Optical Techniques For Shape Measurements

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Abstract:

Optical methods are becoming interesting tools for high resolution surface topography measurements. Micro- and macrostructure measurement techniques were developed to measure the surface topography, resolutions of one micrometer or better can be obtained. The progress made in the last few years is due to the development of laser and solid state detector elements together with very powerful computer support for the processing of information. Methods for optical shape measurements together with future trends and some limitations will be discussed.

1. Introduction

Different techniques can be used for distance and optical 3D-micro- and macrostructure measurements. Time of flight and phase measurement techniques are well known and applied for distance measurements. The principle of triangulation as well as its extension to light sectioning and projected fringe methods can be applied successfully for close range measurements. (1,2) In addition image plane locating systems, interferometric methods as well as confocal principles can also be used for optical topometry.

Moiré techniques or projected fringe techniques are becoming useful tools for topography measurements. They can be applied to determine surface shape or deviation of the shape or vibration amplitudes.

Image plane locating systems have reached a very high technical standard. They can be used to measure the topography of surfaces. Confocal principles were introduced for biological objects mainly. They can be applied for the measurement of the surface geometry of technical objects as well.

Today, laser interferometry is probably one of the most commonly used technique for high resolution measurements in metrology. A stabilized He-Ne-laser is frequently used as light source with an absolute stability of better than 10^{-7}. The accuracy for length measurements is limited by the atmospheric conditions (humidity, temperature, pressure) rather than by the laser stability. Furthermore, single mode diode laser are used in metrology eventhough frequency stability is still a problem especially in interferometry.

Different interferometric techniques are under development to increase the range of application. They may be based on two wavelength , oblique incidence and methods with reduced coherence length. Interferometry, Moiré, holographic and speckle techniques as well as image plane locating systems are frequently used for topometry together with image processing. They are becoming useful tools for precision measurements in research and for industrial applications. Computer analysis is increasingly important for fringe analysis.

The phase shifting technique is very appropriate for digital processing and TV techniques. Two-beam-interferometry together with phase shifting and signal processing lead to a sensitivity of 1/100 of a fringe at any point of the fringe pattern in the TV image. 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 interferometry offers high spatial resolution and interpolation up to 1/1000 of a fringe. Furthermore tools development for CAD needs to be taken into account and adapted when applying topometry in industry.

2. Triangulation

Active and passive triangulation techniques are powerful tools for contactless measurements. Passive triangulation is used in photogrammetry to obtain the topography. For active triangulation a laser spot is projected on to the object. Its image position is recorded on a position sensitive detector or on a CCD-chip (line or array camera). The lateral displacement of the spot image is directly related to the depth variation in the object (fig.1). The resolution of the triangulation techniques is given by

$$dz = \frac{\Delta W . z_0^2}{B} \qquad 1)$$

where z is the working distance, B is the base, Δw is the angular resolution of the detecting system.

Triangulation based 3 D-sensors are appropriate tools for inspection and measurement in industrial environment. Especially synchronized single-spot-scanners fulfil the high requirements upon range, resolution and robustness. In fig. 1 the principle of a scanning triangulation system is shown schematically. The galvano scanner mirrors are controlled by computer to select the x - y coordinates. Angular resolutions of 5 µrad can be obtained. The z coordinate is given by the triangulation principle discussed before. Furthermore a synchronisation of the observation beam with the illumination beam of the scanner may be realized in an optomechanical way, typically by leading the observation beam by a mirror, which is rigidly connected to the scanning mirror of the illumination beam. Due to this rigid coupling of the mirrors there exists one fixed shape, which is imaged onto the scanning position on the detectors. To overcome the lack in synchronisation a computer controlled synchronisation is realized. For this purpose a galvanometer scanner driven mirror is located in the observation beam in front of the imaging lenses (Fig. 2). This mirror deflects the observation beam depending on the angle for all points which lie on the selected reference contour.

