Design of dynamic error detection system for grating scale

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Abstract. Grating scale is a closed-loop detection and control tool for precision machine tools, and its accuracy detection needs a higher precision detection platform. There are two kinds of commonly used detection platform guideways: sliding guideway and rolling guideway. Because of the contact of points or lines, the error caused by the guideway itself is obvious. In order to reduce the error of the platform itself, the air-floating guideway with small friction resistance and no vibration relative to the motion is used as the support mode, and the air pressure is debugged according to the smoothness of sliding. The static accuracy detection method of grating sensor is comparatively mature, but there is no effective solution for its dynamic accuracy detection. To solve this problem, we developed a dynamic error detection system of grating scale based on high-precision grating scale. The experimental results show that the system can detect the dynamic accuracy of grating scale, and has high detection efficiency. It is suitable for mass rapid measurement in practical work.

1. Introduction
With the development of national industry, the requirement of manufacturing industry for precision machine tools is becoming higher and higher. Therefore, the measurement accuracy of grating scale is required to be higher, and the measurement and calibration of grating scale accuracy is becoming more and more important. At present, the static calibration technology of grating scale has been developed more mature, but this calibration technology does not consider the real dynamic operation mode of grating scale in practical work. On the other hand, laser interferometer is usually used for measuring and calibrating grating scales, but the laser interferometer has high environmental requirements and low measurement efficiency, which don’t meet the actual needs of large-scale inspection in factory production.

In this paper, a high-precision air-floating platform is designed, and based on it, a dynamic measurement system of grating scale with high-precision grating scale as benchmark is developed.

2. Structural design of precision detection platform
The accuracy detection platform has special requirements for the stability of motion, so the choice of the guideway support plays an important role. The main support forms are sliding guideway, rolling guideway and static pressure guideway [1]. The sliding guideway relies on the mutual friction of its guide pair to realize the guideway support. Inevitably, there is a creeping phenomenon caused by the
difference of dynamic and static friction coefficient, at the same time, the heating is obvious and the wear is serious. The rolling guideway depends on the ball or the cylinder as a rolling body, realizing rail support by point contact or line contact. The support surface is small so the vibration is more obvious during the movement process, resulting in accuracy measurement error [2,3]. Considering these factors, we changed the guideway to the air-floating guideway. First, because of the lubrication of the gas, the error in the motion of the guideway is homogenized and the local roughness on the surface of the guideway is compensated [4]. In operation, the air-floating block has little wear effect on the guideway, which ensures the stability of the motion.

2.1. Reference positioning grating scale (high precision grating scale)
The laser interferometer described in this paper has the function of detecting positioning accuracy. Laser interferometer includes laser head, laser head bracket, spectroscope, reflector, magnetic seat of accessories, connecting rod, etc. As shown in Figure 1. The laser head body is fixed at the left end of the marble platform through a bracket. The spectroscope is attached to the leftmost limit block of the marble platform through the connecting rod and the magnetic seat. The reflector is attached to the air-floating sliding device through magnetic base and connecting rod.

The center of laser head, spectroscope and reflector are fixed at the same height, and the same straight line is maintained along the moving direction of the air-floating sliding device. We use the dual-frequency laser interferometer to detect the high-precision grating scale, and then compensate the position of the high-precision grating scale according to the test results. The resolution of the compensated high-precision grating scale is 0.0001 mm. The position compensated high-precision grating scale is mounted on the accuracy detection platform. As shown in Figure 2, 3, the measured grating scale is parallel to the high-precision grating scale, and then the high-precision grating scale is used as the reference positioning grating scale. The scale body is installed on the side of marble A. The high-precision grating scale reading head is fixed on the air-floating sliding device. The measured grating scale body is fixed on marble A, and the reading head of the measured grating scale is fixed by the fixture on the air-floating sliding device.

