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Development of Precision One-Dimensional Adjustment Worktable Based on Aerostatic Bearing Technology

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Abstract To achieve the high-precision one-dimensional adjustment of large surface under test in optical and mechanical measurements, a novel worktable based on the aerostatic bearing technology is developed. In the worktable, pitch or tilting motion is achieved by a cambered surface of aerostatic bearing and micro-displacement actuators, and the relationship between the angle of one-dimensional adjustment and the displacement of actuators is analyzed. Furthermore, by using an electronic autocollimator, the resolution of one-dimensional adjustment worktable is measured. Errors of the one-dimensional adjustment system are analyzed and the performance evaluation of the system is given. The experimental results show that the worktable has a pitch or tilting adjustment resolution of 1.2″, adjustment range of ±1° and good stability with 50 kg load. The developed one-dimensional adjustment worktable can satisfy the requirements of higher precision, high resolution, large adjustment range, frictionless, high load stiffness, stabilization and small driving force.

Key words measurement; precision one-dimensional adjustment; aerostatic bearing technology; worktable

OCIS codes 120.3930; 120.3940; 120.4640

基于气体润滑支承技术的大承载精密一维调整技术研究

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摘要 为实现光学和机械测量中对大型被测件位姿的一维高精度测量和调整，发明研制了基于空气静压轴承技术的高精度大承载一维调整装置，并对该一维调整系统的调倾性能进行测定和研究。阐述了基于空气静压轴承技术的调倾工作台的构成及工作原理。利用三维空间坐标变换得到调倾操作的数学模型，并由此得出了驱动器位移与倾斜角度间的关系。采用光电自准直仪构建测量系统，得出基于空气静压轴承技术的大范围高精度工作台倾斜调整的分辨力。分析了测量系统的误差，给出调倾装置的性能评价。实验结果表明：在 50 kg 负载下，调倾操作的分辨力为 1.2″，倾斜调整范围±1°。发明研制的系统满足光学和机械测量中对调整工作台的高精度、高分辨力、大调整范围、无摩擦、易驱动和高承载刚度等要求。

关键词 测量；精密一维位姿调整；气体静压轴承技术；工作台

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1 Introdution

Worktables for pitch and tilting adjustment are important devices in the field of precision measurement[1-4]. For example, in the radius of curvature and focal length measurement of optical elements[5], the axis of surface under test needs to be precisely adjusted to parallel to the measurement axis, and in the surface profile measurement[6], the surface under test should be perpendicular to the measurement axis of sensor, these operations of pitch and tilting

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adjustment are called position and attitude adjustment. The worktable for pitch and tilting adjustment should satisfy the requirements of higher precision, high resolution, large adjustment range, frictionless, large load stiffness and stabilization.

Generally, rolling elements and wedge structure are adopted in the existing worktables for pitch or tilting adjustment[7-10]. It is difficult to guarantee the precision of the rolling element bearings, they are prone to worm, easy to be worn severely if improperly assembled, and directly influenced by surface finish and irregularities on the guide. The worktables with wedge adjustment have advantages of simple structure and heavy load, but the worktable can not be self-locked completely and can not be driven easily. Tsukada *et al*. had developed a computer-aided levelling system for cylindrical form measurement[11]. In the system, motors, gear units, worm couples and wedges are used for driving the levelling worktable, and the precision of levelling adjustment is less than 2×10^{-5} rad.

The above-mentioned methods can not meet the requirements of higher precision, high resolution, no friction, easy to drive, high bearing stiffness in precision optical and mechanical measurements. The aerostatic technology has the advantages of zero static friction, high resolution and repeatability, smooth operation, easy to drive, high load stiffness[12], so a precision one-dimensional adjustment worktable based on the aerostatic bearing technology is developed. The developed worktable has large range and high resolution of pitch and tilting adjustment and can meet the demands of precision measurement.

2 Principle and mathematical model

2.1 Structure of the one-dimensional adjustment worktable

As shown in Fig. 1, the worktable, which is based on the aerostatic bearing technology, comprises workpiece (1), stage for one-dimensional adjustment (2), tension springs (3), support of stage for one-dimensional adjustment (4), air supply (5), Picomotor actuators (6) which produced by New Focus company, orifices (7), film of pressurized air for one-dimensional adjustment (8).