The main advantage of the chip synchronization is the possibility to generate an arbitrary reference contour by altering the dependence between the detection and the projecting scanner. This dependence can be found by a teach-in process, where the shape of a masterpiece is measured, in order to act as a reference for the measurements of the following working parts. It is also desirable to get the reference contour from construction data by an analytical expression for instance.(4)

3. Projected fringe techniques for industrial inspection and micro shape analysis

Light sectioning and projected fringes are an extension of the triangulation for out of plane - and topography - measurements. Projected fringe patterns can be formed by different methods such as projecting a grating like structure or an interference pattern. Height variations or deformations lead to a deformation of the projected fringes, which in turn are compared with the original or synthetic grating like structure. Typical contour-line separations can vary between micrometer and millimeter.

In Moiré techniques a deformed grating structure is superimposed onto the original grating to lead to Moiré fringes. The grating structures do not need to be resolved by the image forming system used to form the image of the fringe pattern or the grating onto the detector. Topography, deformations and vibration amplitudes can be analysed.

A number of techniques has been developed for micro - and macrotopography measurements. The choice of an appropriate technique depends on the sensitivity required, which in turn can be adjusted. Furthermore, grating like structures to be projected onto the object can be generated by means of liquid crystal cells. Moiré and projected fringe techniques are not as sensitive as interferometric and holographic techniques but are also less sensitive to environmental disturbances. An arrangement for microscopic topography measurement with projected fringes is shown schematically in fig. 3. The fringe projection occurs at an angle β_1, the observation at an angle β_2 . The projection of the grating as well as its image forming on the CCD camera occurs with the same objective, L_4. High lateral and vertical resolution of the order of 1 µm and 0,1 µm respectively can be obtained.

The grating projection microscope (GPM) extends the range of applications. It will especially be applied where interference techniques cannot be applied such as for rough surfaces (mean roughness > 0,2 µm). The most demanding objects are objects with rough surfaces like sheet-metal, ground and turned metal surfaces, plastics, ceramics as well as biological objects.

The amount of the off-axis shift is matched to the pupil diameter in a way, that the outer first order of the grating spectrum can pass the entrance pupil and sufficient clearance is given for lateral displacement or dispersion of the spectrum of the back-travelling light reflected from inclined or rough surface elements.

For a telecentric GPM-arrangement both the entrance pupil of the imaging system and the exit pupil of the grating projection system lie at infinity in order to compensate variations in height sensitivity.

The grating can be illuminated by a tungsten halogenide lamp L as shown in fig. 3 via Lenses L_1 and L_2 and imaged onto the object by L_3 or can be generated interferometrically. The grating structured image distorted by the object topography is formed onto the CCD interline transfer camera with 756 x 581 picture elements by the objective L_4 and the lens L_5. The conversion of the height variation Δh due to a local fringe displacement Δx in x-direction is for a grating projecting angle ß and an observing angle - ß:

$$\Delta h = \frac{\Delta x}{2 \sin \beta} \qquad 2)$$

4. Interferometry with extended range for precision measurements

The introduction of the laser in 1960 and the progress made recently in automatic fringe analysis are mostly responsible for the widespread application of interferometry in industry today. Fringe analysis is not only important in interferometry, but also in holography, speckle applications and Moiré techniques.

Automatic quantitative evaluation of interferograms requires accurate interference phase measurements, independent of fringe position and intensity variations superposed onto the interferograms. For the fringe analysis <u>static</u> and <u>dynamic</u> techniques are used. Whereas in dynamic techniques an active phase shifting in the interference arrangement is required, it is not necessary in static methods. In many interferometric arrangements, however phase shifting or heterodyne techniques have been introduced for automatic 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^o or 120^o, for instance. The phase of the interference patterns can then be computed from the different stored intensity values. Very frequently 5 interferograms are analysed with 4 phase shifts between. The phase shifting technique is very appropriate for digital processing and TV techniques. Two-beam-interferometry 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. In heterodyne methods the relative phase increases linearly in time and the reference phase is measured electronically at the beat frequency of the reconstructed wave-fields. Heterodyne interferometry offers high spatial resolution and interpolation up to 1/1000 of a fringe. It requires somewhat more electronics and mechanical scanning of the fringe pattern. Alternatively, phase locked techniques can be very attractive for some applications.

