

DESIGN AND ANALYSIS OF A NANO-STEPPING DEVICE

Y. Gao *, X. Liu, K. Yuen

Department of Mechanical Engineering, Hong Kong University of Science and Technology
Clear Water Bay, Kowloon, Hong Kong
* E-mail: meygao@ust.hk

Introduction

As the development of manufacturing technology is shifting its focus to the nanometer level resolution, many research and development facilities and applications are demanding low cost and convenient to use displacement measurement and calibration facilities at the nanometer level resolution. Current measurement and calibration devices, that are capable to achieve nanometer level precision, mainly rely on the techniques utilizing the heterodyne interference [1-2], the Fabry-Perot (F-P) interference [3-4], the swept-frequency interference [5], and the differential interference principle [6-8]. The devices can be complex and expensive, and sensitive to external environmental influences, with a very limited measurement range.

To address the above issues, a new nanometer level stepping displacement measurement and calibration device is proposed. The device is based on the multi-beam interference principle and photoelectric sensors. The working principle of the proposed device is introduced, key design parameters are analyzed. The expected resolution is 0.2nm and displacement range 100 μ m. Simulations and numerical analysis are performed to demonstrate the characteristics of the device.

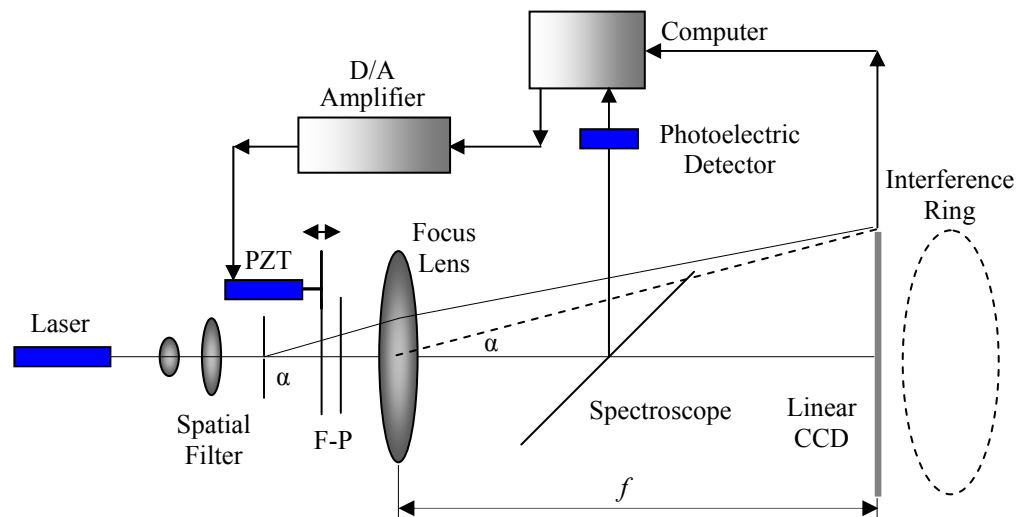


Fig. 1 Schematic diagram of the nano-stepping device

Working Principle

The proposed nano-stepping device (Fig. 1) consists of a laser with a stabilized frequency, a spatial filter, a F-P etalon as the multi-beam interference cavity, which consists of two plane mirrors with reflective index of more than 90%, a focus lens, a linear CCD detector, a PZT

driver, and data sampling and control circuits. According to the multi-beam interference principle [9], when a group of rays from the pin hole of the spatial filter incident onto the first mirror at an angle α , multiple beams are generated behind the second mirror with a parallel propagation direction. The beams are focused by the focus lens on to the focus plane for interference. The obtained interference patterns correspond to the optical path difference between the beams, which can be expressed as $2d\cos\alpha$ [9], d is the distance between the two mirrors.

