METROLOGICAL STUDIES WITH AN ELECTRO-OPTICAL SENSOR

By

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TO

Shrila Kishori Saran Babaji Maharaj

My Silent Preacher

C E R T I F I C A T E

Certified that the dissertation entitled "Metrological Studies with an Electro-Optical Sensor", which is being submitted to the Indian Institute of Technology, Delhi by LAKHAN SINGH TANWAR in fulfilment for the award of the degree of DOCTOR OF PHILOSOPHY is a record of the student's own work carried out by him under my supervision and guidance. The matter embodied in this dissertation has not been submitted for the award of any other Degree or Diploma.

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Dr. B.N. Gupta
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A C K N O W L E D G E M E N T S

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(L.S. Tanwar)

S U M M A R Y

Sensor is an indespensable device for any dimensional measurement, one of the core areas for the advancement of science and technology. Non-contact electro-optical (EO) instrumentation for sensors is coming up very fast to fulfil the present day demands of Advanced Manufacturing Technology's (AMT) on-line and in-line high speed production and quality control. A new optical triangulation principle based EO sensor for precision laboratory and high speed measurement has been developed. The sensor's design parameters alongwith its characteristics have been investigated and some of its applications are reported in the thesis. The thesis has been divided into 4 chapters. The chapterwise brief discussion is as follows:

The first chapter entitled "The introduction of EO sensor", introduces the field of dimensional metrology in general and that of sensors in particular. The significance of various length measurements to different discipline of science and engineering ranging from the size of nucleus to that of light year scale is indicated. Restricting to the usage of length measurement to industrial applications, broad classification of dimensional measuring instruments is given. A length measuring system irrespective of its one, two or three-coordinates measuring capabilities has

been analysed into its three precision deciding components namely; the sensor, the main displacement measuring device and the reading device. It is followed by a brief survey of the different principles used for the three components with their performance capabilities.

The fast developments in the manufacturing engineering such as automation, high speed with accurate material removal processing and the integration of computer and digital data handling capabilities have resulted in the AMT placing new demands for its industrial metrology. It is shown that the main displacement measuring systems alongwith their reading devices have sufficient margin to cope with the new situation in respect to their resolution and operational speed, the sensor remains the weakest link in the AMT high speed production and quality control loop. Limitations of the conventional sensors in this context have been listed out. The technological gap thus created has been filled by the development of the EO sensors. The first chapter ends with the introduction to EO sensing characteristics needed to meet the high speed adaptive control requirements.

Chapter 2 entitled, "The principle of the developed EO sensor" begins with a brief description of the various EO principles followed by the limitations in general of the available EO sensors. The principle of the developed EO sensor is discussed next. Optical triangulation based system using white light illumination and differential photo-detection at oblique angles is sensitive to both polished and rough surface targets. General theory of the triangulation based sensor is therefore presented. Experimental details of the set-up used and the characterstics of the EO sensor studied are discussed. The sensor using micro-optic components is assembled on a UMM. Light from a halogen lamp through glass fibre bundles illuminates an aperture projected on to the target surface. The target surface is aligned with its normal to the y-axis of the UMM, the measuring direction. In the specular reflection direction pick-up optics images through reflected or scattered light the light fleck on a difference photo detector . The displacement of the target causes the movement of the detection fleck on the detection plane, thereby giving corresponding difference signal. Symmetric illumination of the two photo-diodes gives rise to null photo signal displayed on an x-y recorder. After giving an account of necessary alignment procedures the sensitivity curves shown for different surfaces are drawn. The sensor has been found to be sensitive practically to all types of material surfaces giving linear displacement signal in $\pm$ 70 μm range. The discussion of the effect of design parameters on sensitivities is also given. The parameters discussed are, focal lengths of detection optics, and illumination and detection angles. The two angles should be equal in case of polished surface targets.

Any tilt from the ideal directions of the EO sensor leads to sensors measurement errors in case of polished targets. Theoretical investigations and the experimental tilt error free adjustment procedure have therefore, been described in a separate section. The important conclusion is that the detector plane and the target plane must be conjugate planes. A simple procedure to achieve this is reported.

Null and deviation modes of measurement of the EO sensor are explored in the last section of chapter 2. Resolution and repeatability of the order of 0.01 µm in case of plane polished target surfaces is established.

Chapter 3 contains an account of the application of EO sensor. It has been applied for

(i) laser interferometric block gauge calibration.

(ii) surface roughness measurement

(iii) linear thermal expansion measurement

(iv) vibration detection and measurement, and

(v) silicon wafer thickness variation detection.

For gauge block interferometric calibration, a cross EO sensor has been assembled. It is to gauge both the faces of the block gauge one after the other. Laser interferometer has been coupled in the gauging direction to measure the distance travelled between the two null positions. Because of the slide restrictions, the calibration has been performed for two gauges; one for slip gauge upto 70 mm length and another of 1 m end gauge. Precesion of 0.05 µm and 0.3 μm have been achieved respectively in the two cases. The latter precision is limited due to the presence of induced vibrations in the set-up.

In the next section, surface roughness measurement using the EO sensor is discussed. Five standard steel grooved rough surfaces have been chosen with different roughness for this study. These rough surfaces are scanned by the light fleck and the difference photo-signal is plotted. The standard deviation of the trace is taken as a measure of surface roughness. The trace characteristics i.e. its amplitude and frequency, however, have been found to be dependent on the design parameters of the EO sensor. These investigations reveal that for a configuration and a surface roughness, the amplitude deviations are minimum for a particular fleck size. The phenomen has been explained on the basis of the grating like behaviour of the grooved surfaces. An equivalent grating constant determined by EO sensor has therefore, been suggested to characterise the surface roughness by the non-contact method.

Surface roughness study also suggests the proper position of rough surfaces with respect to the measuring and groove directions to minimise the errors in length measurement.

Linear thermal expansion measurement by the EO sensor is described as the third application. It utilizes the high resolution of 0.02 μm in its linear range of ± 70 μm.

Thermal expansion of an alumina rod of 55 mm length is measured by attaching a plane mirror to the dilatometer extension rod. The simple technique offers high resolution for small specimen.

The presence of induced vibrations in the experimental set-up for 1 m end gauge calibration has been detected by the EO sensor. The investigations in this connection are reported under this head. The sensor can detect the presence of small amplitude vibrations in wide frequency range. The experience gained in detecting the vibrations with the EO sensors has been utilized in mounting the sensor at a location of minimum vibration amplitude on the machine bed for performing the calibration.

Preliminary studies on non-contact silicon wafer thickness variation detection and measurement have been presented as the last application of the EO sensor in this chapter. Using cross EO sensor both the faces can be gauged alternately or simulteneously depending upon the provision for adjusting the feeler constant of the cross assembly. The former approach has been adopted and a precision of 0.2 μm has been achieved in its initial studies.

Chapter 4 contains the conclusion and suggestions for the further work in this direction. Apart from the high resolution and in-built linear range capabilities of the developed EO sensor, the sensor's performance has been compared with other commercially available sensors. Its ability to find highest point and two dimensional measuring capability are highlighted. As further developments, use of modulated light beam with normalised photo-signal processing has been suggested. Ultimately the sensor's flexibility for wide range of applications by fulfilling the desired sensor gap has been indicated by listing out some of the applications it can be put to use.

I N D E X

CHAPTER 1 Page

DIMENSIONAL METROLOGY
SENSORS

CHAPTER 2

PRINCIPLE AND DESIGN OF THE DEVELOPED EO SENSOR

CHAPTER 3

SOME APPLICATIONS OF EO SENSOR