Interferometry in a microscope arrangement with fringe analysis can be used for microstructure analysis. Linnik Type 2-beam interference or differential interferometry or Normarski interference contrast can be used with depth resolution of a few Angstroms. For some applications methods based on the principle of very limited coherence length can be useful for topography. A laser source with a coherence length of a few micrometers leads to interference fringes in the limited object height range only. The maximum local fringe contrast in a two beam interference arrangement indicates the smallest optical path difference and can therefore be used for topography measurements.

4.1 Interferometry with oblique incidence

Interferometry is a powerful tool for high resolution measurement of the topography of polished surfaces. It can however not be applied to study and measure the topography and microstructure of optical rough surfaces. Height variations Δz of the object will change the phase ϕ of the reflected object beam. This phase variation detected by an interferometer, for instance can be measured as a function of position x on the surface. A problem occurs when the surface has step height variations greater than $\lambda/2$ in reflection. A discontinuous height variation Δz introduces a phase jump $\Delta\phi$ given by $\Delta\phi = (4\pi/\lambda)\Delta z$. However, the interferometer can only determine the phase ϕ modulo 2π . A reduction in sensitivity is obtained by an oblique incidence of the wavefront onto the test object. The optical path difference in air is $W = 2n\Delta z\cos\theta$, where Δz is the distance between the reference surface and the object in a Fizeau arrangement and θ the angle of incidence onto the object. The optical sensitivity is therefore reduced by $\cos\theta$. For $\theta = 81^\circ$ the effective or synthetic wavelength is 4 µm for a HeNe laser source with λ = 633 nm. In Fig. 4 the incident beam is separated by the prism surface into the reference and object beam with oblique incidence. The reference wave is phase shifted by the piezo driven reference mirror before the reference and object beam are combined. The fringe pattern is projected onto the CCD chip. The special arrangement avoids multiple reflections and image distortions.

4.2 Interferometry with two wavelengths

Surface profiling is a useful application of interferometry where the object beam is focused on an object that is scanned perpendicularly to the beam. The application of interferometry could be drastically increased, when the technique is extended to optically rough surfaces. In addition, with interferometry phase measurement can only be determined with modulo 2π. An increase of the laser wavelength would be useful for the metrology of technical surfaces. Laser sources and the appropriate detectors are frequently not or not yet available. In addition, the high lateral resolution is lost when a IR-laser wavelength is used.
In two-wavelength interferometry where the laser emits light with two slightly different wavelengths λ_1 and λ_2, the interferometer detects two separate interference patterns.
By an appropriate processing of the two individual interference patterns a new interference term of the form $\cos(4\pi\ z/\Lambda)$ is created where Λ is an equivalent or beat wavelength given by
$\Lambda = \lambda_1\ \lambda_2/\ |\lambda_1 - \lambda_2|$
Since the wavelength difference $|\lambda_1 - \lambda_2|$ is usually small, the equivalent wavelength is much larger than the original wavelength used. Laser diodes can be easily tuned and they are capable of generating a wide range of equivalent wavelengths.
The two-wavelengths used can either by time multiplexed or can be present continuously. Furthermore the two-wavelength techniques can be applied in interferometry as well as in holography and speckle-interferometry.

