optical frequency change induced by di change in the driving current.

The relative phase difference Φ between the reference and the object beams depends on the optical path length difference in the interferometer and the wavelength number k

$$\Delta\Phi = k\Delta L, \tag{6}$$

where ΔL is the optical path length difference in the intereferometer and

$$k = \frac{2\pi}{\lambda}. \tag{7}$$

The optical phase shift is introduced by the change of the driving current and, therefore, the wavelength λ. The phase change can be expressed as

$$\Delta\phi = \frac{2\pi}{c} k_\nu di \Delta L, \tag{8}$$

where c is the velocity of light.

This property can be used to introduce the phase shift needed for realization of different measurement techniques.

A serious disadvantage of semiconductor lasers is their sensitivity to optical feed-back. The light coming back from the optical system can disturb proper functioning of the laser by causing multimode emission, coherence reduction, mode hopping or power fluctuations. One of the solutions is the use of an optical isolator – a Faraday rotator introduced in the optical path right after the laser light collimator. Typical isolation factor is of the order of 30 dB which in most cases ensures the monomode functioning of the laser. However, for lasers with higher output power (more than 100 mW) this may be not sufficient and isolators with better attenuation of the back signal must be used. Optical isolators are usually quite expensive so the other solution is the use of "pig-tailed" laser diodes. These are commercially available assemblies in which the laser light is coupled into the fiber with the front facet cleaved at an angle of about 7°. It eliminates the need of the Faraday rotator and miniaturizes the design.

4. Interferometer setup

Optical fiber ESPI systems were reported in arrangements for static measurements of in-plane displacements [26, 27], out-of-plane displacements [5, 28], in-plane displacement derivative [29, 30], out-of-plane displacement derivative [31], contouring [28] and slope [31]. Also dynamic measurements of out-of-plane vibrations by the time average method were presented [8], using stroboscopic illumination [16] and heterodyning [32], as well as measurements of the derivative of the vibration amplitude [33].

All these systems were used to investigate in-plane and out-of-plane sensitivity vector directions separately. There are no reports about ESPI devices reconfigurable to measure both quantities. The novelty of the proposed design is its ability to be configured for measurements of in-plane and out-of-plane displacements, the amplitude and phase of vibrations, as well as their derivatives. The system can be also used for surface contouring and slope measurements. Another characteristics of this system is the reduced number of elements and realization of the phase shifting methods for most of the measurement types by the laser diode light wavelength modulation.

4.1. Out-of-plane displacement configuration

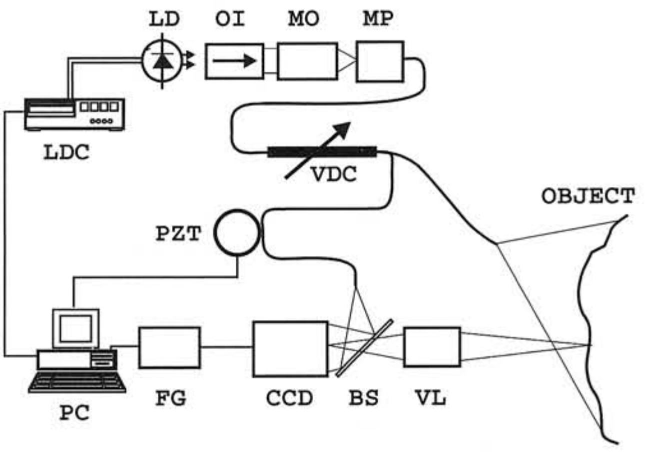

Fig. 3. Out-of-plane displacement sensitive ESPI system based on fiber optics and laser diode. LDC, laser diode driver and temperature controler; LD, laser diode; OI, optical isolator; MO, microscope objective; MP, micro positioner; VDC, variable directional coupler; PZT, piezoceramic phase shifter; VL, video lens; BS, beam splitter; CCD, CCD camera; FG, frame grabber; PC, personal computer.

The schematic of the ESPI system based on optical fiber components and using laser diode is presented in Fig. 3. Laser diode Hitachi HL7851G (LD) is used as a light source in the system. Emitted light is collimated at first by an aspheric lens and then launched into a monomode optical fiber using a Melles Griot micropositioner (MP) and a 20 × microscope objective (MO). Between the objective (MO) and the laser diode with the collimator (LD) the optical isolator (OI), Optics for Research OI-7-NIR2, is introduced. The laser light traveling in the fiber is split into the reference and object beams by means of a variable ratio directional coupler (VDC). This device makes possible continuous adjustments of the relative amplitude/intensity distributions into the beams, therefore, adjusting their ratio for in-plane and out-of-plane displacement sensitive configurations. It is the first reported system using this type of directional coupler.

Images of the object under test are collected by a Coreco Oculus F/64 frame grabber with integrated DSP TI 34040 processor which allows real time subtraction of two TV frames. Digitized images are transferred to the 486DX100 PC host computer for further processing. The image processing software will be discussed in Section 5.

The laser diode current is controlled by a Seastar LD 3210 laser diode driver integrated with a TC 5100 temperature controller (LDC). External modulation capabilities of the driver allow to control the injection current from the computer by means of data acquisition board Ambex LC1116-12. For in-plane displacement investigations the same card is used to feed the voltage to the PZT phase shifter for phase shifting.

