Study on the Control of Micro-Environmental Parameters in Long Distance Laser Interferometry

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Abstract. Fluctuation in environmental parameters has become an important factor affecting the performance of ultra precision measurement. Aiming at the long-distance and high-speed laser interferometer measurement system, a method combining structure design and closed-loop control is proposed to reduce the measurement error caused by environmental parameters. The uniform pressure structure is designed, and the control system of micro environmental parameters is established. The simulation and experimental research on the uniformity of temperature and pressure on the optical path measured by laser interferometer are carried out. The simulation and experimental results show that this method can achieve temperature uniformity and stability above 0.01℃ and pressure uniformity and stability above 1Pa, and can be widely used in micro environment parameter control of long-distance ultra precision measurement.

Keywords: Laser interferometer; Micro-environment parameters; Closed loop control; Equalizing pressure structure; Computational fluid dynamics

1. Introduction

In IC manufacturing and optical detection, the real-time positioning and alignment of silicon wafers or workpieces require not only nanoscale accuracy, but also large stroke [1,2]. Laser interferometer(IF) is widely used in nano-resolution and long-range dynamic measurement because of its advantages such as fast measuring speed, high measuring precision, high resolution, large dynamic measurement range and non-contact measurement [3,4].

The measurement error of IF is not only related to the measurement principle, but also directly affected by its environment [5], especially in the long distance and high speed laser interferometry, the diversity of environmental parameters and the random fluctuation have more significant influence on the measurement error, which has become an important error source for ultra-precision measurement [6].

At present, the method of environmental parameter error compensation is widely used to correct the measurement error of IF [7-9]. However, it is necessary to analyze the measurement errors caused by environmental parameters in depth and then adopt reasonable structural design and real-time closed-loop control of environmental parameters to ensure the performance of the measurement system.
2. Environmental Error Analysis of Laser Interferometry System

Take the typical lithography machine wafer stage system as an example. The system consists of plane motor, IF, main controller, marble table, vibration absorber, wafer stage and so on, as shown in figure 1. The plane motor makes the wafer stage produce multi-degree of freedom motion; the main controller controls the motion of the plane motor; the IF feedback the relative motion information of the wafer stage by measuring the optical path difference on the optical path; the vibration absorber is used to isolate the external vibration.

The main environmental parameters that cause the system error of IF include temperature, pressure and humidity. The fluctuation of these environmental parameters will cause the change of air refractive index, and then cause the fluctuation of optical path difference on the optical path of IF [10].

![Figure 1. wafer stage system.](image)

The relationship between wavelength $\lambda$ and refractive index $n$ is as follows:

$$\lambda = \lambda_0 n_0 / n$$  \hspace{1cm} (1)

The refractive index has the following relation with environmental parameters:

$$n = 1 + (2.8793 \cdot 10^{-7} \cdot P)/(1 + 0.003671 \cdot T) - 3.6 \cdot 10^{-8} \cdot P_w$$  \hspace{1cm} (2)

The $P$ is pressure, the $T$ is temperature, and the $P_w$ is water vapor partial pressure.

The temperature, pressure and humidity of a point in space are also functions of space coordinate $r$ and time $t$. Furthermore, the refractive index of a point in a light path measured by a IF can be further expressed as

$$\lambda = f(n, t) = g(T(r,t), P(r,t), P_w(r,t))$$  \hspace{1cm} (3)

When the environmental parameters fluctuate, the wavelength of different points in the IF will change with time and space, resulting in the following optical path difference:

$$\Delta l = \int_0^L \Delta \lambda \cdot dx$$  \hspace{1cm} (4)

The $\Delta \lambda$ is the variation of the wavelength of the $dx$ distance with the fluctuation of the environment, and the $L$ is the length of the optical path.

Take the optical path of 1 meter, Considering the 1nm optical path difference, from (1)–(4) formula: The temperature needs to be stabilized at 0.001K; Pressure needs to be stabilized at 0.37Pa; Humidity needs to be stabilized at 0.1%RH.

In the actual laser interferometry system, the influence of environmental parameters on the measurement error is superimposed.

3. Environmental Error Control Method

From the formula (3), we can see that the environmental parameters of each point in the optical path are not equal in terms of space scale, and the change of environmental parameters at each point in the optical path is random in terms of time scale. Direct error compensation will face the following
problems: compensation point is difficult to choose, because the environmental parameters of each point in space are different and the compensation period is difficult to determine, because the environmental parameters fluctuate randomly. It is difficult to achieve the consistency of environmental parameters in the whole optical path space by using single point closed loop control.

The idea of solving the above problems is to combine structural design, closed-loop control and error compensation into three steps as shown in figure 2:

1) First of all, we rely on some kind of structural design to realize the consistency of environmental parameters in space;
2) Then the frequency and amplitude of environmental parameter fluctuation are reduced by closed loop control;
3) Finally, error compensation is carried out to improve the measurement accuracy.