5. Real time holography for topometry

For holographic topography measurements double exposure techniques can be used. Between the exposures the refractive index, the wavelength or the direction of incidence onto the object needs to be changed. In figure 5 the object as well as the reference wave consist of two or more wavelengths in a four wave mixing holographic arrangement. The object illuminated at an angle θ_q is imaged onto the crystal by the lenses L_1 and L_2 and superimposed to the reference.
In the photorefractive crystal $Bi_{12}SiO_{20}$ (BSO) two holograms are stored when two wavelengths are used simultaneously. In the photorefractive crystal the intensity distribution is changed into a density and refractive index variation respectively. The two wavelengths in the reference and object beam from a Krypton laser for instance formed a hologram for each wavelength in the BSO. For the reconstruction only one wave is selected by the mirror. In the plane O" the reconstructed image superimposed with contour lines. The separation of the contour lines is given for

$$\frac{f'_1}{f'_2}\sin\theta_q = \sin\theta_r$$

by

$$\Delta z = \frac{\lambda_1\lambda_2}{(1+\cos\theta q)(\lambda_1-\lambda_2)}$$

where θ_q and θ_r are the incidence angles of the object waves in the object space and reference waves on the BSO. For $\lambda_1 =$ 520,83 nm and $\lambda_2 =$ 530,87 nm contour line separations of 13,9 μm are obtained as can be seen from fig. 6 where contour lines of a coin are shown. They were obtained in quasi real time and can be analysed by image processing. Contour lines in less than one second can be observed.

6. Speckle interferometry for 3D-topometry

Double exposure speckle interferometry can be used for 3D-topometry. Again the wavelength, the refractive index, the direction of the incidence of the wavefront can be changed between two exposures leading to a phase change. An experimental set up where the incident direction was changed in the two illuminating directions by lateral displacement of a low power negative lens or alternatively by the collimating lens is shown in Fig. 7. A tilt variation in the two beams in opposite direction can be introduced with the beam arrangement shown without a noticable disturbance of the wavefront . A simple and robust set up was obtained in this way. With the arrangement shown in fig. 7a no tilt of the contour lines occurs, which would be the case by a tilt in one beam only. Furthermore multi wavelength can be applied for shape measurement of a surface. A wavelength change introduced by means of a diode laser leads to a phase shift between two exposures. The optical arrangement is shown in fig. 7b, where the surface under test is illuminated by a normal incident wave front. For convenience a diffuser is placed in the reference beam. After the reference speckle field is recorded, a second exposure after a wavelength change is recorded. The rate of change of the wavelength by changing the temperature was 0,08 nm/°C. A sensitivity variation of the contour line separation between 20 μm and 3,8 mm was obtained. It should be noted that by a variation of the injection current an undesirable change of the speckle intensities occurs. The method was found convenient to obtain the topography when using speckle interferometry for deformation and vibration analysis of 3D-objects. No other technique needs to be applied for obtaining the topography. Using speckle substraction and automated fringe analysis a 3D-topometry is obtained, leading to a very convenient combined electronic speckle pattern analysis system.

7. Heterodyne Interferometry

Heterodyne interferometry will lead to very useful future applications in precision measurements. For vibration analysis at given points, heterodyne interferometry gives not only the amplitude component of the vibration parallel to the line of sight, but also the frequency. In addition, it can be very useful for fringe analysis in holographic and speckle interferometry.
In a heterodyne interferometric set-up two waves are superposed to lead to a frequency shifted interference phenomenon.
The detected heterodyne signal is arranged to be shot noise limited. There are different techniques to introduce the frequency shift such as using an acousto optical modulator (AOM) or a rotating grating or by using the Zeeman splitting in a laser cavity.
In the DHI (double heterodyne interferometry) two heterodyne interference systems are superposed to lead to a beat frequency of the two wavelengths responsible for the distance measurement.
The heterodyne signals $I_h(t)$ are

$$I_h(t) = 2\sqrt{I_{r_1} I_{s_1}}\cos(2\pi f_1 t + \phi_1) + 2\sqrt{I_{r_2} I_{s_2}}\cos(2\pi f_2 t + \phi_2) \qquad 3)$$

