Design of a Novel Low-Cost and Long-Stroke Co-Planar Stage for Nanopositioning

Neuartiger preisgünstiger Zwei-Ebenen-Positioniertisch für die Nanopositionierung

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Summary 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 to a developed Micro-CMM. Other than the common motor-ballscrew or linear motor driven type, this co-planar stage is moved by the friction force of an ultrasonic motor with the push-pull mode in each axis. This push-pull mechanism follows the Abbé principle that the measuring axis is in line with the moving axis. The developed new nanoscales can provide the displacement readings to 1 nm resolution after signal interpolation. The measuring length is about 20 mm. After careful assembly, the straightness and the flatness of the table can be achieved to submicron order. ►►►

Zusammenfassung Ein neuer Zwei-Ebenen-Positioniertisch wurde auf der Basis des Abbe-Prinzips sowie des Bryan-Prinzips mit einer symmetrischen Struktur entwickelt. Er kann sowohl für makroskalige als auch für nanoskalige Positionierung verwendet werden, sodass er als X-Y-Tisch in einer entwickelten Mikro-CMM eingesetzt werden kann. Anders als Tische mit Kugelumlaufspindel oder mit Linearmotoren wird dieser Positioniertisch durch die Reibkraft eines Ultraschallmotors im „Push-Pull-Modus" in jeder Achse bewegt. Dieser Push-Pull-Mechanismus erfüllt das Abbé-Prinzip, weil die Messachse linear mit der beweglichen Achse angeordnet ist. Die entstandenen neuen Nanobereiche können Abstandsmessungen mit einer Auflösung bis zu 1 nm nach Signalinterpolation liefern. Die Messlänge beträgt etwa 20 mm. Nach sorgfältigem Zusammenbau können die Geradheit und die Flachheit des Tisches bis unter 1 μm erreicht werden.

Keywords Co-planar stage, Abbé principle, Bryan principle, Micro-CMM, push-pull mechanism ►►►
Schlagwörter Zwei-Ebenen-Positioniertisch, Abbé-Prinzip, Bryan-Prinzip, Push-Pull-Mechanismus

1 Introduction

Long-stroke stage for nanopositioning is always regarded as an 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 guide-way 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 X-Y stage is normally stacked up by two commercially available linear stages for X and Y motions, respectively. It is known that commercial stages are constructed by components in micrometer accuracy level. It is hard to achieve nanometer accuracy after integration. In addition, the Abbé error of the lower stage is large due to the large Abbé offset. To construct an X-Y 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.

The authors' group has developed a co-planar stage to allow the X and Y motions are along one common plane, which could eliminate the Abbé error in the vertical direction [2; 3]. However, the Abbé error in the horizontal direction still existed due to the structure of side-driven type, as shown in Fig. 1. In order to totally avoid the Abbé error, a push-pull type co-planar stage was designed by the authors, as shown in Fig. 2 [4], which is immune from the angular errors of both moving axes because of no Abbé offset. However, experimental results showed somewhat reversal errors due to the clearance between the linear slide and its slideway. Besides, the straightness error in X and Y motions cannot not be removed, namely the Bryan error [1; 5], due to the straightness of the slides and the flatness of the common baseplate.

In this paper, a newly designed symmetrical type push-pull co-planar stage will be presented, including the design principle of the co-planar stage, the optical principle of the nanoscale, assembly inspection and the method of Bryan error removal.

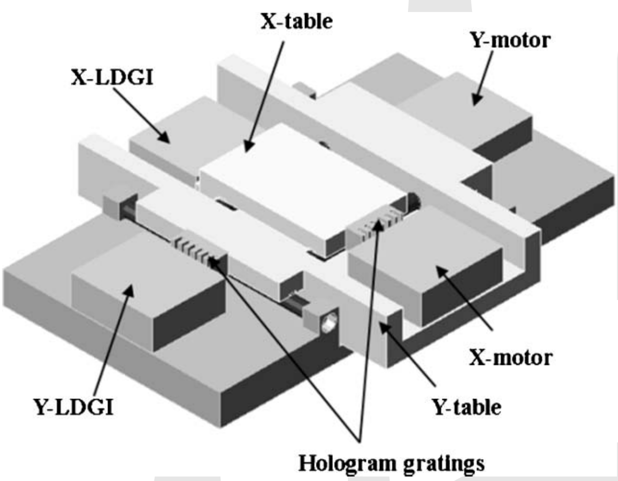

Figure 1 A co-planar stage of side-driven type.

