4-DOF Mechanism Design for Reflectors in Vacuum

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Abstract. The paper developed a new type of 4-DOF mechanism design for reflectors in vacuum, which had the ability of assembling the reflector stably and realizing 4-DOF movement (one-translation and three-rotation) of the reflector in vacuum by adjustments outside the vacuum. Then the equations of kinematic analysis were finalized based on the mechanism design. Finally the 4-DOF mechanism design was testified by a practical example. The mechanism design can be used in the field of extreme ultraviolet lithography, as well as other precision machining and positioning applications.

Introduction

Lithography machine has been the key equipment for integrated circuits industry [1]. Extreme ultraviolet (EUV) lithography, with 13.5nm wavelength, becomes the most promising candidate technique for next-generation lithography [2]. Because the wavelength is so short that nearly everything can absorb EUV, there are two basic characters for EUV lithography; one is that, all optical paths should be in vacuum; the other is the optics should be reflective system. Moreover, the reflectors in vacuum should be assembled stably, and have the ability of realizing multi-DOF adjustments.

This paper proposes a new type of mechanism design for EUV reflectors, which can move inside the vacuum by adjusting the parts out of vacuum. The movement has four degrees of freedom (4-DOF), consisting of one in translation along the vertical axis of reflector surface, and three in rotation about three perpendicular axes of reflector body [3]. The design results could also be applied in the fields of precision machining and positioning applications, such as robotics engineering, machine tools, space telescope and so on.

Mechanical Design

The 4-DOF mechanism design is shown in figure 1, including vacuum chamber, reflector, mirror frame, fixing system, sliding system and adjusting system. The reflector is mounted steadily in the mirror frame by the fixing system. There are two kinds of adjusting system, A and B; in the design there are four adjusting systems (three for A and one for B) corresponding to 4-DOF. The sliding system is used to support the mirror frame with the reflector and fixing system as a whole, while the sliding system and adjusting system work together to realize 4-DOF adjustment of the mirror frame.

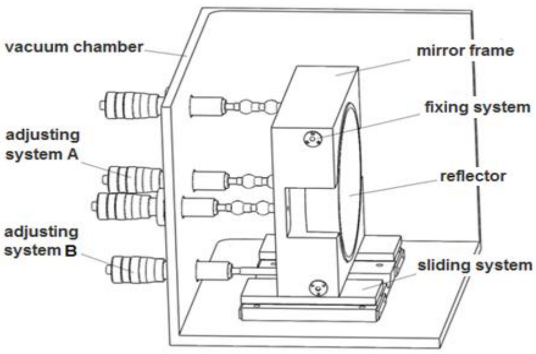


Figure 1. 4-DOF mechanism design for a reflector in vacuum.

Reflector

The reflector, with the diameter of several hundred millimeters and the weight of dozens of kilograms, is shown in figure 2.

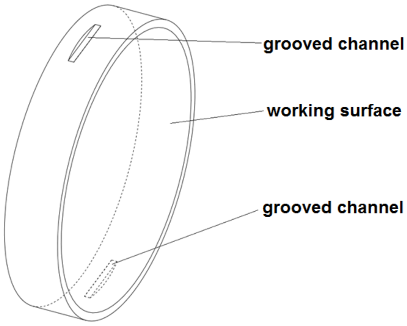


Figure 2. The reflector with two grooved channels.

There are two grooved channels, located in opposite sides of the reflector, which are used for the fixing system to integrate the reflector with the mirror frame. The working surface should face outwards, and the other inside surface should cling to mirror frame, so that the heat the reflector gets from working surface could be easily transferred outside through mirror frame.

Mirror Frame

The front and dorsal views of mirror frame are shown in figure 3 and 4 respectively. There are two symmetrical convex plates for directly supporting the side of reflector, while other circumferential parts are conical for the purpose of integrating the reflector conveniently. The two grooves can provide space for handling the reflector, and four bolt holes can be used to push and remove the reflector. There are five possible positions of screw holes for adjusting system, but in fact we only use four of them to provide four inputs for 4-DOF outputs. There are also interfaces for fixing system and sliding system, especially a ball socket connecting the sliding system.

