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A Large Range Linear Displacement Calibration System Based on Coordinate Measurement and Laser Interference

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Abstract. The linear displacement sensor is widely used in industrial measurement. The linear displacement sensor with measuring range less than 200mm is usually measured on a universal length measuring instrument. There is no good method to calibrate linear displacement sensor with measuring range larger than 200mm. The calibration system of linear displacement based on coordinate measurement and dual frequency laser interference is developed. The guide rail and measuring positioning system of coordinate measuring machine is used. The sampling signal of dual frequency laser interferometer is connected with the pulse signal triggered by coordinate measuring machine. The accurate position information of the linear displacement sensor is obtained and processed by industrial computer. According to JJF 1305-2011 Calibration Specification for Linear Displacement Sensor, a large range of linear displacement sensors is calibrated. The accuracy and reliability of linear displacement calibration system based on coordinate measurement and laser interference is verified.

1 Introduction

Linear displacement sensor is used to measure displacement, distance, position, strain, etc. It is widely used in engineering fields[2]. Coordinate measuring machine is regarded as one of the most typical measuring instruments in length measurement. It can be used in automatic precise positioning. Calibration of linear displacement sensors is an important part of the National Metrology Department and metrology laboratories. Linear displacement calibration system in this paper can be traced to the wavelength of the laser interferometer system.

The linear displacement calibration system involves direct measurement of laser interferometer and the precise positioning of coordinate measuring machine. The laser wave length is used as the measuring reference. The interference mirror is placed on the worktable of the coordinate measuring machine. The linear displacement sensor is directly measured by laser interference. The Leitz coordinate measuring machine is used as the precision motion table, and the laser frequency is used as the length standard to calibrate the absolute displacement of the linear displacement system.

The linear displacement sensor with measuring range less than 200mm can be measured on a high-precision universal length measuring instrument. Due to the present structure size limitation of the linear displacement measurement system, there is no good method to calibrate the linear displacement sensor with measuring range larger than 200mm. In this paper, the linear displacement calibration system based on coordinate measurement and dual frequency laser interferometer is developed. The calibration system can be used to calibrated linear displacement sensors with measuring range between 200mm and 1000mm.

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2 Designment of linear displacement calibration system

This paper mainly focuses on the following aspects:

1. A motion control module and automatic positioning module based on the coordinate measuring machine is designed. A signal acquisition system based on an industrial computer is established, with that dual-frequency laser interference signal, temperature sensor signal, humidity sensor signal, barometric pressure sensor signal can be collected.
2. A measuring program to control the movement of the linear displacement sensor is developed. Software is used to collect and process data.
3. A mathematical model of the measurement system is established and the measurement uncertainty is analyzed.

2.1 Linear displacement calibration system

The HP5529 laser interferometer which includes a 5520 laser interferometer side head and a data acquisition card is used. Laser data acquisition card and sensor signals are access to industrial computer. The laser interferometer works as the core of the linear interferometer system and the coordinate measuring machine works as the main body. The air refractive index automatic compensation function runs with temperature, humidity and barometric pressure measurement unit.

Dual frequency laser interferometer is an incremental instrument for measuring length . Laser wavelength is used as its standard for measuring length and the linear accuracy is up to 0.3 μm . The reflector and the sensor are mounted on the coordinate measuring table and moved along with the X axis[3]. The measured length is reflected by the displacement of the mirror relative to the reference mirror. The system based on coordinate measuring and dual frequency laser interferometer is designed as shown in figure 1.

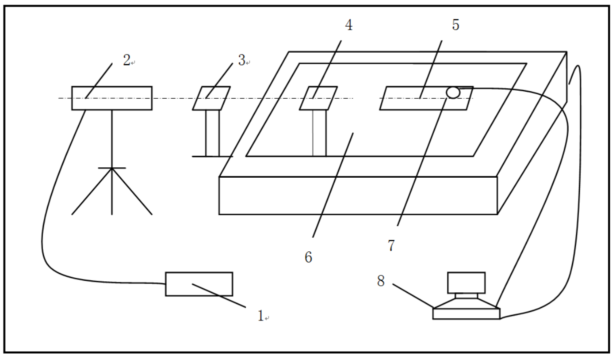

Figure 1. Coordinate measuring system based on dual frequency laser interferometer

The system consists of a dual frequency laser interferometer IPC 1, laser head 2, fixed mirror 3, movable mirror 4, the measured workpiece 5 and three coordinate measuring machine moving table 6, temperature sensor 7, three coordinate measuring machine computer control system 8.

