

NANO-LINEAR ENCODER INVESTIGATION USING DUAL FIBER AND GRATING SYSTEM

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ABSTRACT

Measurement of linear displacement to nanometer levels represents a relative broad industry need within the variety of assemblies currently under development as part of the nanotechnology. In the area of manufacturing, some notable examples that require nanometer level measurement include miniature machine tools, microlithography position stages, dip-pen and imprint lithography stages, and scanned probe microscopes to name but a few.

In present encoder technology linear encoders comprise a wavelength dependent dual grating system, with an illumination source, beam splitter and a detector. This paper presents an investigation to eliminate the optics and use dual fiber (illumination) system, one grating and a detector. Two optical fibers are separated by a distance $\lambda/4$ or $(2m-1)\lambda/4$, each optical fiber will produce a sine wave and, because they are separated by $\lambda/4$ (a spatial phase shift of 90°), will produce an A/B output. Detail mathematical study on dual fiber and grating interaction is being undertaken. A mathematical model and is presented. From this model using Matlab diffraction was observed with separation distance between grating and fiber as 5 mm. Along with theoretical developments an experimental program is in progress. The experimental apparatus consist of a grating attached to a computer controlled PZT driven platform and the stationary dual fiber system running over the grating. Constant separation distance between the grating and the fiber maintained using flexure based support and a skid mount. Dual fibers run over the grating relatively with collection of the intensity variation data from a photo diode (FDS 100) located below the grating. Data acquisition was accomplished using LabView program. Near filed approach using dual fiber- grating system is considered as future steps of the investigation.

INTRODUCTION

Length measurements in the nanometer-scale regime are accomplished by a number of methodologies, including, capacitance,

inductance, tunneling, atomic-force, electron, and visible and ultraviolet light optical interactions (usually interference). Computer modeling and standards development are also integral parts of the measurement process. Optical Encoders with gratings divided into micro-meter pitch are widely used on machines and metrology systems. Renishaw, SONY and Heidenhain manufacture encoders with resolution to a few nanometer levels or below. Principally these encoders measure displacement by monitoring the phase change of a laser beam as it passes through, or reflects from, a grating. These include either two grating system or single grating double pass system. Figure-1 below shows the typical operation principal of the SONY laser scale.

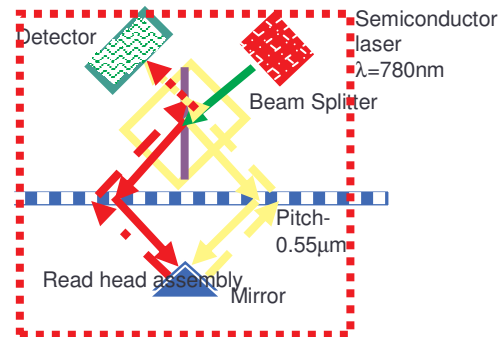


FIGURE-1 OPERATIONAL PRINCIPAL OF SONY LASER SCALE

The beams are collected at the detector where the detector system converts the interfering beams into electrical signals. Most optical encoder systems are arranged to produce A/B quadrature, when the scale moves, phase of the two signals changing in proportion to the direction and amount of travel. The encoder resolution is limited by several factors such as the grating pitch (that is, in turn, limited by the wavelength of the illuminating beam), light collected back at the detector, the phase shift added by the return path light with incident light. It has been found that the installation of detector and the grating scale assembly requires

considerable skill when work volumes are highly compact using present encoders.

Accuracy and resolution of an encoder can directly be enhanced by reducing the pitch of the encoder gratings. When using diffractive based sensing methods, reduction of pitch leads to a higher reflected beam angle, so partial reflected light will be collected at the detector. This will increase the size of the detector as well as creating an ambiguity in phase discrimination thereby imposing a limitation with current designs. The goal of this project is to investigate the possibility of using dual fiber probes as phase producing elements along with a high pitch grating, to measure displacement.

THEORY

To understand the theory of dual fiber and grating interaction a mathematical model is defined as shown in the Figure-2 below.

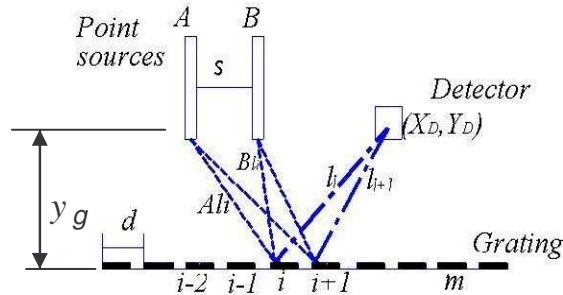


FIGURE-2 MATHEMATICAL MODEL FOR GRATING AND DUAL FIBER

Let d is the spacing between the grating lines, s is the separation distance between dual fibers (A & B), x_o is the distance from a reference to first fiber, let y_g is the constant separation distance between fibers and the grating and the wavelength of light is 633 nm. The amplitude of the illumination at each point on the diffraction grating in a 2-D model can be obtained from the vector sum of the (assumed) coherent illuminations of amplitude A_o from the two point sources. To determine this, it is necessary to know the path length between each source (A and B) and the i^{th} point on the grating. And that can be given by

$$\begin{aligned} A_i &= \left((id - x_o)^2 + y_g^2 \right)^{1/2} \\ B_i &= \left((id - x_o - s)^2 + y_g^2 \right)^{1/2} \end{aligned} \quad (1)$$