![Figure 2. Control principle of environmental error in measuring optical path.](image)

Taking the optical path measured by the IF in figure 1 as an example, the environmental error control method is briefly analyzed. For the convenience of analysis, the fluctuation of environmental parameters in formula (3) can be expanded into signals with different frequencies, amplitudes and phases, so that the optical path difference caused the fluctuation of environmental parameters in the time period \( t \) is as follows:

\[
\Delta l = \int_0^t \int_0^l B(x) \sin(\omega(x) \cdot t + \varphi(x)) \, dx \, dt 
\]  

(5)

Where \( B(x) \) is the amplitude of environmental parameters at different optical path points, \( \omega(x) \) is the frequency of environmental parameters at different optical path points, and \( \varphi(x) \) is the phase of environmental parameters at different optical path points.

Assuming that the frequency, amplitude and phase of the environmental parameters can be adjusted to approximately the same by structural design, the formula (5) can be simplified as follows:

\[
\Delta l = LB \int_0^t \sin(\omega \cdot t + \varphi) \, dt
\]  

(6)

From formula (6), it can be seen that the optical path difference on the optical path is decoupled from the spatial position, so that the error compensation point can be selected at any point in the optical path.

Furthermore, by reducing the frequency and amplitude of environmental parameters through closed-loop control, the optical path difference can be reduced to:

\[
\Delta l = LC \int_0^t \sin(\omega \cdot t + \varphi) \, dt
\]  

(7)

The output waveform of the environment parameters can be expressed as:
$$h(t) = C \sin(\alpha \cdot t + \varphi)$$  \hspace{1cm} (8)

When the measurement error is limited to $R$, maximum compensation period $Z_{\text{max}}$ satisfy the following relationship:

$$Z_{\text{max}} < R/[dh(t)/dt]_{\text{max}} = R/(C \cdot \omega \cdot \varphi)$$  \hspace{1cm} (9)

As long as the compensation period is less than $Z_{\text{max}}$, The ideal compensation effect can be achieved.

Taking optical path of 1m and the measurement error of 1nm as an example, if the amplitude of temperature fluctuation is controlled by 0.01K, the maximum compensation equivalent is 0.01. When the frequency of temperature fluctuation is 1Hz, the compensation period is $Z_{\text{max}} < 0.1$ second; the compensation period can be increased to 1 second when the temperature fluctuation frequency is 0.1Hz.

From the above analysis, it can be seen that through the structural design, the consistency of measuring the fluctuation of environmental parameters at each point in the optical path is ensured, and the problem of compensation point selection is solved. The frequency and amplitude of environmental parameter fluctuation are suppressed by closed-loop control.

Due to space limitation, this paper mainly studies structural design and closed-loop control. Because temperature and pressure are more sensitive to refractive index than humidity, two environmental parameters, temperature and pressure, are mainly analyzed here.

4. Structural Design and Simulation Research

Based on the design of uniform pressure structure, the temperature and pressure uniformity in optical path space of IF is studied by simulation.

4.1. Structural Design

The design of the uniform pressure structure needs to consider the spatial uniformity of the temperature and pressure and the output is laminar flow to avoid back-flow.

![Uniform pressure structure](image)

**Figure 3. Uniform pressure structure**

The vertical air shower structure is designed as shown in figure 3. Air at the air inlet with a certain speed $V_1$ and pressure $P_1$ is transported to the vertical air shower structure, and the air mixing is realized by static pressure chamber, which plays the role of uniform temperature and pressure. Gradient width of static pressure chamber ensures the uniformity of outlet surface velocity $V_2$ and pressure $P_2$. The back pressure filter is arranged on the below surface of the air shower structure, so that the air of velocity $V_3$ and pressure $P_3$ is output on the whole air outlet surface uniformly. For practical application, the outlet pressure $P_3$ and velocity $V_3$ can be adjusted by selecting filters with different densities.

4.2. Simulation Research

Because of the complexity of fluid flow in space scale, CFD method is used to verify the results of uniform pressure structure design. The system of the wafer stage of the lithography machine is
simplified as the simulation model shown in figure 4. Two kinds of simulations are carried out to measure the temperature and pressure uniformity of the optical path and to measure the pressure fluctuation of the optical path under different air shower wind speed.

Figure 4. Simplified model of wafer stage system of lithography machine.

4.2.1. Uniformity of Temperature and Pressure. The uniformity of temperature and pressure is simulated by measuring optical path of wafer stage IF. Simulation conditions: the vertical air shower structure shown in figure 3 is adopted. The air shower outlet velocity is 1m/s, the air supply temperature is 22℃, and the inlet and outlet pressure difference is 10Pa. The simulation model is shown in figure 5(a), and the results are shown in figures 5(b) and 5(c), respectively. The results show that the temperature uniformity is better than 0.01℃ and the pressure uniformity is better than 1Pa in the whole IF measuring optical path.