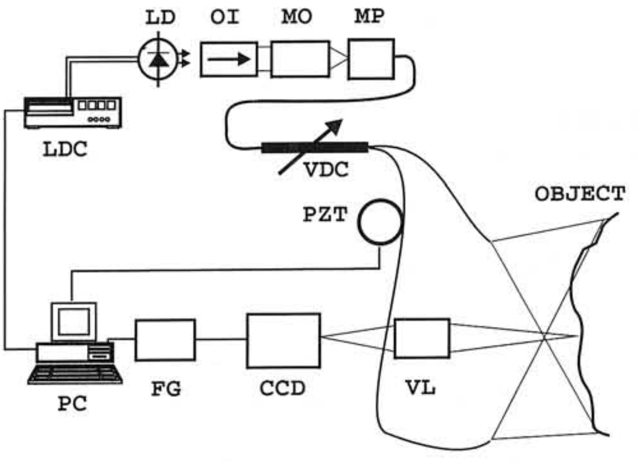

Fig. 4. In-plane displacement sensitive ESPI system based on fiber optics and laser diode. LDC, laser diode driver and temperature controler; LD, laser diode; OI, optical isolator; MO, microscope objective; MP, micro positioner; VDC, variable directional coupler; PZT, piezoceramic phase shifter; VL, video lens; BS, beam splitter; CCD, CCD camera; FG, frame grabber; PC, personal computer.

4.2. In-plane displacement configuration

Figure 4 shows the configuration used for investigations of in-plane displacements. For this arrangement the laser power is distributed equally between the beams and no reference beam is used. Both beams are used to illuminate the object. In this case phase shifting is done using a PZT device introduced in one arm of the interferometer. The optical fiber phase shifting device (Fig. 5) usually consists of a piezo-ceramic cylinder with a number of fiber loops wrapped around it [34]. By applying the voltage to electrodes, the PZT cylinder expands stretching the fiber and changing the optical path length in the fiber. Due to low voltage requirements the direct control using a typical D/A converter is possible. However, this type of phase shifter has some limitation (low frequency bandwidth) which eliminates it from using in the methods employing heterodyning at higher frequencies (a typical device made of PZT 5H material of diameter of 1" has its first resonant frequency around 25 kHz). In the presented design the phase shifting implemented by the

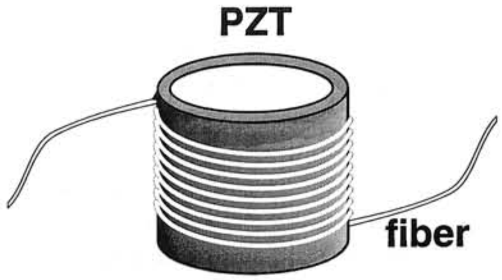

Fig. 5. Fiber optic PZT transducer used for phase shifting.

modulation of the light wavelength is proposed for higher frequency range applications and shearing interferometry methods.

4.3. Displacement derivative configuration

For investigating the displacement derivatives the only change required in the interferometer is to replace the ESPI head, Fig. 6, with the one containing a Michelson type interferometer (Fig. 7).

The shear is introduced by tilting of one of the

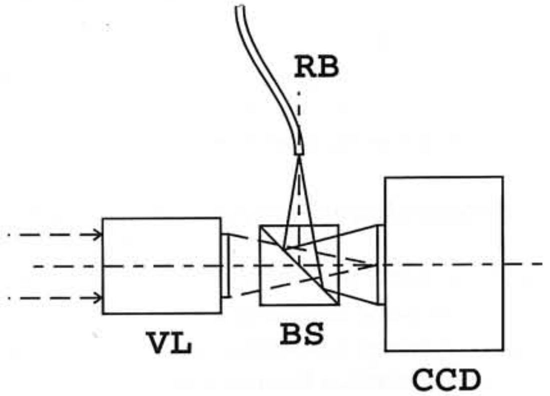

Fig. 6. A conventional head for the ESPI system. VL, video lens; BS, beam splitting cube; CCD, CCD camera detector; RB, reference beam.

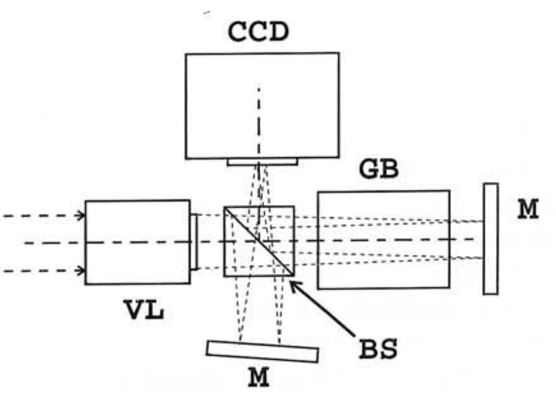

Fig. 7. Speckle pattern shearing head for the ESPSI system. BS, beam splitting cube; VL, video lens; M, mirrors; GB, glass block; CCD, CCD camera detector.