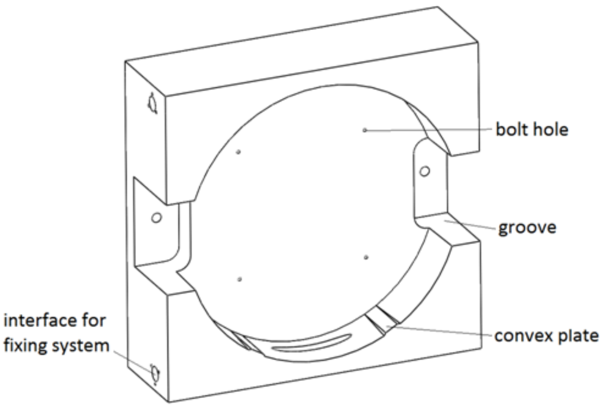


Figure 3. Front view of mirror frame.

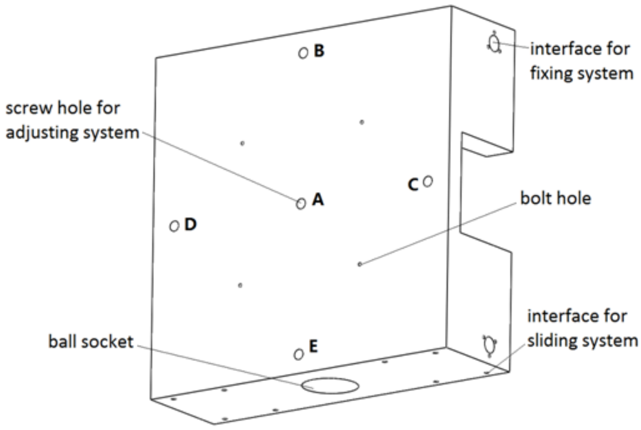
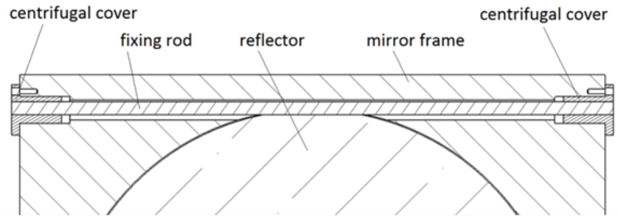


Figure 4. Dorsal view of mirror frame.

Fixing System

The cross-sectional drawings of fixing system are shown in figure 5 and 6. The fixing system is composed of a fixing rod and two centrifugal covers. Inside the centrifugal cover there is a through hole, with different axis from the cover's central axis and the same diameter as the fixing rod. The diameters of the cover's shoulder and corresponding hole of mirror frame keep consistent, so that the centrifugal covers with the fixing rod passing through can go inside the mirror frame. Also the fixing rod crosses the grooved channel of the reflector. Then if we rotate the two centrifugal covers in one direction, the fixing rod inside will move around, contact the edge of the grooved channel and push the reflector. When the reflector moves to the limit position, the covers can be fixed to the mirror frame with pre-tightening force. Therefore, the reflector is locked in the mirror frame by the fixing system (figure 6).



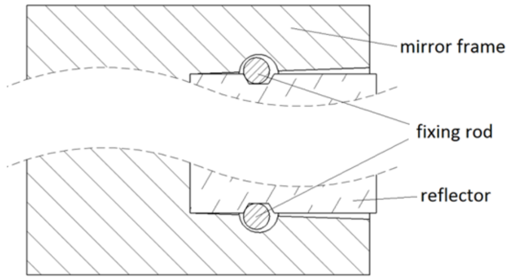


Figure 5. Sectional drawing I of fixing system. Figure 6. Sectional drawing II of fixing system.

Sliding System

Figure 7 shows the sliding system, including two intermediate plates with several position-limiting balls below, a base plate with three cylindrical channels, several baffles for the channels, and a sliding ball. The base plate is fixed with the vacuum chamber, while the intermediate plates are integrated with the bottom of mirror frame (figure 4). The sliding ball connecting the adjusting system can match the sliding channel and the ball socket of mirror frame (figure 4), so that the base plate can withstand the weights of the sliding ball, the mirror frame and the reflector. Moreover, we can move the sliding ball by the adjusting system along the sliding channel, so as to move back and forth the mirror frame and the reflector as a whole. The baffles are set to limit the range of movement.