The ray angle corresponding to the m th order bright interference ring behind the focus lens satisfies $2d\cos\alpha=m\lambda$. According to the lens focusing principle, the ring diameter corresponding to the incidence angle α is $D=2f\tan\alpha$, where f denotes the focal length of the focus lens. The obtained interference ring distribution on the whole focus surface, also the CCD plane, is shown in Fig. 2.

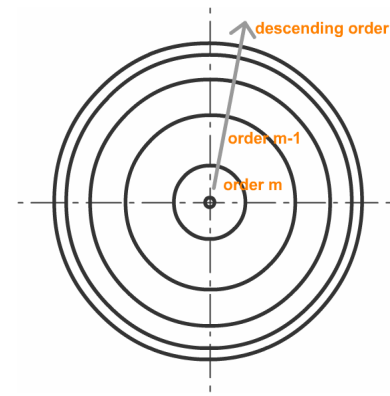


Fig. 2 Interference rings on CCD

When the distance between the two mirrors in the F-P etalon is changed, the diameters of all orders of interference rings on the focus plane will vary. The zero order ring shrinks into, or come out, of the center on the photoelectric detector surface. Thus the displacement related with the relative movement of the two mirrors can be obtained through interference ring acquisition and analysis. If the intensity at the center is examined through the photoelectric detector, it will help to achieve a large displacement range that corresponds to integer multiples of $\lambda/2$. For the design, we can calibrate the displacement of the PZT that drives one of the mirrors to change the distance between them. The stepping displacement for calibration is to be realized through driving one mirror by the PZT to generate a stepping displacement which is accurately monitored by the CCD and the photoelectric detector. If the ratio between the interference ring diameter change and the distance change of the two mirrors is sufficiently large, the displacement measurement of a very high resolution can be achieved. To achieve a large measurement range, the interference ring order will be counted through the use of the photoelectric detector at the center. The device can be compact in size. The Abbe principle and the shorted link rule for precision mechanism design can be easily satisfied to achieve good stability and immunity to environmental disturbances for ease of use and reliability under laboratory conditions.

Design Analysis

For the proposed design, for the objective of a displacement range of $100\mu\text{m}$ and a resolution of 0.2nm , suitable design parameters should be determined to ensure a larger ratio. This means that, when the distance d of the two mirrors varies in the whole scope of $100\mu\text{m}$ by 0.2nm , the CCD detector is able to distinguish the diameter change of the interference ring on the surface. Other parameters are selected. The length of the linear CCD is 48mm . Its resolution, or the distance of two neighboring pixels, is $7\mu\text{m}$. The wavelength of the laser is 632.8nm . The main parameters that affect the resolution and range of the displacement stepping device are the focus length of lens f , the distance range of the two mirrors d , and the wavelength drift $\delta\lambda$, caused by the laser instability.

Preliminarily, the distance between the mirrors is $250\mu\text{m}\pm 50\mu\text{m}$. Close to the distance of $200\mu\text{m}$, the order number of the interference ring corresponding to 0 incidence angle is m_0 , where m_0 can be obtained as $m_0=\text{fix}(2d/\lambda)=632$. From the above, $2d=m_0\lambda$. Similarly, close to the distance of $300\mu\text{m}$, the order number m_1 can be obtained as $m_1=\text{fix}(2d/\lambda)=948$. Based on the analysis,

$$2d \frac{2f}{\sqrt{D^2 + 4f^2}} = m\lambda, \text{ and } d = \frac{m\lambda}{2} \sqrt{\left(\frac{D}{2f}\right)^2 + 1}. \quad (1)$$

Therefore,

$$\frac{\partial D}{\partial d} = \frac{16fd}{m\lambda\sqrt{4d^2 - m^2\lambda^2}}, \frac{\partial d}{\partial f} = -\frac{4m\lambda D^2}{f^2\sqrt{D^2 + 4f^2}} \text{ and } \frac{\partial d}{\partial \lambda} = \frac{m}{2} \sqrt{\left(\frac{D}{2f}\right)^2 + 1}. \quad (2)$$

The linear CCD can discern the change of distance d only when the change of ring diameter D caused by the d change is larger than the CCD resolution of $7\mu\text{m}$. In an optical design, the error of f is usually controlled under 0.1mm . The measurement error of displacement induced by the error of focus length should be less than the required resolution of 0.2nm . Thus the two conditions

$$\frac{\partial D}{\partial d} > \frac{7000}{0.2}, \text{ and } \left| \frac{\partial d}{\partial f} \right| < \frac{0.2}{100000}, \quad (3)$$

should be satisfied.