mirrors (M) of the interferometer. To introduce the path length imbalance the distance of the mirrors from the 50 beam splitting cube (BS) is set different. This path difference is needed for phase shifting methods by changing the laser wavelength. A glass block (GB) is inserted in one of the arms to compensate the difference in magnification. This arrangement was presented in [35] and [29]. The replacement of heads is very easy and takes about a minute. The shearing head can be also adapted for measurements of in-plane and out-of-plane displacement derivatives using the approach proposed by Rastogi [36]. In this method im-

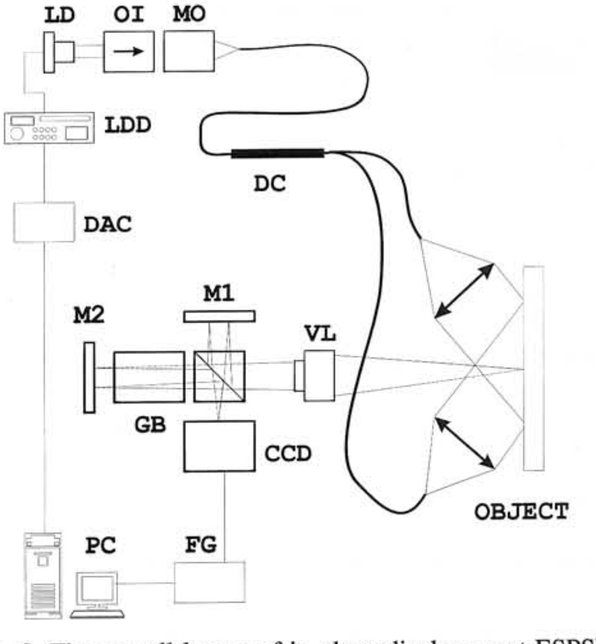

Fig. 8. The overall layout of in-plane displacement ESPSI system. LD, laser diode; OI, optical isolator; MO, microscope objective; LDD, laser diode driver; DC, directional coupler; DAC, digital to analog converter; M1 and M2, mirrors; GB, glass block; VL, video lens; CCD, CCD camera; FG, frame grabber; PC, personal computer.

ages are acquired with one of the Michelson interferometer arms blocked. Such interferograms are then evaluated and their comparison by subtraction and addition yields in-plane and out-of-plane displacement derivatives. This approach can be realized in the presented setup by introducing optical shutters in front of the interferometer mirrors.

The object is imaged in the plane of the CCD matrix (CCD) by a video lens (VL). The interference pattern of the object beam superimposed on the reference beam by means of a beam splitting cube is observed in the plane of the CCD chip. The cube has the transmission of 90%. Figure 6 shows the details of a head for in-plane and out-of-plane displacement measurements mounted on the camera. In the system a zoom objective Practicar MC with focal distance of 35–70 mm and F-number of 3.5 to 22 is used. For measurements of in-plane quantities the fiber normally used for delivering the reference beam is removed and used to illuminate the object.

The shearing head was successfully used to build a configuration for measurements of in-plane and out-of-plane displacement derivatives. The details of the setup is shown in Fig. 8.

Lateral shear interferograms of optical fields generated by symmetrical illuminating beams are independently recorded. The phases are calculated and their subtraction/addition is performed by software to yield the derivatives of in-plane and out-of-plane displacements, respectively. The approach can be treated as digital implementation of the principle of overlapping two lateral shear interferograms using the moire fringe technique as proposed in [37, 38, 39] for optical differentiation in moiré/grating interferometry.

4.4. Vibration analysis arrangements

The interferometer can be used for vibration analysis using the time average method or the linear part of the Bessel function describing the intensity distribution of vibration fringes. The setup was configured for out-of-plane displacement measurements (Fig. 3).

4.4.1. Heterodyning configuration

Heterodyning is a widely used interferometric technique for recovering the amplitude of a vibrating object. In conventional ESPI arrangements the sinusoidal modulation of the optical phase in the reference beam is introduced by vibrating mirrors on PZT transducers [40, 41, 42]. In fiber optic systems, the fiber wrapped PZT transducers were reported in [43, 8]. Atcha and Tatam [32] have presented a setup employing the wavelength modulation of a semiconductor laser to introduce a sinusoidal signal in the reference beam. The visualization of vibrations was achieved by subtraction of consecutive TV frames. For this method the phase shift of π between the frames was introduced by a standard PZT phase shifting device.

Here the attention is focused on the ESPI system in which modulation of the laser diode emission is used for simultaneous realization of the heterodyning process and phase shifting by between consecutive frames for visualization of high contrast vibration fringes.

The fiber optics ESPI system using a semiconductor laser is configured for out-of-plane displacement investigations as described in Section (Fig. 3). In the time-average method the intensity pattern resulting from the interference between the beam reflected from the vibrating object and the reference beam is integrated within duration of one TV frame and registered by a CCD camera. Such image contains information about the amplitude of vibration, but to reveal it one of the visualization methods must be used. Commonly used technique is based on subtracting of two consecutive TV frames shifted in phase by π [14]. Correlation fringes can then be displayed directly on the TV monitor. For harmonically vibrating object the intensity distribution of correlation fringes is expressed by the expression

$$I_R(x,y) = I(x,y)J_0^2(\Omega)_t(x,y)\,, \tag{9}$$

where J_0 is the zero-order Bessel function of the first kind. The argument of the Bessel function is

$$\Omega_t(x,y) = \frac{4\pi}{\lambda}U_M\,, \tag{10}$$

where U_M is the amplitude of vibrations, and λ is the light wavelength.