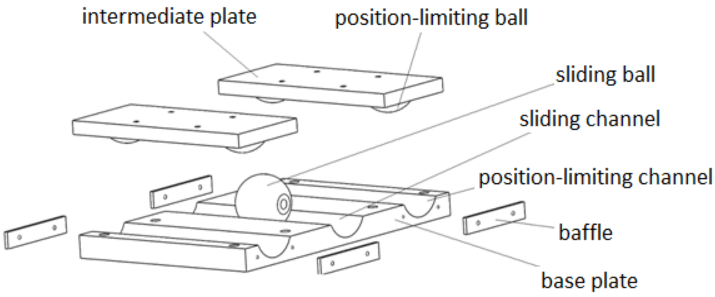


Figure 7. The sliding system.

The diameter of position-limiting balls is smaller than that of position-limiting channels, so that the balls are located inside the channels. The gaps between the balls and channels can bear three rotational DOF of the mirror frame, and can be designed to limit the rotational ranges.

Adjusting System

The adjusting system A and B are shown in figure 8 and 9. The linear feedthrough, which is linked to the flange on the vacuum chamber, can transfer rotational motion out of vacuum to linear movement in vacuum. In figure 8, the spherical joint composed of a ball and housing can provide universal rotation. In figure 9, the part of linear feedthrough inside the vacuum is directly connected to the sliding ball. If rotating the three linear feedthroughs of three adjusting system A, we can change the positions of six spherical joints to realize 3-DOF rotation of mirror frame about three perpendicular axes which are all pass through the center of sliding ball. Moreover, if rotating the linear feedthrough of adjusting system B, we can change the position of sliding ball to realize 1-DOF translation of mirror frame. Therefore, the mechanism design given can realize 4-DOF movement by rotating the four adjusting systems.

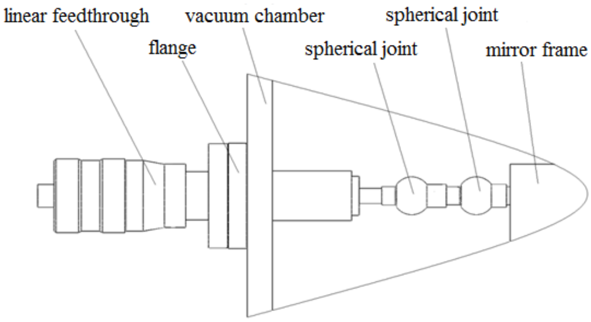


Figure 8. The adjusting system A.

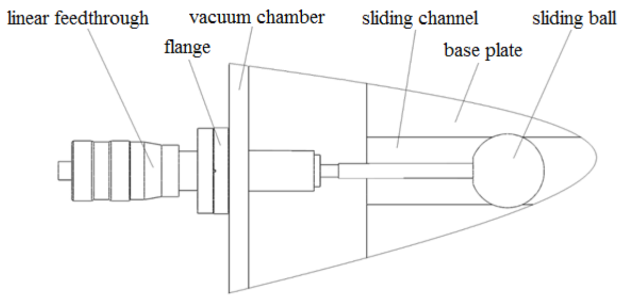


Figure 9. The adjusting system B.

Kinematic Analysis

The kinematic diagram of the new 4-DOF mechanism design is shown in figure 10. D1, D2, D3 and D4 stand for the positions of the four adjusting systems in the vacuum chamber; A4 stands for the center of sliding ball; A1, A2, A3 and A4 are in the same section of mirror frame; C1, C2, C3 C4, B1, B2, B3 and B4 stand for the center of spherical joints. A space coordinate system XYZ is fixed to the vacuum chamber with D4 for origin, D4D2 for X axis and D4A4 for Z axis, while another coordinate system X'Y'Z' is fixed to the mirror frame with A4 for origin, A4A2 for X' axis and D4A4 for Z' axis.