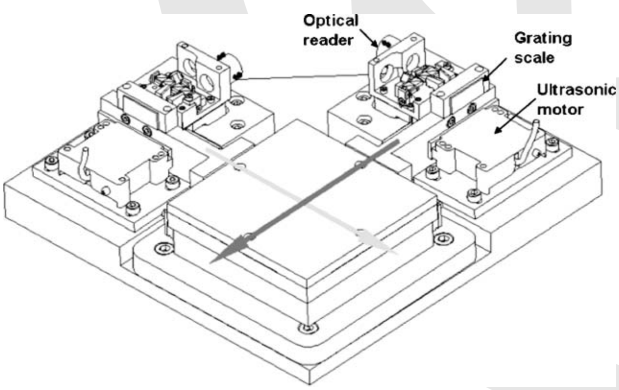

Figure 2 A co-planar stage of push-pull driven type.

2 Design of a Co-Planar Stage

A new co-planar stage following the Abbé principle has been redesigned, as shown in Fig. 3. 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 co-planar 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 measuring axis (the LDGI gratings) is always in line with its moving axis in each direction and two directional axes always intersect at the functional point of the table. With this kind of arrangement, the Abbé principle can be totally observed. In addition, the measuring axis is located on the other side of the driving axis, the vibration of ultrasonic force generated by HR4 will be absorbed by the four slides mounted on the peripheral of the moving table and, thus, no longer be transferred to the scale reading. Besides, the reversal error at the driving side will be largely reduced at the scale side due to the significant decrease of push-pull force on this side. 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

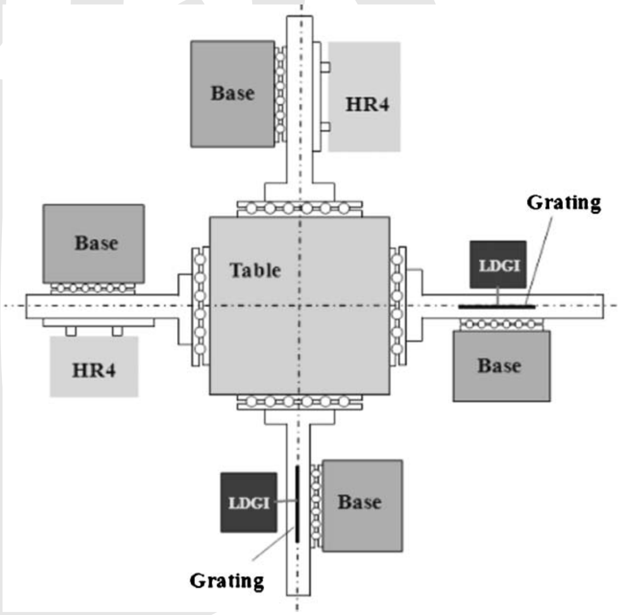

Figure 3 The symmetrical push-pull co-planar stage.

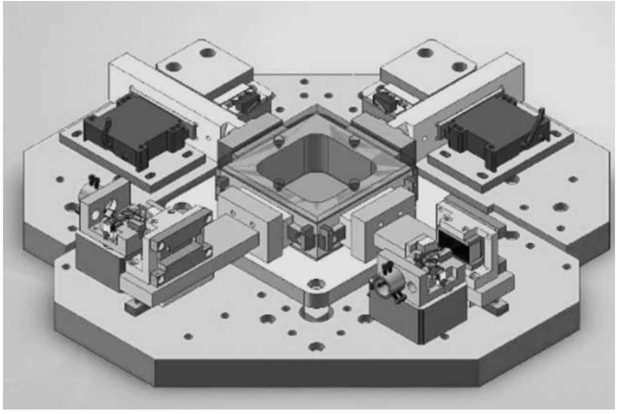

Figure 4 Structure of the co-planar stage.

plane, it is very thin, low cost and high precision. Figure 4 shows the CAD drawing. The hollow space underneath the moving table can mount a straightness sensor so that the Bryan error can be compensated [5].

3 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 [3;6]. 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. 5.