![Diagram](image.png)

**Figure 1.** High-precision air-floating platform and laser interferometer device
1. Servo motor 2. Air supply device 3. Marble A 4. Marble B 5. Marble C

**Figure 2.** High-precision air-floating platform and laser interferometer device

1. Reference positioning grating scale (high-precision grating scale)  
2. Measured grating scale

**Figure 3.** High-precision air-floating platform and laser interferometer device

### 2.2. The design of the detection platform’s main structure

As shown in Figure 4, 5, 6, the platform structure is mainly composed of marble, air-floating sliding device, reference positioning grating scale (high-precision grating scale), leveling screw, servo motor, gas supply device, etc. Marble A and marble C are connected with a screw to marble B. As shown in Fig. 4, marble C acts as the guide rail of the air-floating sliding device. Guideway plays a guiding role. The straightness error of guideway is very important for precision measurement. The factors affecting the straightness of guideway are the smoothness of the guideway’s surface, the structure of the guideway...
Material selection of guideway is the first consideration. Material selection should satisfy the shape stability in long-term operation and is not easy to wear and deform. Due to the uniform structure inside the marble, the compressive strength is high, the physical properties are stable, the shape is not changed, the material particles have a uniform mirror effect, the surface is free of burrs, and the friction coefficient is low, so the marble guideway is selected.

As shown in Fig. 5, the air-floating sliding device is composed of a semi-enclosed slider and an air-floating block. There are many holes on the air-floating sliding device, which can be clamped to different sizes of gratings, ball grids and magnetic grids. The air-floating block has two structures: circular and square. In order to reduce the width of the guideway and make full use of the limited space, we choose rectangular air-floating block. Its throttling forms include orifice throttling, capillary throttling and slit throttling. As shown in Fig. 6, two small holes and a closed groove type 48*22 micro groove are used in this paper. The air supply device has the functions of oil pollution filtering and air pressure regulation. The air flows out of the orifice and fills the closed groove quickly, forming the closed area I and area II. Area I is a constant pressure area, which ensures that the force is uniform everywhere and increases the stability of the support [5]. In the choice of position, our air-floating sliding device is surrounded by four thicker iron plates around the marble slideway. There are three air-floating blocks on the left and right sides of the slideway, which are not in the same straight line. The installation positions on the left and right sides are symmetrically distributed. The upper four air-bearing blocks, two in a straight line, constitute two parallel lines. Two air-floating blocks are distributed on the lower line corresponding to the middle line of the two lines, and the symmetry of the four sides is ensured to ensure stable operation.
1. Semi-enclosed slider  2. Air-floating block

**Figure 5.** Air-floating sliding device

1. Semi-enclosed slider  2. Air-floating block

**Figure 6.** Bottom structure of air-floating block

In order to prevent the deflection of the air cushion block in installation, the support mode of the air cushion block is fixed on the sliding frame by the structure type of ball head bolt. The constraint of the direction of movement of the air-floating block is achieved by installing an adjusting nut on the air-floating block. The purpose is to ensure that the air-floating block can be fine-tuned under the sliding frame during the movement, overcome all kinds of deviations caused by the processing and assembly, and keep the sliding device and guideway in parallel at any instantaneous motion.

3. **Working principle of control system**

The core of the control system is made up of computer and its special control and data processing software. First, the computer sends the start command. During the movement of the air-floating sliding device, the displacement signal detected by the measured head of the measured grating scale is processed by the signal acquisition card and sent to the computer.

At the same time, the high-precision grating scale transmits the collected displacement signal to the computer, and the results of measurement are compared and displayed by the special control and data
processing software. The measurement accuracy of the high-precision grating scale is higher than that of the measured grating scale, and the accuracy error of the grating scale is calculated by comparing the difference between their measured values at different points. As shown in Figure 7, the computer is used as a host computer to control the start and end of the whole system, the magnitude of the velocity acceleration, the collection and processing of the measured values, and the output of the results.

![Figure 7. Principle of system work](image)

The host computer software mainly uses windows form program under the environment of .net framework to realize the functions of measurement process control (measurement and motion control), data processing, error curve display and report generation. The system software has perfect functions, simple operation and efficient execution, which ensures the effective detection work.

