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Design of a Novel Low-cost and Long-stroke Co-planar Stage for Nanopositioning

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ABSTRACT

A new co-planar stage has been designed based on the Abbé principle, symmetrical structure, and Bryan principle. It is used for the long-stroke and nanopositioning to be equipped as the X-Y stage of a developed Micro-CMM. Different from the common motor-ballscrew or linear motor driven type, this coplanar stage is moved by the friction force of an ultrasonic motor with the push-pull mode in each axis. The moving table is suspended by four linear slides along four arms. The in-plane X and Y motions are realized by the other four linear slides around four edges of the table to allow the push-pull motion possible. This push-pull mechanism can eliminate the vibration from the motor and the reversal error due to the clearance of the linear slide. Two developed new nanoscales can provide the displacement readings to 1nm resolution after signal interpolation. The measuring length is about 20mm. After careful assembly, the straightness and the flatness of the table can be achieved to submicron order.

INTRODUCTION

Long-stroke stage for nanopositioning is always regarded as expensive equipment as it normally requires a high precision two-stage assembly for long-and-short motions respectively, and a laser interferometer for displacement feedback to the motion control. In addition, the guideway has to be as low friction as possible by using air bearing or electro-magnetic bearing. It yields to not only complicated structure and multi-dimensional control strategy, but also additional sensors and mechanism for the compensation of Abbé error due to inherent 6 DOF geometrical errors in order to enhance the accuracy [1]. Conventional XY stage is normally stacked up by two linear stages. Not only the position-dependent cross-talk between the axes cannot be avoided, the Abbé error of the lower stage is large due to the large Abbé offset. To construct an XY stage for long-stroke and nanopositioning the effort will be more difficult as all error sources have to be considered, such as the drive error, guide error, scale error, geometric error, environment error, control error, etc. This paper will present the design principle of the co-planar stage, the optical principle of the nanoscale, assembly and

DESIGN OF A CO-PLANAR STAGE

A new co-planar stage following the Abbé principle has been redesigned based on the authors' previous systems [2, 3]. As shown in Fig. 1, it is a symmetrical structure for the X and Y motions, that one side of each axis has an extension arm on which an ultrasonic motor (Nanomotion Co. model HR4) is equipped by the side as the drive actuator and the other side of the arm is mounted on a nanoscale (LDGI) as the feedback sensor. All components are made by precision machining only that 8 linear slides are purchased with the highest grade from the market (THK Co. model SRS9N).The moving table is suspended by four linear slides along four arms yielding to low friction motion. The in-plane X and Y motions are realized by the other four linear slides around four edges of the table. Different from the common motor-ballscrew or linear motor drive type, this coplanar stage is moved by the friction force of ultrasonic motor to push the arm forward and pull it backward to make the push-pull motion possible. The vibration of HR4 and the reversal error can be eliminated by the linear slides. The top table, HR4 base and LDGI base are all made of low thermal expansion Invar steel so that the heat generated will cause minimum thermal error. Since the X and Y stages are integrated into a common plane, it is very thin, low cost and high precision. Fig. 2 shows the CAD drawing. The hollow space underneath the moving table can mount a straightness sensor so that the Bryan error can be compensated [4].