I_{r1} , I_{s1} , I_{r2}, I_{s2} are the intensities of the interfering reference and signal beams for the two wavelengths λ_1 and λ_2 , f_1 and f_2 are the heterodyne frequencies

$$\begin{aligned}\phi_1 &= \frac{4\pi}{\lambda_1}z - 2\pi\left[\frac{\nu_1+f_1}{c}\right]L \\ \phi_2 &= \frac{4\pi}{\lambda_2}z - 2\pi\left[\frac{\nu_2+f_2}{c}\right]L\end{aligned} \qquad 4)$$

z is the object distance to be measured and c the velocity of the light, ν_1 , ν_2 are the frequencies of the corresponding wavelengths λ_1 and λ_2 , L is the reference path. The heterodyne signal after the mixer is $I_{sh}(t)$ (superheterodyne signal)

$$I_{sh}(t) = 4\sqrt{I_{r_1} I_{s_1} I_{r_2} I_{s_2}}\cos\left[2\pi(f_1-f_2)t + \frac{4\pi}{\Lambda}z - \frac{2\pi}{c}(\nu_1+f_1-\nu_2-f_2)L\right] \qquad 5)$$

where $\Lambda = \lambda_1\lambda_2/|\lambda_1-\lambda_2|$

In double heterodyne interferometry two laser wavelengths and two heterodyne frequencies are used simultaneously. A low frequency detection signal with a phase shift that corresponds to the effective wavelength is generated. A two-wavelength double heterodyne interferometer (DHI) setup consists basically of two independent heterodyne interferometers working at different wavelengths λ_1 and λ_2 and different heterodyne frequencies f_1 and f_2 The phase of the beat frequency $f_1 - f_2$ depends on the effective wavelength and can therefore be examined for distance evaluation as has been shown in (9,10).

The DHI is very appropriate for high precision absolute measurements. There are different possibilities for the realization of a DHI. At first two diode lasers giving λ_1 and

λ_2 look very promising. An interesting way to obtain various wavelengths is to use a single laser diode in combination with a Bragg cell working at very high frequency (> 500 MHz) and two acousto optic modulators (AOM's).

Heterodyne interferometry is a powerful tool for high precision distance measurements and vibration analysis. Two wavelength heterodyne techniques become very interesting for absolute distance measurement. A synthetic wavelength can be generated by two shorter ones, leading to techniques for absolute measurements and measuring on optically rough surfaces. The theory is based on the assumption that the optical path difference is to be compared with the synthetic wavelength. For object shape measurement the DHI system will be combined with a x-y scanner. Very high depth resolution is obtained from optically rough surfaces.

Conclusion

Different optical methods can be used for shape measurement. The range and sensitivity need to be selected. The methods are contactless and fast. Interferometric methods are sometimes, however too sensitive with respect to environmental disturbances and roughness of technical objects. Furthermore surface roughness leads to unwanted speckles to be taken care of by the analysis and information processing. Methods developed are presented to measure the topography of optically rough surfaces. Oblique incidence and 2λ interferometry are possibilities to overcome some of the limitations. For some applications real time holographic contouring and speckle techniques can be very useful.

References

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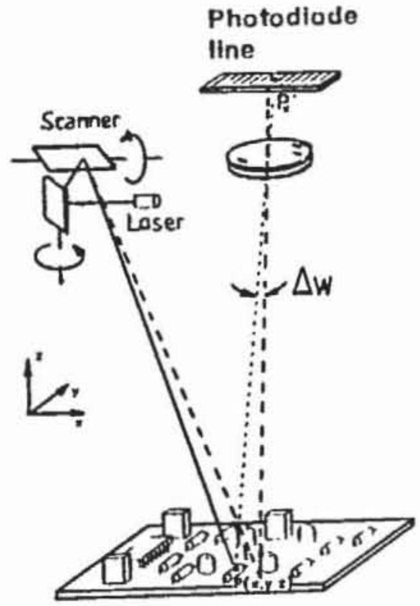