Source wavelength change providing means to change relative phase between the beams and spectral characteristics of semiconductor lasers can be used for this purpose. Since the wavelength modulation bandwidth is broad, it can be applied to both the sinusoidal phase modulation technique (heterodyning) and π step change implementation. The use of the PZT cylinder or other phase shifting devices can complicate the design. To obtain the phase shift of π the laser wavelength change can be applied thus avoiding the need for any other devices. At the same time the wavelength modulation can be used to introduce the heterodyne sig-

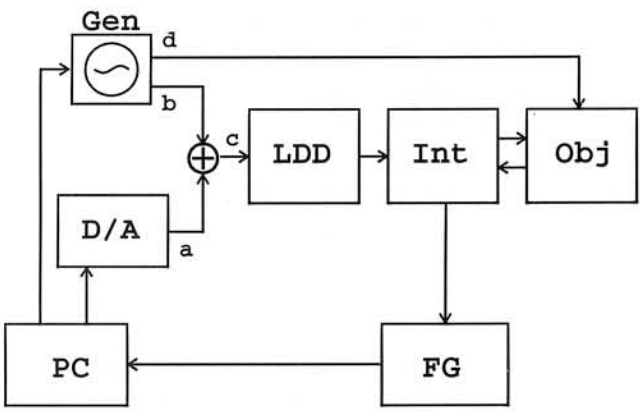

Fig. 9. The block diagram of ESPI system with heterodyning and π shifting realized by wavelength modulation.

nal for the phase shifting method. In the presented design these two features can be combined resulting in a very compact design which is shown in Fig. 9.

The speckle interferometer with known optical path length imbalance (Int) is shown as a module. The object can be excited by a PZT or by other means using one output signal from a dual channel signal generator. Such generator consists of two identical modules, each giving sinusoidal signal at the same frequency, with the possibility of changing the relative phase between the signals. One signal was used to drive the test object (signal d), the other was used to realize the heterodyning method to drive the laser diode (signal b). The π shift signal used for visualization of the correlation fringes (signal a) is generated by a D/A converter card mounted in a PC. This signal is synchronized with the blanking signal of the frame grabber so the transitions between 0 and π phase states are triggered in the time between the frame acquisition. Both signals: the heterodyning and the π shift are summed up and fed to the laser diode driver modulating the current of the

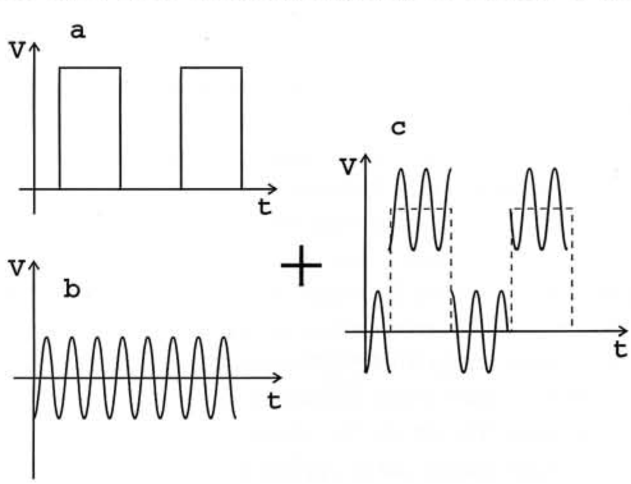

Fig. 10. π and heterodyning signals used to drive the laser diode in the heterodyne interferometer setup of Fig. 9.

laser (signal c). Imposed current changes cause corresponding changes of the laser wavelength and phase. Both signals and their sum are shown in Fig. 10.

By adjusting the relative phase between the object driving signal and the laser diode signal and its amplitude, the required phase shift can be implemented. Amplitude of the π signal needs to be calibrated by other procedures unless the optical path length difference in the interferometer is known a priori [44]. The change in diode current to produce the π phase shift is equal to

$$\Delta i = \frac{c}{2k_v \Delta L}, \tag{11}$$

where c is the speed of light and k_v is the wavelength current coefficient.

The presented technique can be simply extended for the needs of the speckle averaging method as proposed by Joenathan and Korana [45]. In this case another voltage signal which would introduce a number of small phase shifts in order to average the frames must be added to the laser diode driving signal. However, this requires bigger frame storage of the frame grabber and advanced graphical processor able to perform more extensive calculations and display the averaged correlation fringes in real time [42]. In the current setup this feature was not used, but there is a possibility of improving the system performance in this way.