The phase of the incident illumination from each source is proportional to path length and given respectively by the equations

$$\begin{aligned} \phi_{Ai} &= \frac{2\pi}{\lambda} \left((id - x_o)^2 + y_g^2 \right)^{1/2} \\ \phi_{Bi} &= \frac{2\pi}{\lambda} \left((id - x_o - s)^2 + y_g^2 \right)^{1/2} \end{aligned} \quad (2)$$

Consequently, these two illuminations will combine vectorially to produce a new source at the point i on the grating of magnitude

$$A'_{oi} = A_o \left[\frac{1}{A_i^2} + \frac{1}{B_i^2} + \frac{2}{A_i B_i} \cos(\phi_{Ai} + \phi_{Bi}) \right] \quad (3)$$

Substituting (1) and (2) into (3) gives

$$A'_{oi} = A_o \left[\frac{1}{(id - x_o)^2 + y_g^2} + \frac{1}{(id - x_o - s)^2 + y_g^2} + \frac{2 \cos\left(\frac{2\pi}{\lambda} \left[\left((id - x_o)^2 + y_g^2 \right)^{1/2} + \left((id - x_o - s)^2 + y_g^2 \right)^{1/2} \right]\right)}{\left((id - x_o)^2 + y_g^2 \right)^{1/2} \left((id - x_o - s)^2 + y_g^2 \right)^{1/2}} \right]$$

Additionally, it is necessary to know the phase of the source at each i^{th} point on the grating.

$$\begin{aligned} \phi'_{oi} &= \tan^{-1} \left(\frac{\left[\frac{1}{A_i} \sin \phi_{Ai} + \frac{1}{B_i} \sin \phi_{Bi} \right]}{\left[\frac{1}{A_i} \cos \phi_{Ai} + \frac{1}{B_i} \cos \phi_{Bi} \right]} \right) \\ &= \tan^{-1} \left(\frac{\left[\frac{B_i \sin \phi_{Ai} + A_i \sin \phi_{Bi}}{B_i \cos \phi_{Ai} + A_i \cos \phi_{Bi}} \right]}{\left[\frac{B_i \cos \phi_{Ai} + A_i \cos \phi_{Bi}}{B_i \cos \phi_{Ai} + A_i \cos \phi_{Bi}} \right]} \right) \end{aligned}$$

Having an expression that transforms from the fiber sources to the amplitudes and phases at each i^{th} scattering point on the grating, it is possible to express the amplitude of the reflected illumination at a detector location (x_D, y_D) . For an infinite grating, this is simply the sum of all illuminations arriving at the detector from each point on the grating given by

$$\sum_{i=-\infty}^{\infty} \frac{A'_{oi}}{l'_{Di}} \cos\left(\phi'_{oi} + \frac{2\pi}{\lambda} l'_{Di}\right) = \sum_{i=-\infty}^{\infty} A_{Di} \cos(\epsilon_i)$$

Where l'_{Di} is the distance from the i^{th} scattering point on the diffraction grating to the detector. The above can be reduced to a simple amplitude A and phase θ of the form

$$A_D = R \cos(\theta)$$

Where

$$R = \left[\sum_{i=-\infty}^{\infty} (A_{Di} \cos(\epsilon_i))^2 + \sum_{i=-\infty}^{\infty} (A_{Di} \sin(\epsilon_i))^2 \right]^{1/2}$$

$$\theta = \tan^{-1} \left(\frac{\sum_{i=-\infty}^{\infty} (A_{Di} \sin(\epsilon_i))}{\sum_{i=-\infty}^{\infty} (A_{Di} \cos(\epsilon_i))} \right)$$

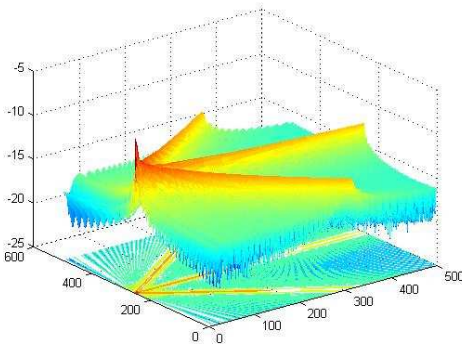


FIGURE-3 DIFFRACTION ORDERS FOR 1 μm GRATING SPACING AND DUAL FIBER GRATING SEPARATION OF 5 mm

The 3D plot of the intensity computed from this analysis is as shown in the Figure-3 for a separation distance of 5 mm which is a typical example of fraunhofer diffraction. Various parameters such as grating spacing, separation distance between grating and fibers, fiber separation distance were analyzed. Intensity plots variations were observed with change in especially grating spacing and grating separation distance.