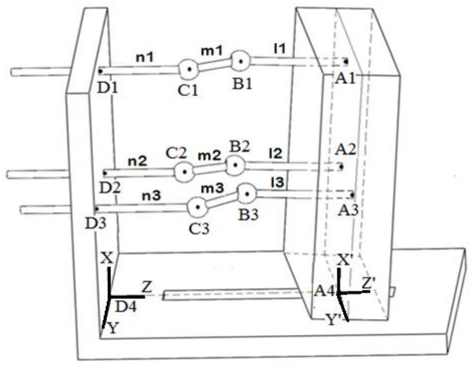


Figure 10. Kinematic diagram of the 4-DOF mechanism design.

The coordinate system X'Y'Z' can be transformed from the system XYZ, and the transformation equation is as following.

$$\begin{bmatrix} X' \\ Y' \\ Z' \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ \Delta Z \end{bmatrix} + R(\varepsilon_x)R(\varepsilon_y)R(\varepsilon_z)\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \tag{1}$$

In equation (1), ΔZ means translation parameter, while ε_x, ε_y and ε_z mean rotation parameters. The rotation matrices$R(\varepsilon_x)$, $R(\varepsilon_y)$ and $R(\varepsilon_z)$ are defined by the following equations.

$$R(\varepsilon_x) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\varepsilon_x & \sin\varepsilon_x \\ 0 & -\sin\varepsilon_x & \cos\varepsilon_x \end{bmatrix} \tag{2}$$

$$R(\varepsilon_y) = \begin{bmatrix} \cos\varepsilon_y & 0 & -\sin\varepsilon_y \\ 0 & 1 & 0 \\ \sin\varepsilon_y & 0 & \cos\varepsilon_y \end{bmatrix} \tag{3}$$

$$R(\varepsilon_z) = \begin{bmatrix} \cos\varepsilon_z & \sin\varepsilon_z & 0 \\ -\sin\varepsilon_z & \cos\varepsilon_z & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{4}$$

Then we can get the new transformation equation:

$$\begin{cases} X' = \cos\varepsilon_y\cos\varepsilon_z X + \cos\varepsilon_y\sin\varepsilon_z Y - \sin\varepsilon_y Z \\ Y' = \left(-\cos\varepsilon_x\sin\varepsilon_z + \sin\varepsilon_x\sin\varepsilon_y\cos\varepsilon_z\right)X + \\ \left(\cos\varepsilon_x\cos\varepsilon_z + \sin\varepsilon_x\sin\varepsilon_y\sin\varepsilon_z\right)Y + \sin\varepsilon_x\cos\varepsilon_y Z \\ Z' = \Delta Z + \left(\sin\varepsilon_x\sin\varepsilon_z + \cos\varepsilon_x\sin\varepsilon_y\cos\varepsilon_z\right)X + \\ \left(-\sin\varepsilon_x\cos\varepsilon_z + \cos\varepsilon_x\sin\varepsilon_y\sin\varepsilon_z\right)Y + \cos\varepsilon_x\cos\varepsilon_y Z \end{cases} \tag{5}$$

If defining *n1* as the distance from D1 to C1, *n2* as the distance from D2 to C2, *n3* as the distance from D3 to C3, and *n4* as the distance from D4 to A4, we can change *n1*, *n2*, *n3* and *n4* by rotating the four adjusting systems. So we can get:

$$\Delta Z = -n_4 \tag{6}$$

To simplify the kinematic analysis, we assume the distances D2D1, D2D3, D2D4, A2A1, A2A3 and A2A4 are equal, and define as *r*. So we can obtain the coordinate values of C1, C2 and C3 in coordinate system XYZ, which are ($2r$,0,n_1), (r,0,n_2) and (r,r,n_3) respectively.

By using equation (5), we can gain the coordinate values of C1, C2 and C3 in coordinate system X'Y'Z', which are as follows.

$$\text{C1:}\begin{bmatrix} 2r\cos\varepsilon_y\cos\varepsilon_z - \sin\varepsilon_y n_1 \\ 2r\left(-\cos\varepsilon_x\sin\varepsilon_z + \sin\varepsilon_x\sin\varepsilon_y\cos\varepsilon_z\right) + n_1\sin\varepsilon_x\cos\varepsilon_y \\ 2r\left(\sin\varepsilon_x\sin\varepsilon_z + \cos\varepsilon_x\sin\varepsilon_y\cos\varepsilon_z\right) + n_1\cos\varepsilon_x\cos\varepsilon_y - n_4 \end{bmatrix}$$