4. Error and calibration of test platform

The test platform has a high requirement for the stationarity of the measuring equipment. The factors that affect the stationarity are divided into internal factors and external factors. The factors include guideway type, rail structure, throttle, gas thickness, rail stiffness and surface roughness of parts. The guideway type and the guideway structure are described in detail in the previous chapter, which are no longer described here.

The most commonly used methods of throttling are torus throttling, slit throttling and small hole throttling. The torus throttling of which the air consumption is large and the flow velocity is fast has strong bearing capacity. But at the same time, the vibration caused by too fast velocity affects the smoothness of the motion. The air consumption of small hole throttling is much smaller than that of the torus throttling. Due to the light weight of the bearing measuring instrument, the small hole throttling is enough to bear and the slow flow speed ensures the smoothness of operation [6].

Gas thickness has a great relationship with stability. The gas is compressible. The more the gas is, the worse the motion stability will be. The thin gas will reduce the load capacity and is not conducive to smooth operation. The main factors affecting gas thickness are orifice diameter and gas pressure. Considering the bearing capacity, only when the clearance is two times greater than the roughness of the surface of the contact surface, the member supported by air is floated. The diameter of the airflow has an influence on the bearing capacity. With the increase of the aperture, the bearing capacity is changing from large to small. Chosing the hole with a diameter of 0.14 mm and a set of gas supply system is used to control the pressure value to test the suitable gas source pressure.

The layout of the air-floating blocks has a very large influence on the stability of the motion. At first, two air-floating blocks are arranged on each side of the air-floating sliding device in a horizontal line. The upper and lower air-floating blocks are far from the guideway, which results in unstable shaking
during the test. In order to solve this problem, we add an air-floating block on the top and the two sides. The air-floating block on each side is not in a straight line. The relative surface symmetrically places the air-floating block, which has an effective restraint effect on the shaking in the motion process.

The smaller running speed of the guideway, the better the stability of the guideway, because too fast movement will bring the vibration of the driving motor, and the vibration will be transmitted to the guideway, which will affect the stability.

Thermal expansion and cold shrinkage will change the shape of the instrument, resulting in contact instability, vibration and environmental disturbance. The vibration of surrounding environment will also affect the stability of the system. Using micrometer to check whether the error range is within acceptable range [7].

5. Testing and Analysis
The measured grating scale is an incremental grating scale with a length of 350 mm and a resolution of 5 μm. At the speed of 600 mm/s, six repetitive tests were carried out with a measurement interval of 17.5 mm. The measured data are shown in Table 1 (the first 21 groups are forward direction measured data and the last 21 groups are reverse direction measured data):