Figure 5. Simulation of temperature and pressure uniformity.

4.2.2. Pressure Fluctuations at Different Wind Speeds. The air shower wind speed is set to two cases: 0.1m/s low velocity air shower and 1m/s high velocity air shower, the wafer stage moves at an acceleration of 12.5m/S^2, and the simulation results are shown in figures 6(a) and (b) respectively. It can be seen from the diagram that under the high speed air shower, the pressure fluctuation of the IF measuring optical path is smaller than that of the low speed air shower, which will cause smaller IF measurement error.
5. Closed-loop Control of Environmental Parameters

The air temperature and pressure are adjusted by air temperature and pressure control device (ATPC) and heat exchange (HE), as shown in figure 7. The process of air circulation is as follows: after mixing the air from the wafer stage system and the external environment in the mixing chamber, the air is inhaled the ATPC, and then flowing through the HE, the vertical air shower structure is transported to the optical path of the IF. Among them, the ATPC plays the role of primary temperature and pressure regulation, the HE carries on the secondary temperature regulation, the vertical air shower structure realizes the uniform temperature and the pressure, and ensures that the air is output to the IF in laminar flow state. The circulating water of the input of the HE comes from the water temperature control device (TCU) with higher temperature control accuracy. Through closed loop control, constant temperature and constant pressure are realized. After the data acquisition card obtains the temperature and pressure value of the air shower outlet, it is send to the main controller, the main controller sends out data and instructions to the TCU and ATPC. In order to avoid the influence of vibration and pollution on the measuring device, TCU, ATPC and the main controller are placed in the ordinary clean room.

Using cascade control, the control principle is shown in figure 8. According to the measured value $T_{as}$, $P_{as}$ and $T_{a}$ of air shower outlet surface, by comparison with set temperature $T_s$ and pressure $P_s$, the optimal set temperature $T_{aw}$ and pressure $P_{aw}$ of air temperature and pressure control device is calculated by control algorithm and the optimal set temperature $T_{bw}$ of the water temperature control device is also calculated by control algorithm in the main controller (MC). Then, the secondary controller 1(SC1) in the air temperature and pressure control device adjusts the heating and cooling through the control algorithm to make the outlet temperature $T_a$ approach the set temperature $T_{aw}$. The SC1 in the air temperature and pressure control device adjusts the frequency converter (FC) through the control signal circuit.
algorithm to make the outlet pressure $P_s$ approach the set pressure $P_{sw}$. The secondary controller 2(SC2) in the water temperature control device adjusts the heating and cooling through the control algorithm, so that the outlet water temperature $T_w$ is close to the set temperature $T_{tw}$.

![Figure 8. Schematic diagram of temperature pressure cascade control.](image)

6. Experiment Verification

According to figure 8, the temperature and pressure control test device is established, the air temperature and pressure control device with variable frequency fan and with 0.05°C temperature control accuracy(ATC); The water temperature control device with temperature control precision of 0.01°C(TCU); Using Hart 5641 temperature sensors and SETRA pressure sensors; Development of 20-bit data acquisition card(EMB); A main control algorithm runs on a PPC. Design of heat exchanger and vertical air shower structure according to simulation results; Air flow speed of measuring optical path is controlled 1m/s. Two temperature points are arranged at points P1 and P2, and three pressure sensors at points P3,P4,P5, as shown in figure 9. Record two temperature data and three pressure data, and calculate the temperature fluctuation in 5 minutes and 30 seconds. The temperature data are shown in figure 10, the pressure data are shown in figure 11.

![Figure 9. Layout of temperature and pressure sensors.](image)

![Figure 10. Spatial uniformity and stability of temperature.](image)
Figure 11. Spatial uniformity and stability of Pressure.

Figure 10 shows that the temperature fluctuations at P1 and P2 are similar to sine waves, has a periodicity of about 10 min, and the frequency, amplitude and phase are similar. It verifies the effectiveness of structural design and the spatial decoupling is realized. Air temperature control accuracy is better than 0.01°C, the temperature fluctuation within 5 min is better than 0.01°C, and the temperature fluctuates better than 0.002°C for 30 seconds. The effectiveness of closed-loop control is verified. From figure 11, it can be seen that the pressure difference of P3, P4 and P5 is less than 1Pa, which realizes the high spatial uniformity. It verifies the effectiveness of the structure design, and realizes the spatial decoupling. The pressure control accuracy is better than 1Pa, which verifies the effectiveness of the closed-loop control.

7. Conclusion

Ultra-precision measurement has moved towards nanometer scale and even sub-nanometer level, and the fluctuation of environmental parameters has become an important factor affecting the performance of ultra-precision measurement. The measurement error caused by environmental parameters is analyzed for a wide range, high precision and high speed laser interferometry system. The method of reducing measurement error by combining structure design, error compensation and environmental control is proposed. The micro-environment parameter control system is established and simulated under different air shower parameters.

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