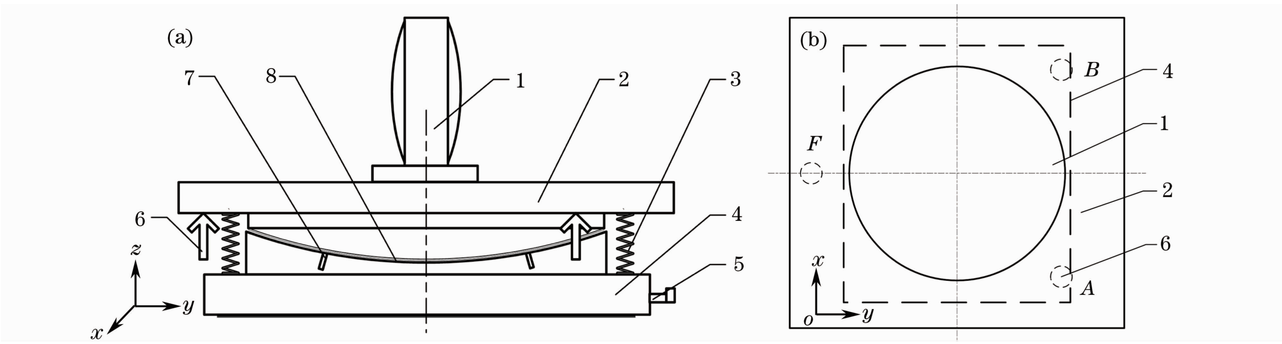

Fig. 1 Schematic of the one-dimensional adjustment worktable

In the one-dimensional adjustment mechanism shown in Fig. 1, the lower surface of stage for one-dimensional adjustment is machined to a convex cambered surface, meanwhile, the upper surface of stage support for one-dimensional adjustment is accurately machined to a concave cambered surface, the two surfaces are one part of a cylindrical surface and mutually complementary. Along the circumferential direction of the upper surface of the stage support, the orifices to produce air film for one-dimensional adjustment are evenly arranged, and these orifices are connected to the air supply. The stage for one-dimensional adjustment is mounted on the stage support, and the Picomotor actuators act on the stage for one-dimensional adjustment to accomplish the pitch and roll motions. The layout of the Picomotor actuators is shown in Fig. 1.

2.2 Principle of the one-dimensional adjustment worktable

When pressurized air is not connected, the stage for one-dimensional adjustment is pressed against support of stage for one-dimensional adjustment by its own gravity, the lower surface of stage for one-dimensional adjustment and the upper surface of stage support for one-dimensional adjustment fit

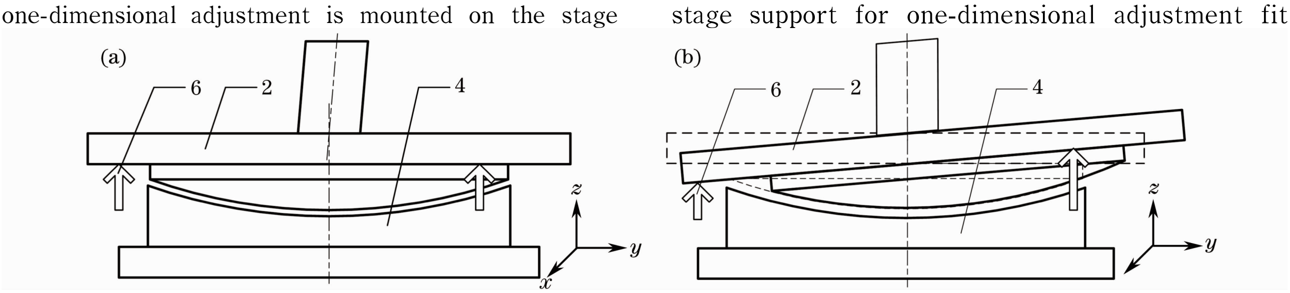

Fig. 2 Principle of one-dimensional adjustment

closely. When pressurized air is connected, between the aforementioned two surfaces, the film of pressurized air for one-dimensional adjustment is achieved by the orifices that restricts or meters the flow of air into the bearing gap, and the stage for one-dimensional adjustment can be driven by the Picomotor actuators and tension springs to accomplish the roll and pitch motions along the profile of the upper surface of stage for one-dimensional adjustment. The principle of the one-dimensional adjustment worktable is shown in Fig.2. Being non-contact of the air bearings, the developed one-dimensional adjustment worktable can avoid the problems of friction, wear, and lubricant handling, and offer distinct advantages in precision pitch and roll motions.