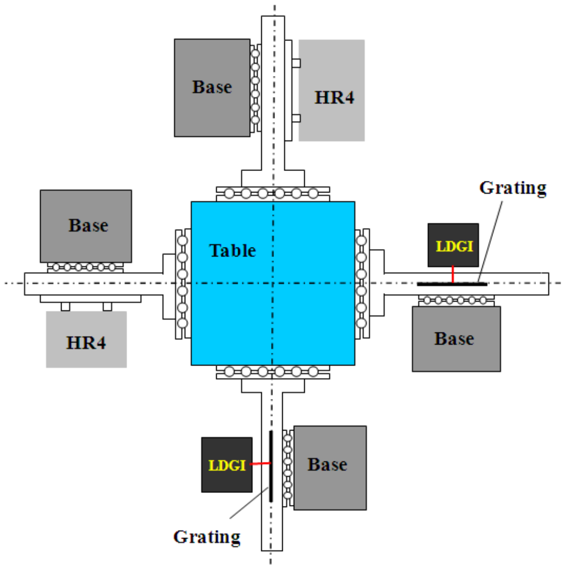


Fig. 1: Configuration of the co-planar stage

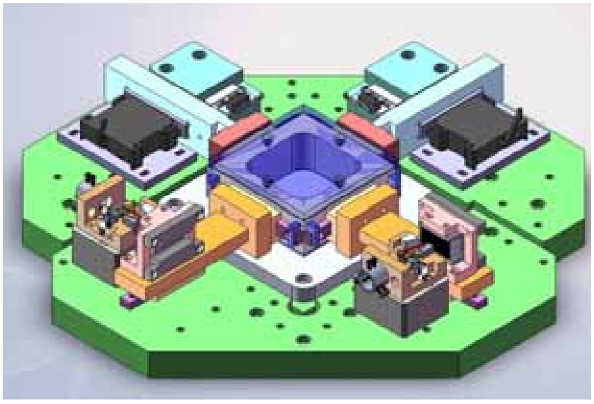


Fig. 2: Structure of the co-planar stage

DESIGN OF A NANOSCALE

The nanoscale is composed of a hologram grating (1200 line/mm from Edmund Optics) and a small-sized linear diffraction grating interferometer (LDGI), which is modified from the authors' previous systems [4, 5]. The optical system employs polarization technique to obtain clear and low noised two sinusoidal waveforms. The optical principle of the LDGI is illustrated in Fig. 3. The laser diode (LS) emits a linearly polarized beam. The P-polarized beam will pass the PBS1 to Q1 (as the left arm beam) and S-polarized beam will be reflected on PBS-1 and PBS2 to Q3 (as the right arm beam). Passing through Q1, the P-polarized left arm beam will change to a right-circularly polarized beam. Similarly, the right arm beam will change to a left-circularly polarized beam after passing Q3. With the emitted angles equal to the grating's ±1 diffraction angles, the input beams will be diffracted back through the same paths to mirrors 1 and 2, respectively. After passing Q1 the left arm will again change to a S-polarized beam and after passing Q3 the right arm will again change to a P-polarized beam. The left arm will be reflected to the Q2-M3-Q2 path and changed to a P-polarized beam, which can pass through PBS1 and PBS2 to Q5, and then changes to a right-circularly polarized beam after passing Q5. Meanwhile, the P-polarized right arm beam will pass through PBS2 and change to a S-polarized after passing through the Q4-M4-Q4 path. Subsequently it is reflected from PBS2 to Q4 and changed to a left-circularly polarized beam after passing Q5. The NPBS divides both the right-circularly and the left-circularly polarized beam into two split beams of equal intensity. These four beams will be divided into 0-90-180-270 degrees by PBS3 and PBS4 (set fast axis to 45 degrees) and interfere with each other. These four orthogonal signals are detected by PD1 to PD4, respectively. Accordingly, by the inspection of phase variation of beat frequency signal, the displacement of grating movement could be measured.

$$\Delta\Phi = \Delta\omega\, t = 4\pi m \frac{v}{d} t = 4\pi m \frac{\Delta x}{d}$$

It is seen that when the grating moves d/2 the beat frequency signal has a phase variation of periodicity (2π). With the holographic grating of 1200 line/mm, there is an orthogonal signal in every 416nm. The optical layout and the photo of this LDGI are shown in Fig. 4.

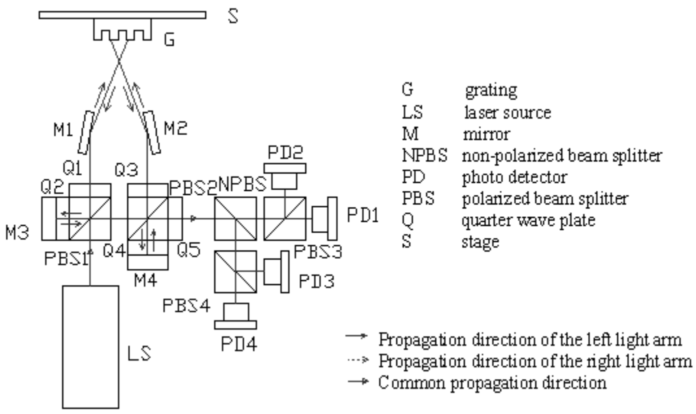


Fig. 3: The optical system design of LDGI

In classical orthogonal waveforms there are three major error sources. As described by Heydemann [5], these are:

1. Lack of quadrature (the phase shift between two signals is not exactly λ/4 or π/2),
2. unequal gain in the detector channels, and
3. zero offset.