4.4.2. Configuration for studying small amplitude vibrations

The designed interferometer can be also used for investigations of the amplitude and phase of small magnitude vibrations [46]. In this setup two consecutive images of the vibrating object are shifted by π and subtracted using image processing board placed in the host computer following the same methodology as for the heterodyning method. The phase shift of π needed for the vibration visualization was realized by the wavelength shift of the laser light in the interferometer with introduced optical path length difference. In order to improve the signal to noise ratio speckle averaging was used – additional signal was introduced to shift the initial phase by $\frac{\pi}{2}$. Four consecutive vibration patterns were added resulting in a smoother vibration fringe profile. The block diagram of the interferometer is similar to the one used in the heterodyning method (Fig. 9). The final voltage signal applied to drive the

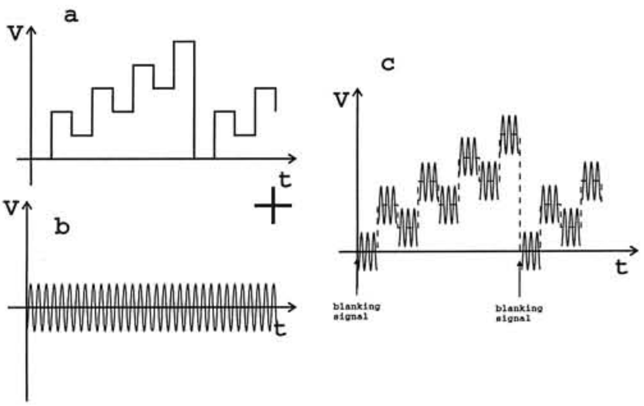

Fig. 11. π, heterodyning and averaging signals used to drive the laser diode in the interferometer setup for studying small amplitude vibrations of Fig. 9.

laser current consisted of π shifting, speckle averaging and heterodyning signals. Their plots are shown in Fig. 11.

The heterodyning signal used in this method is applied to shift the working point to the linear part of J_0^2 function.

The speckle averaging signal and the π signal were produced by D/A converter board placed in the computer and synchronized with the blanking signal of the frame grabber. In this way the transitions between the phase shifted states were triggered between frame acquisitions.

The object was vibrating with maximum amplitude of about 40 nm. In this range the changes of the image intensity associated with the amplitude of vibrations can be approximated by a linear function in the neighborhood of the working point.

4.5. Contouring configuration

Remote shape measurement is one of the most important issues in modern experimental mechanics. Hybrid methodology is making its way to industrial and research laboratories and integration of various specialized packages, e.g., rapid prototyping, FEM, FBM, CAM/CAD, requires precise information about 3-dimensional shape of the object. The measurement process would consist of remote contouring, creation of the object shape model, automatic meshing and finally the analysis based on the calculated and experimentally determined physical properties of the investigated part during evaluation process. This methodology involves several stages that are complicated computationally and experimentally. Reliable shape measurement is one of them.

The interferometer employed for contouring is configured as for the out-of-plane displacement measurements (see Fig. 3). The illumination direction coincides with the observation direction in order to maximize the system sensitivity. A reference frame of an object under test is acquired prior to the wavelength change and stored in the frame grabber operational memory. The wavelength emitted by the laser can be changed by altering the temperature of the junction or the driving current. The frames coming from the CCD camera are subtracted in real time from the reference frame and displayed on the monitor. To achieve the best results the adjustments of the system sensitivity could be made in real time by continuous observation of the amount of the wavelength change.

The method based on the radiation wavelength change by tuning of the junction temperature was reported by Peng et. al [47, 48]. The same effect can be achieved by current modulation but the radiation intensity variations are much bigger than during the temperature changes and to achieve optimum contrast of fringes the output power of the laser diode must monitored and the intensity must be normalized.

After the contour interval is set four phase shifted frames are acquired and sent to the host PC for further processing. The phase shift is realized by the current induced wavelength modulation or using a PZT phase shifter introduced in the reference beam. If the current modulation is used for phase shifting the intensity of acquired images changes introducing errors in the retrieved phase [49]. Normalization of the image intensity must be used or the six-step phase shifting algorithm proposed by Ishii and Onodera [50] must be applied to avoid this influence. Another problem arises from the fact that during the wavelength induced phase shift the difference in wavelengths between the reference and measurement images changes during the phase shifting process. It causes differences in contour interval values between the acquired frames. In this case an additional phase step resulting from the phase shift must be taken into account. It can be compensated using the standard Carre algorithm providing the intensity images are normalized. In measurements with the PZT phase shifter the standard four-frame, $\frac{\pi}{2}$ phase shift algorithm can be used to extract the phase. To have plane contour surfaces the object is illuminated by a plane wavefront.

5. Software

Fringe pattern analysis is a fundamental issue in interferometry and the evaluation methods have been