2.3 Mathematical model of one-dimensional adjustment

As shown in Fig.3(a), A, B and F are three points for supports of the worktable, which are the three vertexes of an equilateral triangle respectively, and the center of gravity of the equilateral triangle and the center of the cambered surface of aerostatic bearing are in the same position. Two Picomotor actuators are mounted at the points of A and B respectively, and a spring support is arranged at point F. When the Picomotor actuators at A and B move with the same displacement in the same direction, the worktable will be driven to create pitch or tilting motion around the Y axis. When the motions at the three supports are smooth under rolling friction condition, the worktable will create a motion under a true rolling condition along the cambered surface of the aerostatic bearing, and then the operation of pitch or tilting adjustment around the Y axis can be obtained.

As shown in Fig.3(b), the point O is one point at the axis of the cylinder, and the cambered surface of aerostatic bearing is a part of the cylindrical surface, R is the radius of the cambered surface of aerostatic bearing, H is the distance between the point O and the upper surface of the worktable, L is the distance between the upper surface of the worktable and the point of support F, WX_{OF} is the distance between the support point F and the center of the worktable O_{Y1}, WX_{OA} is the distance between the support point A and the center of the worktable O_{Y1}. When the Picomotor actuator at point A creates a motion from A_{Y1} to A_{Y2}, the spring support at point F move from F_1 to F_2 and a motion under a true rolling condition along the cambered surface of the aerostatic bearing is caused, the worktable will rotate through an angle α around the Y-axis, and the center of worktable will move from O_{Y1} to O_{Y2}.

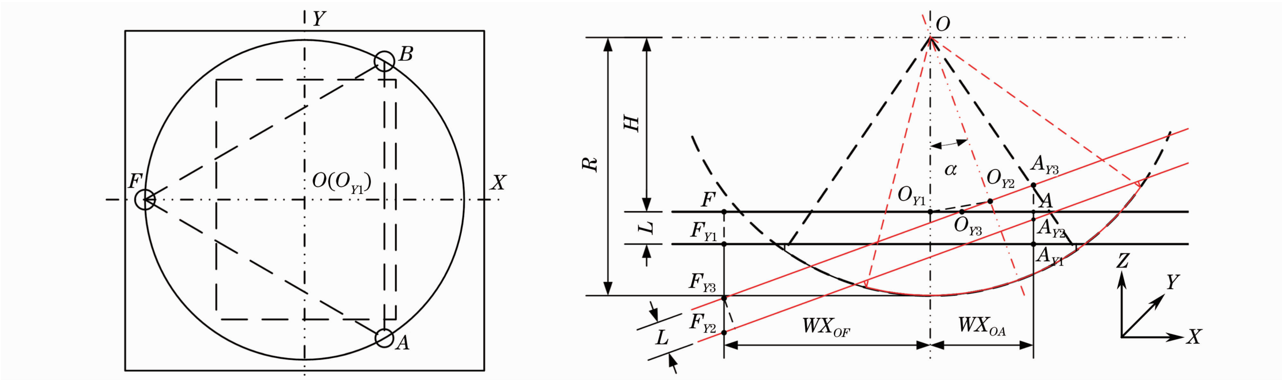

Fig.3 Mathematical model of one-dimensional adjustment around Y axis

For the pitch or tilting adjustment around the Y axis, the operations are equivalent to a coordinate transformation that each point in Fig.3(b) rotates through angle α around Y axis. Therefore, a coordinate system shown in Fig.3(b) is established with origin of the coordinate at point O, and the coordinate of point O_{Y1} is $(0, 0, -H)$. When the worktable rotates through an angle α around the Y axis as shown in Fig.3(b), the coordinate of point O_{Y2} is (x, y, z), and the coordinate (x, y, z) can be obtained by the following Eq.(1):

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix}^{\mathrm{T}} = \begin{pmatrix} 0 \\ 0 \\ -H \end{pmatrix}^{\mathrm{T}} \times \begin{pmatrix} \cos\alpha & 0 & \sin\alpha \\ 0 & 1 & 0 \\ -\sin\alpha & 0 & \cos\alpha \end{pmatrix} = \begin{pmatrix} H\sin\alpha \\ 0 \\ -H\cos\alpha \end{pmatrix}^{\mathrm{T}}. \tag{1}$$