$$\text{C2:}\begin{bmatrix} r\cos\varepsilon_y\cos\varepsilon_z - n_2\sin\varepsilon_y \\ r\left(-\cos\varepsilon_x\sin\varepsilon_z + \sin\varepsilon_x\sin\varepsilon_y\cos\varepsilon_z\right) + n_2\sin\varepsilon_x\cos\varepsilon_y \\ r\left(\sin\varepsilon_x\sin\varepsilon_z + \cos\varepsilon_x\sin\varepsilon_y\cos\varepsilon_z\right) + n_2\cos\varepsilon_x\cos\varepsilon_y - n_4 \end{bmatrix}$$

$$\text{C3:}\begin{bmatrix} r\cos\varepsilon_y\cos\varepsilon_z + r\cos\varepsilon_y\sin\varepsilon_z - n_3\sin\varepsilon_y \\ r\left(-\cos\varepsilon_x\sin\varepsilon_z + \sin\varepsilon_x\sin\varepsilon_y\cos\varepsilon_z\right) \\ +r\left(\cos\varepsilon_x\cos\varepsilon_z + \sin\varepsilon_x\sin\varepsilon_y\sin\varepsilon_z\right) + n_3\sin\varepsilon_x\cos\varepsilon_y \\ r\left(\sin\varepsilon_x\sin\varepsilon_z + \cos\varepsilon_x\sin\varepsilon_y\cos\varepsilon_z\right) - n_4 \\ +r\left(-\sin\varepsilon_x\cos\varepsilon_z + \cos\varepsilon_x\sin\varepsilon_y\sin\varepsilon_z\right) + n_3\cos\varepsilon_x\cos\varepsilon_y \end{bmatrix}$$

If defining *l1* as the distance from A1 to B1, *l2* as the distance from A2 to B2, and *l3* as the distance from A3 to B3, we can obtain the coordinate values of B1, B2 and B3 in coordinate system X'Y'Z', which are ($2r$,0,$-l_1$), (r,0,$-l_2$) and (r,r,$-l_3$) respectively.

If defining *m1* as the distance from B1 to C1, *m2* as the distance from B2 to C2, and *m3* as the distance from B3 to C3, we can get the following equations.

$$m_1{}^2 = \left(2r\cos\varepsilon_y\cos\varepsilon_z - n_1\sin\varepsilon_y - 2r\right)^2 + \left[2r\left(-\cos\varepsilon_x\sin\varepsilon_z + \sin\varepsilon_x\sin\varepsilon_y\cos\varepsilon_z\right) + n_1\sin\varepsilon_x\cos\varepsilon_y\right]^2 + \left[2r\left(\sin\varepsilon_x\sin\varepsilon_z + \cos\varepsilon_x\sin\varepsilon_y\cos\varepsilon_z\right) + n_1\cos\varepsilon_x\cos\varepsilon_y - n_4 + l_1\right]^2 \tag{7}$$

$$m_2{}^2 = \left(r\cos\varepsilon_y\cos\varepsilon_z - n_2\sin\varepsilon_y - r\right)^2 + \left[r\left(-\cos\varepsilon_x\sin\varepsilon_z + \sin\varepsilon_x\sin\varepsilon_y\cos\varepsilon_z\right) + n_2\sin\varepsilon_x\cos\varepsilon_y\right]^2 + \left[r\left(\sin\varepsilon_x\sin\varepsilon_z + \cos\varepsilon_x\sin\varepsilon_y\cos\varepsilon_z\right) + n_2\cos\varepsilon_x\cos\varepsilon_y - n_4 + l_2\right]^2 \tag{8}$$

$$m_3{}^2 = \left(r\cos\varepsilon_y\cos\varepsilon_z + r\cos\varepsilon_y\sin\varepsilon_z - n_3\sin\varepsilon_y - r\right)^2 + \left[r\left(-\cos\varepsilon_x\sin\varepsilon_z + \sin\varepsilon_x\sin\varepsilon_y\cos\varepsilon_z\right) + r\left(\cos\varepsilon_x\cos\varepsilon_z + \sin\varepsilon_x\sin\varepsilon_y\sin\varepsilon_z\right) + n_3\sin\varepsilon_x\cos\varepsilon_y - r\right]^2 + \left[r\left(\sin\varepsilon_x\sin\varepsilon_z + \cos\varepsilon_x\sin\varepsilon_y\cos\varepsilon_z\right) + r\left(-\sin\varepsilon_x\cos\varepsilon_z + \cos\varepsilon_x\sin\varepsilon_y\sin\varepsilon_z\right) + n_3\cos\varepsilon_x\cos\varepsilon_y - n_4 + l_3\right]^2 \tag{9}$$