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 the 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 beam 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 ($\Delta\psi$) of beat frequency signal, the grating movement (Δx) could be measured. The equation can be expressed by [6]:

$$\Delta\phi = 4\pi m \frac{\Delta x}{d} \qquad (1)$$

where d is the grating pitch and m is the number of count. 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 416 nm. The optical layout and the photo of this LDGI are shown in Fig. 6a and 6b. Its physical dimension is about 50 mm × 50 mm × 30 mm.

In classical orthogonal waveforms there are three major error sources. As described by Heydemann [7], these are:

1. lack of quadrature (the phase shift between two signals is not exactly $\lambda/4$ or $\pi/2$),
2. unequal gain in the detector channels, and
3. zero offset.

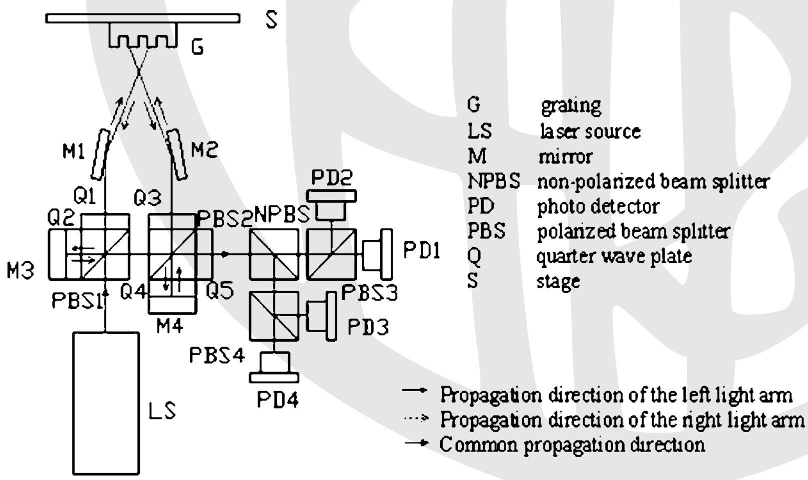

Figure 5 The optical system design of LDGI.

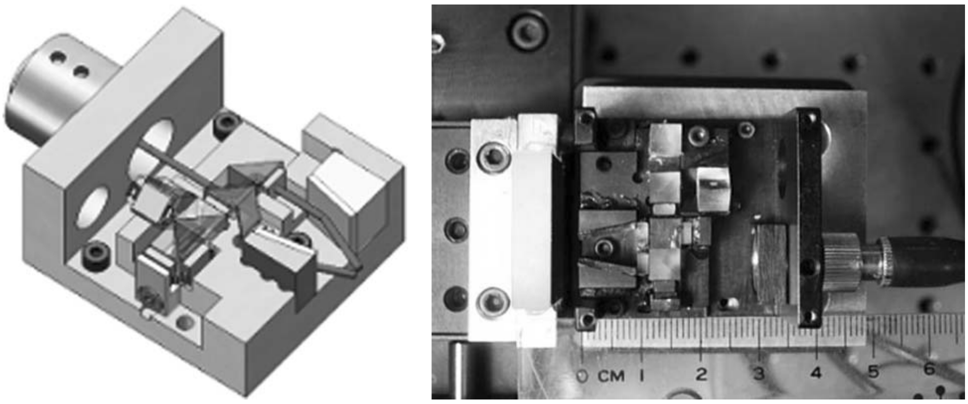

Figure 6 (a) The structure of the LDGI; (b) The photo of the LDGI.

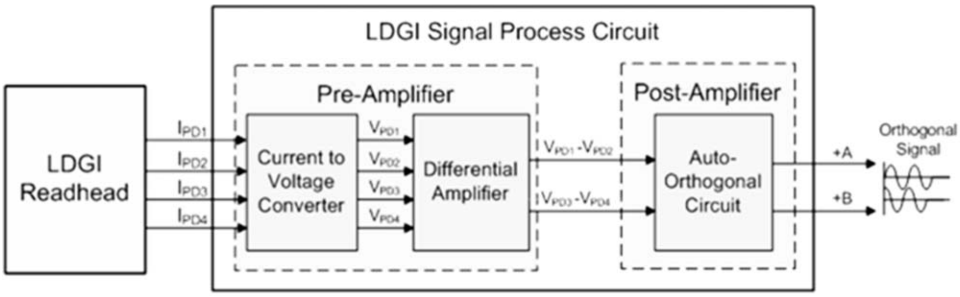

Figure 7 The circuit diagram of LGDI signal process.