Fig.1:
Principle of dynamic triangulation

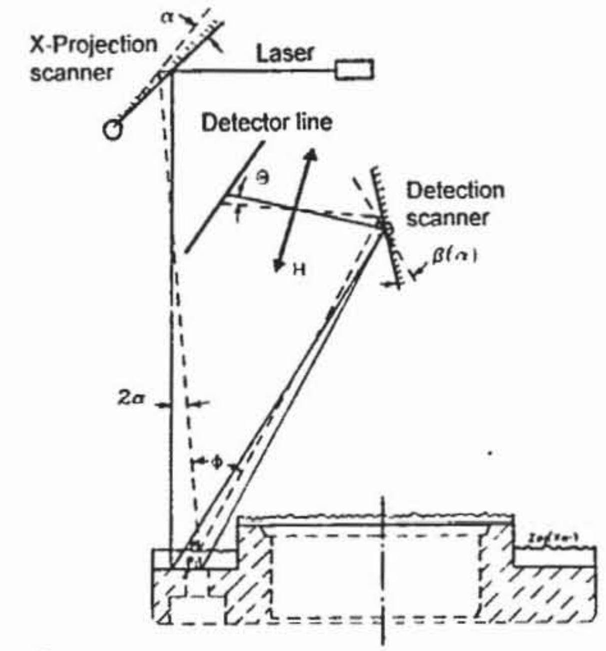

Fig. 2:
Dynamic triangulation with additional computer controlled mirror in the imaging path.