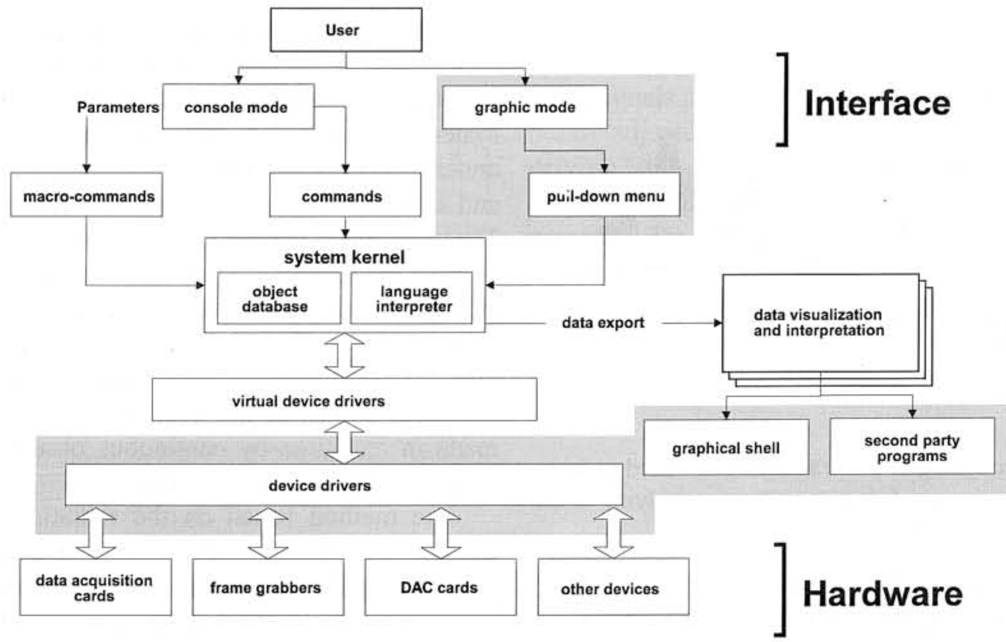

Fig. 12. General architecture of the automatic fringe analysis system. Gray areas show the parts depending on the operating system. All other parts are platform independent.

subjected to constant development throughout last 30 years. The evaluation of speckle images is a quite challenging task because of intrinsic high content of noise and low dynamics of fringes. It is known from experience that it is very difficult to apply, successfully, a predefined set of operators – processing of speckle images is always data dependent and, unless we deal with elementary cases, each data set must be treated separately. There is a large variety of algorithms dealing with this class of data and choosing the right one is an important and sometimes difficult decision. Therefore, there is a need for a system for "full" analysis of optical data. Such a system should have an open architecture, be able to accommodate different algorithms and provide flexibility, in sense of being able to perform complicated tasks automatically, yet giving the operator a full control of the data evaluation process. Also there is a strong tendency to integrate the calculation part with demonstration packages for better evaluation of obtained results.

As the result of a compromise between the goals and the hardware constraints, the idea of the interpreter of the specialized image processing language, oriented towards fringe processing techniques, was proposed. A software package named IMAGE was developed in the Optical Engineering Group -- a program designed to create the environment for the evaluation of data obtained from "fringe methods" and interfacing calculated results to specialized software packages such as FEM programs.

The concept of the interpreter of the specialized image processing language fulfills the whole set of design objectives. The basic operations on images are coded as elementary language commands giving the operator free access to capabilities of the system and making possible the operation on the level of algorithms to test new procedures. At the same time the system has the encoded capability of executing macro commands, i.e., sets of elementary commands and calls to other macro commands as one operation. The mechanism of parameter passing to the macro command execution makes them a very flexible tool similar to the function calls in programming languages such as C or FORTRAN. Most frequently used algorithms such as spatial carrier phase stepping, temporal phase stepping and the fast Fourier transform are coded either as predefined macros or functions of the language itself. The system provides most of frequently used arithmetical functions from the standard mathematical library that can be applied to both images and numbers. It is also prepared to accommodate the image evaluation modules that would realize adaptive functions of the system [51].

The system IMAGE is well suited for all types of fringe data analysis with the emphasis put on the phase stepping techniques and the methods using spatial carrier fringes. The data evaluation is achieved through the execution of sets of commands performing various types of logical and arithmetical operations. The objective of optical techniques is to obtain information about the physical quantity through a set of measurements performed by an optical system. In an interferometric setup the measured quantity is represented by the phase of fringes corresponding to the varying phase of the light wavefront, whereas in other optical arrangements -- to other physical quantities, e.g., moiré technique detects the beat frequency of the projected periodic structure, but still the methodology of measurements is the same – the change of the relative phase of observed fringes is evaluated. IMAGE is well suited to work with phase images which, in turn, after the application of proper algorithms and extraction of quantitative results, can be scaled to the corresponding physical quantity.

Figure 12 shows the architecture of the system. The program philosophy was developed together with Cezary Kosiński and Prof. Malgorzata Kujawińska of the Optical Engineering Group. IMAGE has a modular architecture that allows the configuration to work on different operation system platforms and with different external devices. The choice of frame grabbers, I/O cards and stepper motor controllers is very wide, at the same time they are subject to constant improvements. The system provides a common interface to those groups of devices by standardizing their features, so the core of the system can remain independent of the hardware used. To achieve the hardware independency a layer of virtual device drivers was designed. They communicate with operation system specific device drives which directly drive the hardware. In such a way all commands can be issued in the platform independent format. Of course the performance of the system can vary depending on the devices used. The design of the program makes possible to exploit the very proprietary features of the hardware, therefore, profiting of all its advantages.

IMAGE is designed to perform extensive calculations, acquire data from devices and store them on disk, tape or other storage media accessible from the operating system. Different data types and extensive set of operators specially adapted for the image processing purpose are available to perform all these tasks. The range of operations on floating point and complex numbers covers the basic set of the standard arithmetic library. However, from the point of view of fringe pattern analysis, the most important is the range of operations permitted on image objects. It covers elementary operations such as addition or multiplication but also provides sophisticated operators such as the mask transfer. Along with the set of almost 100 functions it makes possible the design and execution of very complex image processing algorithms.