Based on the theoretical analysis in Matlab the dual fiber and grating interaction in far field yields a diffraction solution

Experimental Setup

Figure-4 below shows the schematic representation of PZT driven and flexure based computer controlled displacement measurement platform setup used for experimentation.

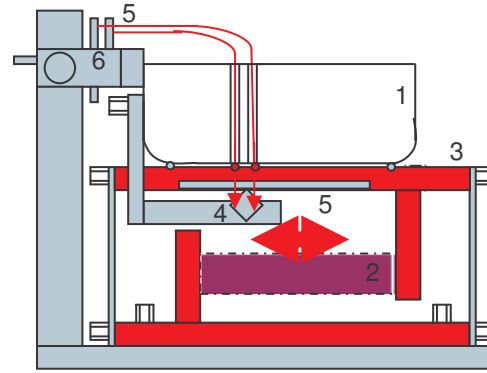


FIGURE-4 SCHEMATIC REPRESENTATION OF DISPALCEMENT MEASUREMENT SETUP
1. SKID-MOUNT, 2.PZT, 3.FLEXURE-STRUCTURE, 4.PHOTO-DIODE, 5.GRATING, 6.DUAL FIBER

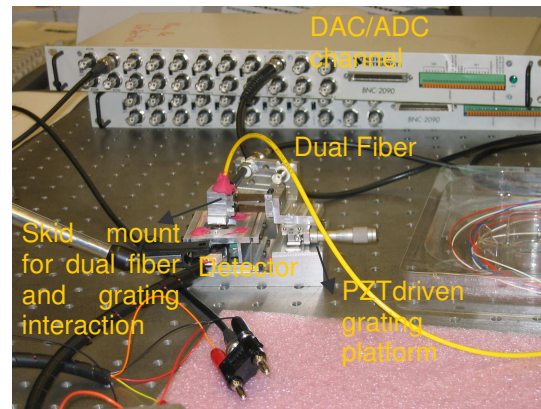


FIGURE-5 EXPERIMENTAL SETUP FOR DISPALCEMENT MEASUREMENT USING DUAL FIBER ANG GRATING

The skid mount and the flexure support makes the fibers run over the grating with constant separation distance. For course motion of the skid mount in the initial adjustments with detector position linear stage is used (Newport-M-SDS25). The laser source used is 633 nm wavelength pigtailed lasers (FDRV0635-005SFO) from Bluesky research co. This laser is operated on 5 V DC source with output power of 5mW, using a fiber coupler and a standard FC connector output from the laser is distributed among two fibers. Two bare fibers were coupled with the coupler fibers using fusion splice technique. Shielding provided on the bare fibers and the ends of the bare fibers were held together by bonding them into a ferrule. Photo diode used in the data collection is FDS 100 from Thorlabs. This photodiode was characterized for the noise, and sensitivity before the experimentation. Based on the characterization results the sensitivity of the diode is 95% and the noise power spectral

density when observed on the spectrum analyzer (SRS 780) is $1\text{mV}^2/\text{Hz}$ for 120 Hz bandwidth. Using an adjustable dial indicator stand the photodiode is positioned below the grating. The photodiode is operated with 15V reverse bias operation. Using electronic circuits for noise and amplitude detector performance was improved. The flexure based platform on which the grating is mounted is calibrated for the 17 micrometer of displacement using a capacitance gauge (Lion Precision™). Voltage is applied to the PZT using LabView program, through a DAC channel, and single channel piezo driver (MDT691 Thorlabs). The output signal from detector was recorded using an ADC. Low pass filter was used in the output signal from detector to eliminate aliasing effect.

RESULTS

Currently the experimental apparatus is being developed to measure the displacement and address issues like repeatability of data. An investigation in near field sensing is also ongoing.

CONCLUSION

The theoretical study has been initiated to identify the diffraction for far field situation. This study also helps understand the details of mathematical modeling of grating and dual source interaction.

Near field approach is considered as next steps of investigation. The future steps are to redesign the platform for grating mounting such that feedback system can be incorporated for near field experimentation. Also design of holding ferrule for dual fiber at some constant separation distance is important. Detector positioning design is critical for collecting signal from the near field interaction.

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