By solving the equations (7), (8) and (9), we can get the following equations

$$n_1 = -2r\sin\varepsilon_y + (n_4 - l_1)\cos\varepsilon_x\cos\varepsilon_y - \sqrt{\begin{gathered} m_1{}^2 - 8r^2 - (n_4 - l_1)^2 + 4r^2\sin^2\varepsilon_y + 8r^2\cos\varepsilon_y\cos\varepsilon_z \\ +4r(n_4 - l_1)\sin\varepsilon_x\sin\varepsilon_z - 4r(n_4 - l_1)\cos\varepsilon_x\sin\varepsilon_y\cos\varepsilon_y \\ +4r(n_4 - l_1)\cos\varepsilon_x\sin\varepsilon_y\cos\varepsilon_z + (n_4 - l_1)^2\cos^2\varepsilon_x\cos^2\varepsilon_y \end{gathered}} \quad (10)$$

$$n_2 = -r\sin\varepsilon_y + (n_4 - l_2)\cos\varepsilon_x\cos\varepsilon_y - \sqrt{\begin{gathered} m_2{}^2 - 2r^2 - (n_4 - l_2)^2 + r^2\sin^2\varepsilon_y + 2r^2\cos\varepsilon_y\cos\varepsilon_z \\ +2r(n_4 - l_2)\sin\varepsilon_x\sin\varepsilon_z - 2r(n_4 - l_2)\cos\varepsilon_x\sin\varepsilon_y\cos\varepsilon_y \\ +2r(n_4 - l_2)\cos\varepsilon_x\sin\varepsilon_y\cos\varepsilon_z + (n_4 - l_2)^2\cos^2\varepsilon_x\cos^2\varepsilon_y \end{gathered}} \quad (11)$$

$$n_3 = -r\sin\varepsilon_y + (n_4 - l_3)\cos\varepsilon_x\cos\varepsilon_y + r\sin\varepsilon_x\cos\varepsilon_y - \sqrt{\begin{gathered} m_3{}^2 - 4r^2 - (n_4 - l_3)^2 + r^2\sin^2\varepsilon_y + 2r^2\cos\varepsilon_y\cos\varepsilon_z \\ +2r^2\cos\varepsilon_x\cos\varepsilon_z + 2r^2\cos\varepsilon_y\sin\varepsilon_z - 2r^2\cos\varepsilon_x\sin\varepsilon_z \\ +2r(n_4 - l_3)\sin\varepsilon_x\sin\varepsilon_z - 2r(n_4 - l_3)\sin\varepsilon_x\cos\varepsilon_z \\ -2r^2\sin\varepsilon_x\sin\varepsilon_y\cos\varepsilon_y - 2r(n_4 - l_3)\cos\varepsilon_x\sin\varepsilon_y\cos\varepsilon_y \\ +2r^2\sin\varepsilon_x\sin\varepsilon_y\sin\varepsilon_z + 2r(n_4 - l_3)\cos\varepsilon_x\sin\varepsilon_y\sin\varepsilon_z \\ +2r^2\sin\varepsilon_x\sin\varepsilon_y\cos\varepsilon_z + 2r(n_4 - l_3)\cos\varepsilon_x\sin\varepsilon_y\cos\varepsilon_z \\ +(n_4 - l_3)^2\cos^2\varepsilon_x\cos^2\varepsilon_y + r^2\sin^2\varepsilon_x\cos^2\varepsilon_y \\ +2r(n_4 - l_3)\sin\varepsilon_x\cos\varepsilon_x\cos^2\varepsilon_y \end{gathered}} \quad (12)$$

Considering the rotation parameters ε_x, ε_y and ε_z are all approximately tiny, we suppose the following equations (i=x, y, z).