From the initial setting of the distance between the two mirrors, m_0 , m_1 , Eq. (2), and the condition (3), it can be seen that, for the expected properties of the proposed design, the focus length should be $f > 391\text{mm}$, and the displacement range can be $d=200\text{-}300\mu\text{m}$, the monitored range for the CCD is $10\text{-}40\text{mm}$. Similarly, based on Eq. (1), the limitation on the wavelength drift of laser source is obtained as

$$\partial d = \frac{m}{2} \sqrt{\left(\frac{D}{2f}\right)^2 + 1} \times \partial \lambda < 0.2. \quad (4)$$

Therefore,

$$\partial \lambda < 0.421\mu\text{m}. \quad (5)$$

The design should have $f=400\text{mm}$, $d=200\text{-}300\mu\text{m}$, and $\delta\lambda < 0.421\mu\text{m}$.

Testing and Discussion

Using the above design parameters, computational testing through simulations were performed to demonstrate the characteristics of the proposed design. The ring diameter D , ring diameter change ΔD , related to 0.2nm displacement against the expected displacement range, were obtained (Fig. 3). It can be seen that the ring diameter changes is larger than 0.01mm for the whole displacement range of $d=200\text{-}300\mu\text{m}$. Since the linear CCD resolution is 0.007mm , the

resolution for the displacement measurement in the whole expected displacement range should be sufficient.

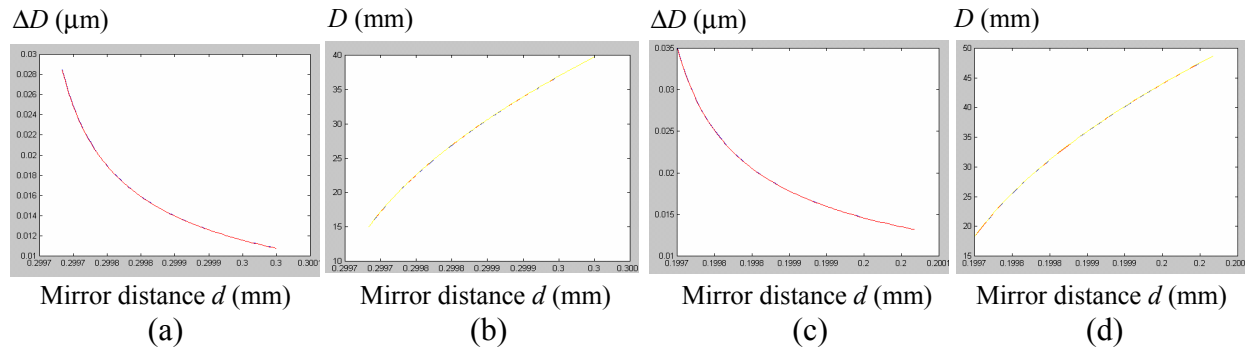


Fig. 3 D and ΔD for the 0.2nm mirror distance change in the range of 0.2-0.3mm $\pm\lambda/2$ and $f=400\text{mm}$

Conclusions

For low cost and ease of use displacement measurement and calibration at the resolution of nanometer level, a new nano-stepping device design for nanometer displacement measurement and calibration is proposed. The design is based on the F-P cavity and the multi-beam interference principle. The analysis shows the device is to have a resolution of 0.2nm and a range better than 100 μm . The device is compact in size. From the Abbe principle and the shortest link rule, it should be stable and immune to environmental disturbances.

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