The displacement at point A, $A_{Y1}A_{Y2}$, can be obtained by:

$$A_{Y1}A_{Y2} = A_{Y1}A + AA_{Y3} - A_{Y3}A_{Y2}. \tag{2}$$

As shown in Fig.3(b), the distance, AA_{Y3}, between A and A_{Y3} can be solved from $\Delta O_{Y3}AA_{Y3}$:

$$AA_{Y3} = AO_{Y3} \times \tan\alpha = (AO_{Y1} - O_{Y1}O_{Y3}) \times \tan\alpha = \left[WX_{OA} - \frac{O_{Y1}O_{Y2}}{2\times\cos(\alpha/2)}\right] \times \tan\alpha. \tag{3}$$

And $A_{Y1}A = L$, $A_{Y3}A_{Y2} = L/\cos\alpha$, thus the displacement at point A, $A_{Y1}A_{Y2}$, can be expressed as,

$$A_{Y1}A_{Y2}=A_{Y1}A+AA_{Y3}-A_{Y3}A_{Y2}=L+\left[WX_{OA}-\frac{O_{Y1}O_{Y2}}{2\times\cos(\alpha/2)}\right]\times\tan\alpha-\frac{L}{\cos\alpha}. \quad (4)$$

Equation (4) shows the relationship between the rotation angle of α around the Y axis and the displacement caused by the Picomotor actuators at points A and B, thus a precision pitch or tilting adjustment around the Y axis can be obtained.

3 Experiment and verification

The experimental setup for adjustment resolution measurement is shown in the Fig. 4, and the measurement is carried out by using the Elcomat 3000 electronic autocollimator and a reflector to test pitch or tilting adjustment resolution of the worktable. The step displacement of the Picomotor actuators for pitch or tilting adjustment in Z direction are 20, 30 and 40 cts (corresponding to about 0.6, 0.9 and 1.2 μm), and the one-dimensional adjustment resolution of the worktable can be obtained by the Elcomat 3000 respectively, which measures the angle of pitch or tilting caused by the step displacement.

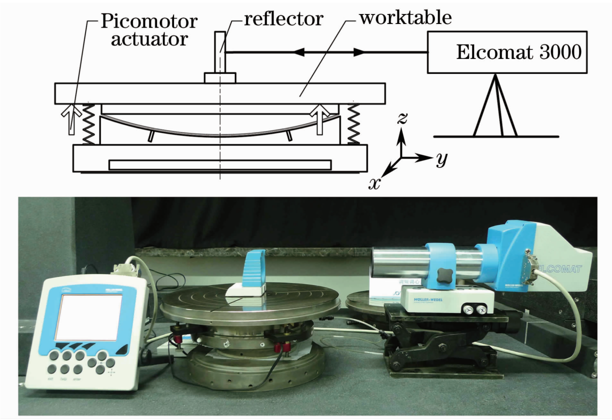

Fig. 4 Setup for the adjustment resolution test

The experimental results are shown in Fig. 5. When the step displacement of Picomotor actuators is 0.9 μm (30 cts) and the load of the worktable is 50 kg, a pitch or tilting adjustment resolution of 1.2″ can be measured by the Elcomat 3000. In the same way, when the step displacement of Picomotor actuators are 0.6 μm (20 cts) and 1.2 μm (30 cts) with the same load of 50 kg, the angles of pitch or tilting caused by the step displacement are 0.8″ and 1.6″.

In Fig. 6, the details about the 30 cts of step displacement and the pitch or tilting adjustment resolution are shown. In the developed one-dimensional adjustment worktable, WX_{OA} = 80 mm, H = 135 mm and L = 25 mm, according to Eq. (4), a rotation angle of 1.2″ corresponds to a displacement of Picomotor actuators about 0.931 μm, so the results of simulation agree with the experimental results. Moreover, the experimental results show that there is a good linearity between the angle of pitch or tilting of the worktable and the step displacement of picomotor actuators.

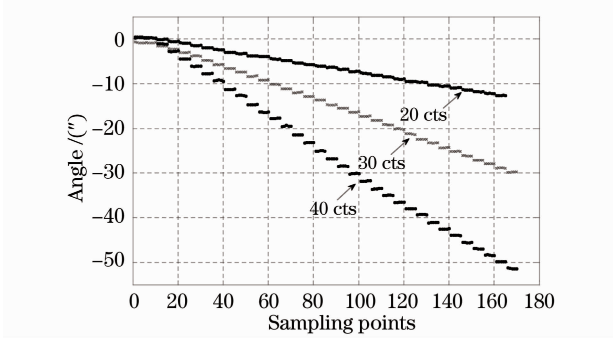

Fig. 5 Results of the adjustment resolution test

When the step displacement of Picomotor actuators is 0.3 μm (10 cts) with the load of 50 kg, an angle of pitch or tilting adjustment about 0.4″ can be measured by Elcomat 3000, but not very stable, and the experimental results are shown in Fig. 7. The instability may be caused by creep, vibration of the base and fluctuation of the air supply. Therefore, it can be concluded that the pitch or tilting adjustment resolution of the developed worktable is better than 1.2″.