The system has been coded in platform independent way and works in all major 32-bit operating systems (UNIX platforms, Windows NT, Windows'95, OS/2) but it does not need to be specially configured to work with a particular computer system.

6. Summary

In this paper we report a fiber optic ESPI system employing a semiconductor laser as a light source. Several measurement configurations have been described to measure displacements, their derivatives, vibration amplitude and phase, and the object shape. In comparison with the interferometers reported in the literature the system built in the Optical Engineering Group is characterized by a superior versatility and flexibility. New components introduced in the interferometer allow application of the same system to measurements of several physical quantities without the need of rebuilding the setup. The only operations required to switch to other types of measurements is the change of the illumination scheme and/or the "conventional" to the shear type ESPI head. Both operations are simple and fast. These features facilitate introducing the optical measurement methods in experimental mechanics laboratories and industry.

In the second part of this paper we will present several examples of measurements performed using the described apparatus.

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References

1. J.N. Butters and J. Leendertz: *Holographic and video techniques applied to engineering measurements.* J. Meas. Control **4** (1971) 349.
2. O. Schwomma: *German patent no.298830.* (1972).
3. A. Macovski, D. Ramsey and L.F. Scheafer: *Time lapse interferometry and contouring using television systems.* Appl. Opt. **10** (1971) 2722.
4. K. Galanulis, T. Bunkas and R. Ritter: *Active stabilisation of ESPI systems for application under rough conditions.* Proc. SPIE **2545** (1995) 103.
5. J.L. Santos, T.P. Newson and D.A. Jackson: *Electronic specle-pattern interferometry using single-mode fibers and active fringe stabilization.* Opt. Lett. **15** (1990) 573.
6. C.R. Mercer and G. Beheim: *Fiber optic phase*

stepping system for interferometry. Appl. Opt. **30** (1991) 729.

7. A. Brozeit and K.D. Hinsch: *Actively phase-compensated portable fiber-optic speckle pattern interferometer (ESPI) for long-term in-sitú measurements*. Proc. SPIE **2860** (1996) 144.
8. J.D. Valera, A.F. Doval and J.D.C. Jones: *Combined fibre optic laser velocimeter and electronic specle pattern interferometer with a common reference beam*. Meas. Sci. Technol. **4** (1993) 578.
9. S.E. Moran, R. Lugannani, P.N. Craig and R.L. Law: *Optically phase-locked electronic speckle pattern interferometer system performance for vibration measurement in random displacement fields* J. Opt. Soc. Amer. **A6** (1989) 252.
10. A. Olszak and K. Patorski: *Integrated fiber optic electronic speckle pattern interferometer for investigations of static and dynamic phenomena and contouring*. Proc. COE'96, (1996) 55, in Polish.
11. A.A.M. Maas and H.A. Vrooman: *In-plane strain measurement by digital phase shifting speckle interferometry*. Proc. SPIE **1162** (1989) 248.
12. H.O. Saldner, N. Krishna Mohan and N.-E. Molin: *Comparative TV holography for vibration analysis*. Opt. Eng. **34** (1995) 486.
13. T. Maack, G. Notni and W. Schreiber: *Three-coordinate measurement of an object surface with a combined two-wavelength and two-source phase-shifting speckle interferometer;, Opt. Commun.* **115** (1995) 576.
14. J.C. Davies, C.H. Buckberry, J.D.C. Jones and C.N. Panell: *Development and application of a fibre optic electronic speckle pattern interferometer (ESPI)*. Proc. SPIE **863** (1987) 194.
15. D. Paoletti and G. Schirippa Spagnolo: *Application of fibre optic digital speckle pattern interferometry to mural painting diagnostics*. Meas. Sci. Technol. **4** (1993) 614.
16. D.J. Anderson, J.D. Valera and J.D.C. Jones: *Electronic speckle pattern interferometry using diode laser stroboscopic illumination*. Meas. Sci. Technol. **4** (1993) 982.
17. A.F. Doval, J.L. Fernández and M. Pérez-Amor: *Phase-stepped additive stroboscopic fiber optic TV holography for vibration analysis*. Proc. SPIE **2248** (1994) 229.
18. A.J.P. van Haasteren and H.J. Frankena: *Real-time displacement using multicamera phase-stepping speckle interferometer*. Appl. Opt. **33** (1994) 4137.
19. K.T. Chan, T.P. Leung and J.Z. Zhang: *High-speed automatic measurement of out-of-plane displacement using ESPI*. Opt. Laser Technol. **25** (1993) 3.
20. M. Owner-Petersen: *Digital speckle pattern shearing interferometry: limitations and prospects*. Appl. Opt. **30** (1991) 2730.
21. J.T. Malmo and E. Vikhagen: *Vibration analysis of a car body by means of TV holography*. Exp. Techn. **12** (1988) 28.
22. R.J. Pryputniewicz, *Private communications*, (1994).
23. E. Vikhagen and O.J. Løkberg: *Detection of defects in composite materials by television holography and image processing*. Material Evaluation **48** (1990) 244.
24. J. Kato, I. Yamaguchi and Q. Ping: *Automatic deformation analysis by a TV speckle interferometer using a laser diode*. Appl. Opt. **32** (1993) 77.
25. T. Flemming, M. Hertwig and R. Ulsner: *Speckle interferometry for highly localized displacement fields*. Meas. Sci. Technol. **4** (1993) 820.
26. R. Höfling and P. Aswendt: *Fiber optic DSPI strain gauge system for engineering applications*. VDI Berichte **1118** (1994) 51.
27. A. Olszak, K. Patorski and L. Sałbut: *Comparative studies of ESPI and grating interferometry methods used for determination of in-plane displacements in presence of out-of-plane displacement gradients*. Simulation and Experiment in Laser Metrology, , Z. Fuzessy et al., ed., (1996) 135, Akademie Verlag, Berlin.
28. H. Atcha and R.P. Tatam: *The use of laser diodes and monomode optical fibre in electronic speckle pattern interferometry*. Proc. SPIE **1584** (1991) 221.
29. K. Patorski and A. Olszak: *Modified in-plane electronic speckle pattern shearing interferometry (ESPSI)*. Proc. SPIE **2860** (1996) 256.
30. Y.Y. Hung and J.Q. Wang: *Dual-beam phase shift shearography for measurement of in-plane strain*. Opt. Lasers Eng. **24** (1996) 403.
31. J.-R. Huang, *Optoelectronic Speckle Shearing Interferometry*, Ph.D. thesis, Cranfield University, UK (1996).
32. H. Atcha and R.P. Tatam: *Heterodyning of fibre optic electronic speckle pattern interferometers using laser diode wavelength modulation*. Meas. Sci. Technol. **5** (1994) 704.
33. J.D. Valera and J.D.C. Jones: *Vibration analysis by modulated time-averaged speckle shearing interferometry*. Meas. Sci. Technol. **6** (1995) 965.
34. G. Martini: *Analysis of a single-mode optical fibre*