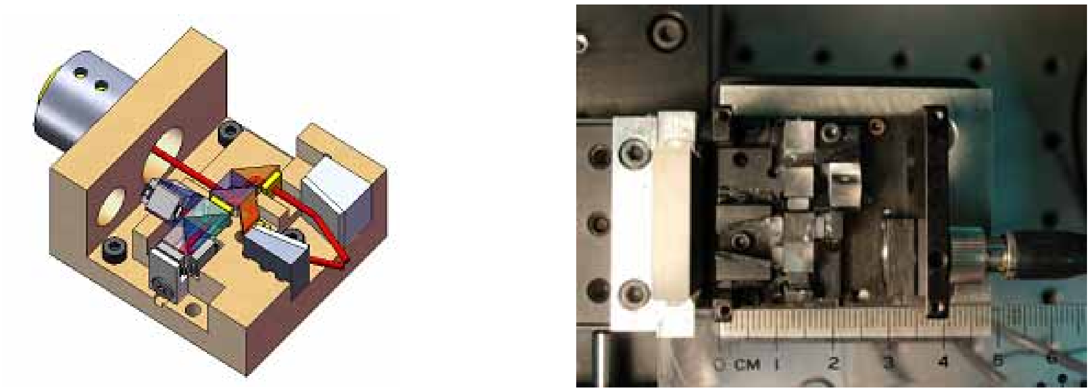


Fig. 4: The structure and the photo of the LDGI

To correct the first error, it is possible to use a vector summation and subtraction operation in order to obtain the exact orthogonal waveforms. The second error should be corrected by a filtering process using an electronic circuit or by software. The third error can be corrected by using differential signals. Fig. 5 shows the circuit diagram of LGDI signal process. Fig. 6 plots the corrected waveform and Fig. 7 plots the perfect Lissagous diagram. Since one wave cycle corresponds to 416 nm of the grating displacement, we can easily reach a 1 nm resolution after a signal subdivision of 400 interpolated signals. Current progress can achieve 20mm range and 15nm standard deviation after calibration. The dimension is only about 55mm x 40mm x 30mm. It is easily equipped into a small nanopositioning stage.

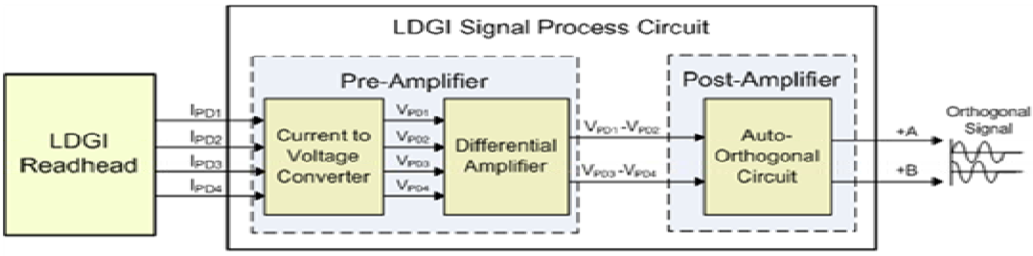
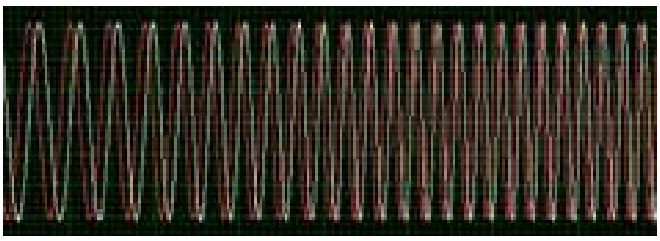


Fig. 5: The circuit diagram of LGDI signal process.



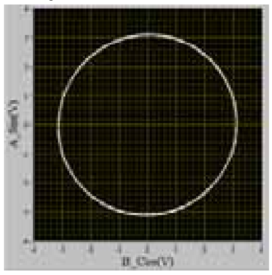


Fig. 6: The corrected waveforms Fig. 7: Lissajous diagram after correction

SYSTEM ASSEMBLY

The whole co-planar stage has been assembled, as shown in Fig. 8. The alignment procedure has to be extremely careful in terms of the grating axis in line with the moving axis, and the LDGI laser beam normal to the grating surface. In addition, the straightness of each axis and the flatness of the moving table have to be patiently adjusted to the minimum error. The tested results in the laboratory show that both errors can be adjusted to the submicron range. The remaining errors can be compensated with software by mounting a straightness sensor at the hollow center underneath the moving table. This will observe the law of Bryan principle.

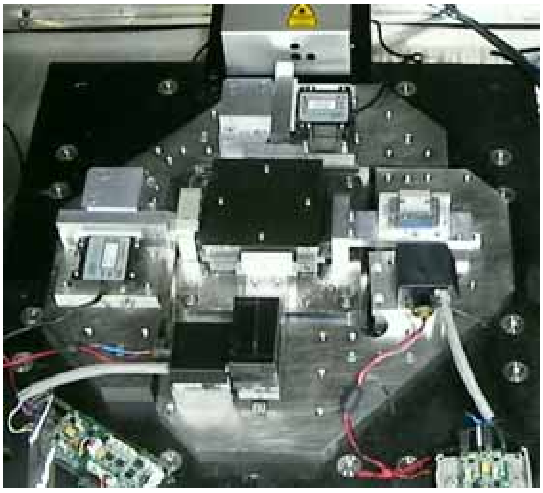


Fig. 8: Photo of the assembled co-planar stage

CONCLUSION

This paper presents the design and fabrication of a co-planar stage that has 20mm travel length in each axis. Using the proposed nanoscale as the feedback sensor, the position reading can achieve 1nm resolution. The ultrasonic motor can push and pull and table with fast and long stroke motion, and slow and fine nanopositioning. After careful assembly, the straightness and the flatness of the table can be achieved to submicron order. Since the X and Y stages are integrated into a common plane, it is very thin, low cost and high precision. In the near futrue, this stage will be integrated into the developed Micro-CMM.

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