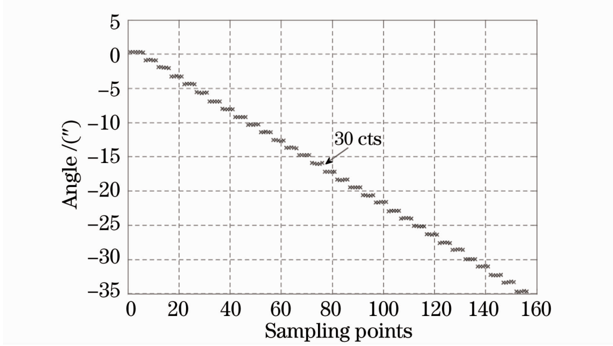

Fig. 6 Result of the adjustment resolution test for 30 cts of step displacement

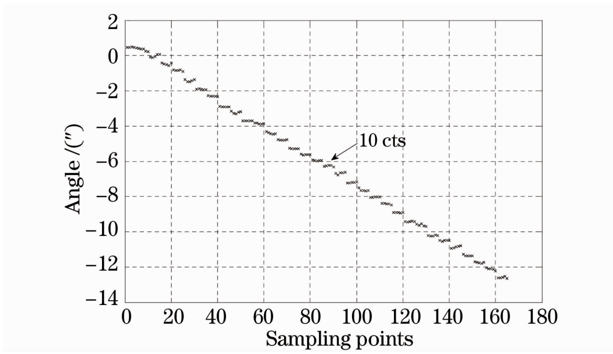

Fig. 7 Result of the adjustment resolution test for 10 cts of step displacement

4 Error analysis

4.1 Error caused by the stability of Picomotor actuator

The linear travel of the Picomotor actuators is 50 mm, and the minimum incremental motion is better than 30 nm with minimal backlash. Owing to the use of piezo and screw, the Picomotor actuators can exert a 22 N force and have exceptional longterm stability. Moreover, because pitch angle of the screw is greater than the friction angle, picomotor actuator can hold their position with no additional force applied. The good stability makes the picomotor actuators unique for precision positioning in optical and mechanical measurement.

In the practical test, when making the picomotor actuators stop at a specified position, position variation caused by the picomotor actuators can be measured by a precision displacement sensor. After several groups of experimentation, the position drift is less than 15 nm in 30 min.

4.2 Error of pitch and tilting adjustment

Because the picomotor actuators do not have internal encoders, the step displacement can vary over 20% between the forward and backward directions and the minimum incremental motion is about 30 nm. For the pitch or tilting adjustment, if the error, Δs, caused by the picomotor actuator is 30 nm, the error of pitch and tilting adjustment, θ, caused by the error Δs can be obtained by the Eq.(5):

$$\theta = \Delta s \Big/ \left(\frac{\sqrt{3}}{2}\overline{AB}\right). \tag{5}$$

In the developed system, $\overline{AB} = 260$ mm, thus the θ is about 0.13 μrad. So the error of pitch and tilting adjustment of the worktable caused by the step displacement error of picomotor actuators, Δs, is negligible.

5 Conclusion

On the basis of high precision requirements for the pitch or tilting adjustment of large surface under test in optical and mechanical measurements, a novel one-dimensional adjustment worktable based on the aerostatic bearing technology is developed. In the worktable, a cambered surface of aerostatic bearing which is used for support and guide is designed, and Picomotor actuators is adopted to provide precision positioning with tens of nanometers. The structure and principle of the one-dimensional worktable are introduced, and the mathematical model is established to analyze the relationship between the angle of one-dimensional adjustment and the displacement of Picomotor actuators. By using the Elcomat 3000, the resolution of pitch or tilting adjustment is measured. Errors of the one-dimensional adjustment system are analyzed.

According to the experimental results, it can be concluded that the worktable has a pitch or tilting adjustment resolution of 1.2″, adjustment range of ±1° and good stability with 50 kg load. The developed one-dimensional adjustment worktable, which is based on the aerostatic bearing technology, can meet the demands of higher precision, high resolution, large adjustment range, frictionless, high load stiffness, stabilization and small driving force.

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