piezoceramic phase modulator. Optics and Quantum Electronics **19** (1987) 179.
35. J.-R. Huang, H.D. Ford and R.P. Tatam: *Source modulation for phase shifting in static and dynamic speckle shearing interferometry*. Proc. SPIE **2860** (1996) 275.
36. P.K. Rastogi: *Measurement of in-plane strains using electronic speckle and electronic-shearinbg pattern interferometry*. J. Mod. Opt. **43** (1996) 1577.
37. K. Patorski, D. Post, R. Czarnek and Y. Guo: *Real-time optical differentiation for moiré interferometry*. Appl. Opt. **26** (1987) 1977.
38. K. Patorski and M. Wojciechowska: *Real-time differentiation of moiré interferometry patterns by incoherent superimposition of lateral shear interferograms*. Opt. Appl. **20** (1990) 93.
39. K. Patorski, Handbook of the Moiré Technique, Elsevier Science Publishers, Amsterdam (1993).
40. O.J. Lϕokberg and K. Hogmoen: *Use of modulated reference wave in electronic speckle pattern interferometry*. J. Phys. E. **9** (1976) 847.
41. R.J. Pryputniewicz and K.A. Stetson: *Measurement of vibration patterns using electo-optic holography*. Proc. SPIE **1162** (1989) 456.
42. K.A. Stetson, W.R. Brohinsky, J. Wahid and T. Bushman: *An electro-optic holography system with real-time image processing*. J. Nondestruct. Eval. **8** (1989) 69.
43. J.D. Valera, D. Harvey and J.D.C. Jones: *Automatic heterodyning in fiber optic speckle pattern interferometry using laser velocimetry*. Opt. Eng. **31** (1992) 1646.
44. A. Olszak and R.P. Tatam: *Calibration of optical path imbalance in fibre optic ESPI system*. Meas. Sci. Technol., in press.
45. C. Joenathan and B.M. Khorana: *Contrast of the vibration fringes in time-averaged electronic speckle-pattern interferometry: effect of speckle averaging*. Appl. Opt. **31** (1992) 1863.
46. K. Hϕogmoen and O.J. L#okberg: *Detection and measurement of small vibrations using electronic speckle pattern interferometry*. Appl. Opt. **16** (1977) 1869.
47. Y. Zou, X. Peng and H. Tiziani: *Two-wavelength DSPI surface contouring through the temperature modulation of a laser diode*. Optik **94** (1993) 155.
48. X. Peng and Y.L. Zou and G. Pedrini: *A simplified multi-wavelength ESPI contouring technique based on a diode laser system 2: Automatic fringe analysis*. Optik **92** (1993) 114.
49. P. Hariharan: *Phase-stepping interferometry with laser diodes. 2: Effects of laser wavelength modulating*. Appl. Opt. **28** (1989) 1749.
50. Y. Ishii and R. Onodera: *Laser-diode phase shifting interferometer insensitive to the changes in the laser power*. Proc. SPIE **2544** (1995) 173.
51. C. Kosiński, A. Olszak and M. Kujawińska: *Adaptive system for smart image processing*. Machine Graphics and Vision **5** (1996) 245.