| Table 1. Dynamic measurement data of grating scale |
|-----------------------------------------------|
|     | F1  | F2  | F3  | F4  | F5  | F6  | R1  | R2  | R3  | R4  | R5  | R6  |
| 1   | -2.3| -1.9| -2.5| -2.3| -1.3| -1.5| -0.7| -0.9| -1.1| -0.6| -1  | -0.6|
| 2   | -4.5| -4  | -5  | -3.6| -3  | -2.8| -2.1| -2.9| -3  | -2.5| -3.1| -2.6|
| 3   | -6.4| -5.6| -6.8| -5.6| -5  | -4.8| -3.1| -5.2| -4.9| -4.5| -5  | -4.5|
| 4   | -5.5| -5.5| -6.7| -5.8| -5.2| -5.1| -6.3| -5.5| -5.5| -5.1| -5.7| -4.7|
| 5   | -4.1| -3.8| -6.2| -3.9| -3.4| -3  | -5  | -3.6| -3.5| -3.1| -3.3| -2.5|
| 6   | -3.1| -2.2| -3.7| -2.4| -2  | -1.5| -6.7| -2.1| -1.9| -1.6| -1.7| -1.2|
| 7   | -2.7| -2  | -3  | -1.9| -1.4| -1  | -7  | -1.3| -1.2| -1.1| -1.4| -0.6|
| 8   | -2.2| -1.6| -2.6| -1.7| -0.8| -0.5| -8  | -1.2| -0.7| -0.3| -1  | 0   |
| 9   | -1.1| -0.9| -2  | -0.7| 0   | 0.5 | -9  | 0.1 | 0   | 0.5 | 0.2 | 0.8 |
| 10  | -1.9| -1.4| -2.5| -1.4| -1.1| -0.6| -10 | -1.1| -1.1| -0.8| -0.9| -0.5|
| 11  | -2.3| -1.8| -2.9| -1.5| -1.1| -0.4| -11 | -1.3| -0.9| -0.8| -0.9| -0.5|
| 12  | -1.1| -0.2| -1.6| -0.6| -0.1| 0.5 | -12 | 0.8 | 0.2 | 0.1 | 0.2 | 0.5 |
| 13  | -2.9| -2.2| -3.2| -2.2| -1.3| -1  | -13 | -1  | -1.7| -1.5| -1  | -1.3| -1|
| 14  | -4.4| -3.8| -4.8| -3.4| -3  | -2.7| -14 | -2.3| -3.2| -3.1| -2.8| -3  | -2.5|
| 15  | -5.4| -4.9| -5.7| -4.9| -3.7| -3.7| -15 | -3.2| -4  | -3.5| -4  | -3.5|
| 16  | -4.9| -4.3| -5.2| -4.3| -3.5| -3.3| -16 | -2.7| -3.6| -3.6| -3  | -3.3| -3|
| 17  | -5.3| -4.8| -6.2| -4.7| -4.3| -4  | -17 | -3.7| -4.4| -4.1| -3.7| -4  | -3.8|
| 18  | -4.8| -4.5| -5.8| -4.3| -4.2| -4.7| -18 | -2.5| -4.2| -3.9| -3.7| -4.2| -3.5|
| 19  | -3.7| -3.6| -4.9| -3.2| -3.1| -2.5| -19 | -1.8| -2.7| -2.8| -2.6| -3.3| -2.2|
| 20  | -2.9| -2.7| -3.9| -2.7| -2.4| -1.8| -20 | -0.9| -2.1| -2.1| -1.9| -2.5| -1.3|
| 21  | -2.4| -1.7| -2.6| -2.2| -1.4| -0.8| -21 | -0.2| -1.7| -1.3| -1  | -1.4| -0.5|
|     |     |     |     |     |     |     |     |     |     |     |     |     |
| Forward |     |     |     |     |     |     |     |     |     |     |     |     |
| Reverse |     |     |     |     |     |     |     |     |     |     |     |     |

The accuracy is calculated by the first forward measurement data, and the return errors are 1, 11 and 21 as observation points. The repetition precision is calculated using all the data in Table 1, and the maximum repetition error is taken as the repetition precision of the grating scale [8].

| Table 2. Dynamic error of grating scale |
|----------------------------------------|
| Measurement                          | Result/μm |
| Accuracy degree                      | ±3.2       |
| Repeatability precision              | 0.6628     |
| Hysteresis error                     | 2.5        |

The dynamic repeatability of the grating was measured at 400, 600, 800, 1000 mm/s. The results are shown in Table 3:
### Table 3. Measurement repeatability at different speeds

| Speed/mm·s⁻¹ | 400    | 600    | 800    | 1000   |
|--------------|--------|--------|--------|--------|
| Repeatability precision /μm | 0.4193 | 0.6628 | 0.8623 | 1.115  |

### 6. Conclusion

It is known from the experimental results that the grating scale shows different repeating precisions at different speeds, and the greater the speed, the worse the dynamic repeatability. The reason may be that the deviation of the reading due to the elastic deformation of the grating reading head during operation affects the accuracy of the entire system. However, the overall test results are not much different, and the dynamic measurement system can accurately characterize the performance of the grating scale at different speeds.

Practice has proved that the detection system is simple to operate. The detection system has good anti-interference ability, high detection efficiency, and high reliability. It can realize the dynamic error detection of grating ruler, and is suitable for mass rapid measurement in production site.

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