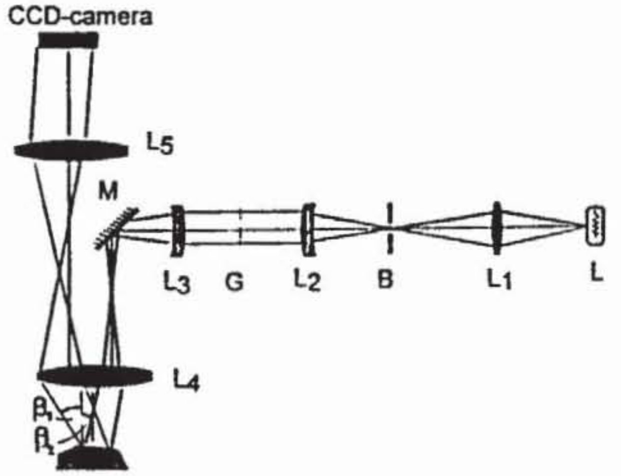

Fig.3:
Fringe projecting microscope

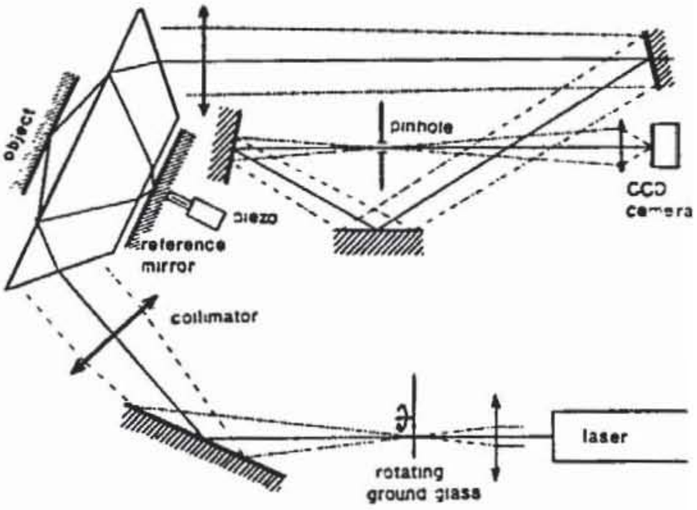

Fig.4:
Arrangement for interferometry with oblique incidence

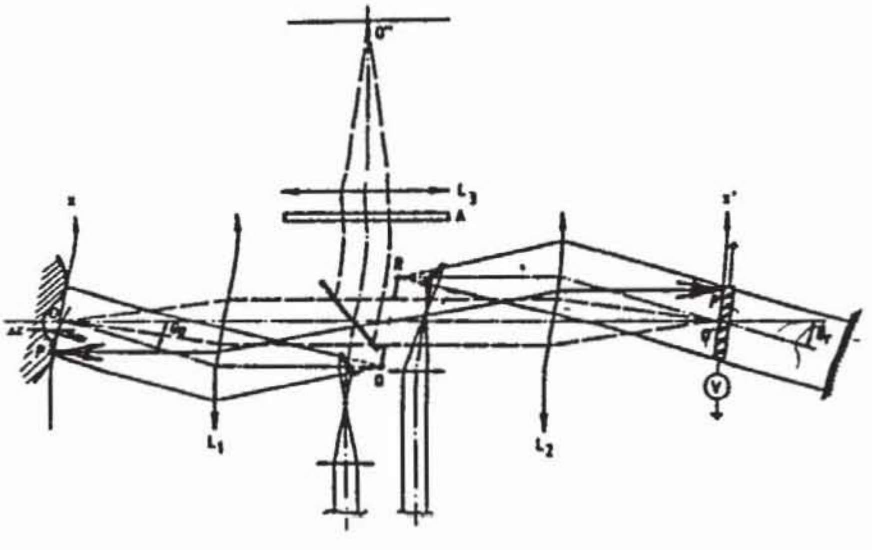

Fig.5:
Arrangement for quasi realtime contour holography with two and more wavelength using a BSO storage material

Fig. 6:
Result of a quasi real time contouring of a coin by using
λ_1 = 520,83 nm and
λ_2 = 530,87 nm
leading to a contour line separation of 13,9 um

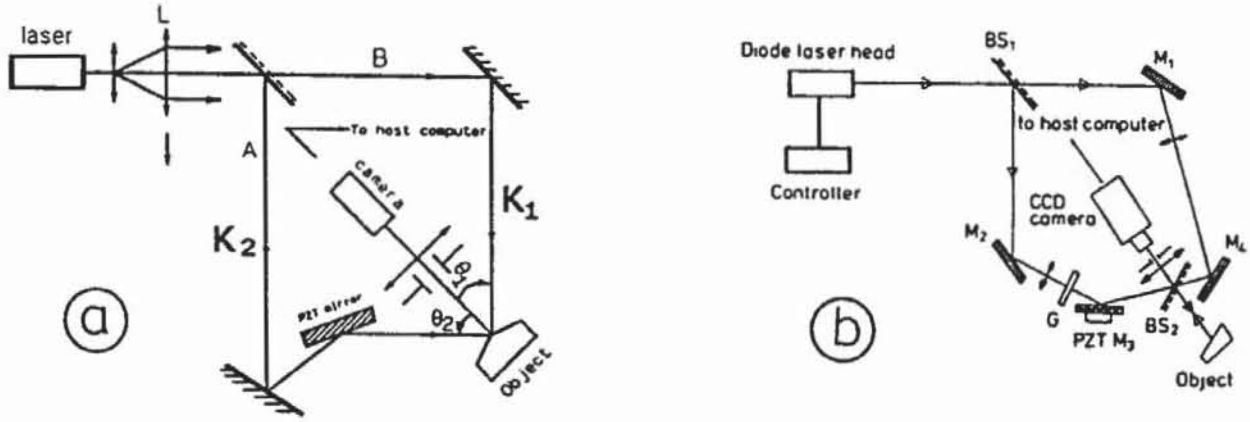

Fig. 7:
Principle of set up for contouring using
7a) double exposure speckle interferometry with different tilts and
7b) different wavelengths