$$\cos\varepsilon_i = 1 \quad (13)$$

$$\sin\varepsilon_i = \varepsilon_i \quad (14)$$

By using equations (13) and (14), we can gain the following equations.

$$n_1 = (n_4 - l_1) - 2r\varepsilon_y - \sqrt{m_1{}^2 + 4r^2\varepsilon_y{}^2 + 4r\cdot(n_4 - l_1)\varepsilon_x\varepsilon_z} \quad (15)$$

$$n_2 = (n_4 - l_2) - r\varepsilon_y - \sqrt{m_2{}^2 + r^2\varepsilon_y{}^2 + 2r(n_4 - l_2)\varepsilon_x\varepsilon_z} \quad (16)$$

$$n_3 = (n_4 - l_3) - r\varepsilon_y + r\varepsilon_x - \sqrt{\begin{gathered} m_3{}^2 + r^2\varepsilon_x{}^2 + r^2\varepsilon_y{}^2 + 2r(n_4 - l_3)\varepsilon_x\varepsilon_z \\ +2r(n_4 - l_3)\varepsilon_y\varepsilon_z + 2r^2\varepsilon_x\varepsilon_y\varepsilon_z \end{gathered}} \quad (17)$$

So the results of kinematic analysis are the equations (6), (15), (16) and (17), by which we can get the precise positions of four adjusting systems if knowing the required parameters of the 4-DOF mechanism design.

Practical Example

Based on the design provided above, the real 4-DOF mechanism manufactured for reflectors in vacuum is shown in figure 11.

A practical example using the real 4-DOF mechanism is shown in figure 12. The reflector is elliptical with the diameter 300mm; the lamp is a point source, located at one focus position of the elliptical reflector. We can realize 4-DOF movement of the reflector by rotating four adjusting systems of the mechanism design, so as to get the clear light spot at the other focus position of the elliptical reflector.

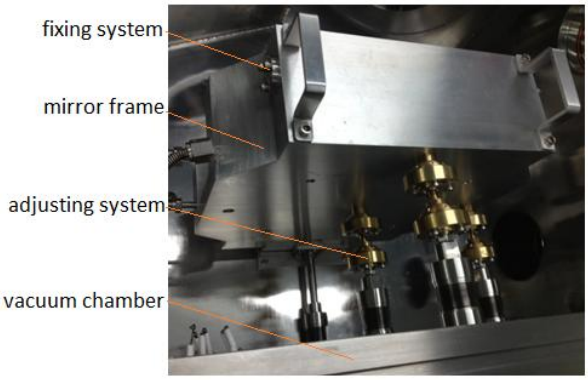


Figure 11. The real 4-DOF mechanism for reflectors in vacuum.

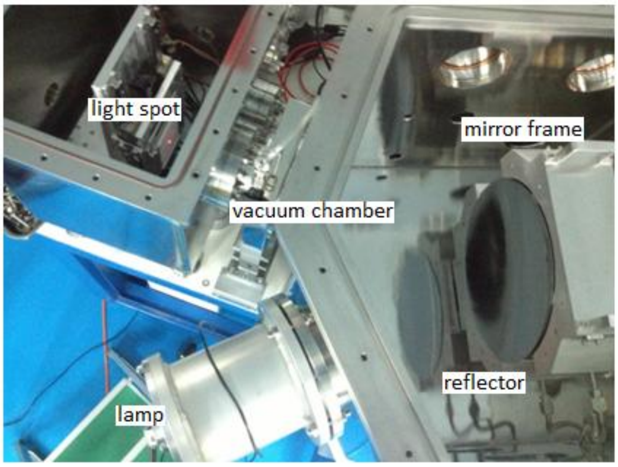


Figure 12. A practical example using the mechanism.

Conclusion

1) A new type of 4-DOF mechanism was designed for reflectors in vacuum. The reflector was fixed in the mirror frame by the fixing system; the mirror frame was supported by the sliding system in vacuum chamber; the adjusting systems had the ability of realizing the 4-DOF movement of the mirror frame and the reflector in vacuum by adjustments outside the vacuum.

2) The kinematic analysis of the 4-DOF mechanism was made, and the calculation results were finalized.

3) A practical example was proposed to testify the feasibility of the 4-DOF mechanism design for reflectors in vacuum.

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