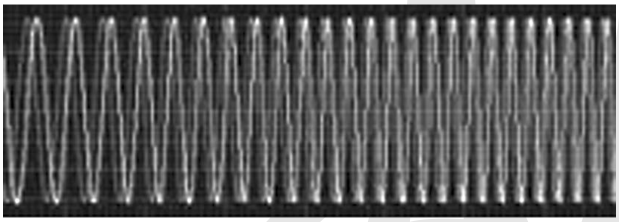

Figure 8 The corrected waveforms.

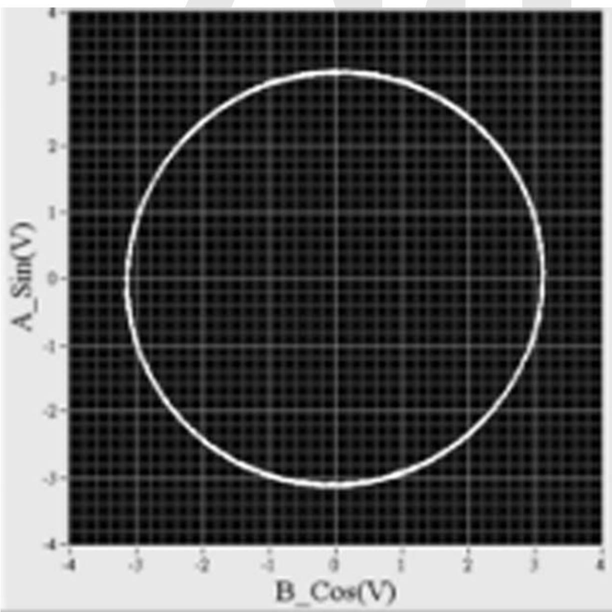

Figure 9 The Lissajous diagram after correction.

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. Figure 7 shows the circuit diagram of the LGDI signal process. Figure 8 plots the corrected waveform and Fig. 9 plots the perfect Lissajous 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 20 mm range and 15 nm standard deviation after calibration. The dimension is only about 55 mm × 40 mm × 30 mm. It is easily equipped into a small nanopositioning stage.

4 System Assembly

The whole co-planar stage has been assembled, as shown in Fig. 10. The alignment procedure has to be extremely careful to ensure that the grating axis is in line with the moving axis, and the LDGI laser beam is 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.

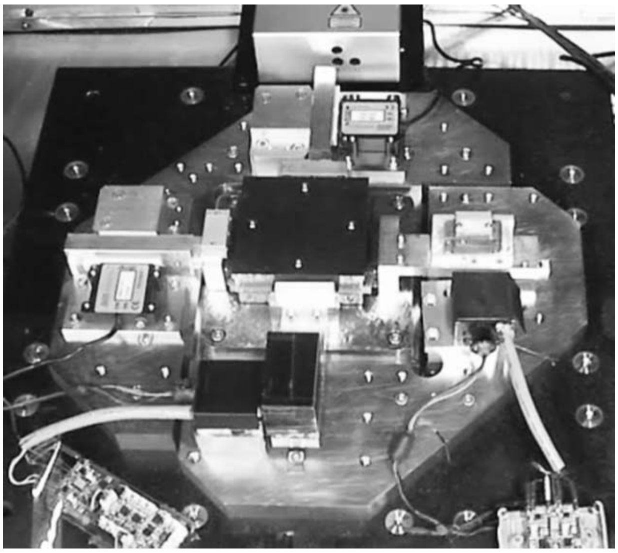

Figure 10 Photo of the assembled co-planar stage.

5 Conclusion

This paper presents the design and fabrication of a co-planar stage that has 20 mm travel length in each axis. Using the proposed nanoscale as the feedback sensor, the position reading can achieve 1 nm resolution. The ultrasonic motor can push and pull the 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 future, this stage will be integrated into the developed Micro-CMM.

Acknowledgements

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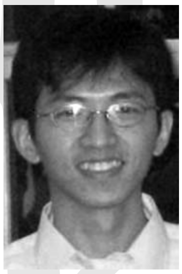

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