The measurement principle of dual frequency laser interferometer is optical interference principle and frequency difference produced by Doppler effect. When it is working, the laser head produces left-handed f_1 and right-handed f_2 circularly polarized light with the same amplitude but different frequencies. Two beams of light pass through the optical path of an optical element such as a deflection detector, a filter, a fixed mirror, a moving mirror. Then interference fringes of light and dark is formed. The interference fringes are received by photoelectric elements and converted into electrical signal. The electrical signal is received by the amplifier. The amplification signal is read by the computer. Through subtraction in computer, the signal difference $\pm\Delta f$ is calculated. The number of N pulse signal is counted by the counter. The following formula can calculate the velocity v and the distance l (length of the measured workpiece) of the movable mirror.

$$v = \frac{\lambda}{2}\Delta f \tag{1}$$

$$l = \int_0^t v dt = \frac{\lambda}{2}\int_0^t \Delta f dt = \frac{\lambda}{2}N \tag{2}$$

Formula (1) , (2) :

λ — Wavelength of the laser in the measurement process.

Δf — Frequency difference due to the movement of the moving mirror

t — Measurement time.

N — Number of pulses recorded by the computer.

3 Solution scheme for calibration system

The key to this measurement system is to obtain the accurate value of the laser wavelength λ in the measurement process. The wavelength λ is related to the refractive index n of the air, and the refractive index of the air is affected by the measured environmental parameters, such as measurement of environmental temperature t ,pressure p ,humidity f and so on. The mathematical expressions between them are as follows:

$$\lambda = \frac{\lambda_0}{n} \tag{3}$$

$$n = F(t, p, f) \tag{4}$$

λ_0 — Wavelength in the vacuum

F — Some function relationship. In order to obtain accurate numerical value of laser wavelength, the relative accurate value of refractive index n should be calculated by the relation of function F .

In this paper, the three coordinate measuring machine is used as the measuring platform, and the absolute displacement of linear displacement sensor with measuring range between 200mm and 1000mm can be measured. It is a universal measuring instrument with wide range of measurement, high accuracy and good repeatability. Due to superior measurement performance, the three coordinate measuring machine is used as the moving mechanism and measuring platform in the experiment in this linear displacement calibration system. During the measurement, the target is measured by the displacement signal of the measuring head of the measuring machine. The length is measured by the laser interferometer. The whole measuring system is controlled by software. The temperature, pressure and humidity sensors measuring on-site environmental parameters are collected to correctly calculate the refractive index of air n according to the modified Edlen formula by the software. Then the laser wavelength relatively accurate value λ is obtained.

When measurement begins, the coordinate measuring machine and laser measurement system are initialized. The coordinate measuring machine with double frequency laser interference linear displacement measurement system is adjusted to establish the coordinate system. The flow chart of measurement process is shown in figure 2.

The positioning point and range is set to ensure that the coordinate measuring machine is automatically running correctly and the interference of dual frequency laser interferometer is correct. The counting of the dual frequency laser interferometer is stored in the computer. When the linear displacement sensor is calibrated, the display value of the linear displacement sensor is observed and recorded in the computer.

During the measurement, the linear displacement sensor is measured 3 times. The coordinate measuring machine is used to measure the linear displacement measurement system. The measurement is carried out forward and backward as a measurement cycle. The three linear cycles are measured. According to the measurement results of the three cycles, the reference linear equation is calculated by the least squares method. The linear sensor manufactured by Celesco test specification: PT8600-025-8088 is selected as the measuring object. It is placed in the calibration laboratory enough time for isothermal measurement.

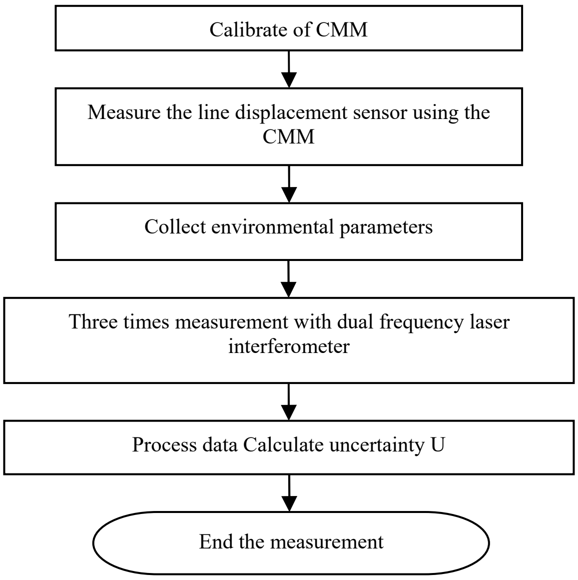

Figure 2. Flow chart of measurement process

The high precision and high efficiency LEITZ PMM-C measuring machine is manufactured by HEXAGON. With two solid granite as the guide rail of the mobile bridge, a linear screw transmission and a nano-grating, LEITZ PMM-C measuring machine ensures the accuracy of the linear displacement sensor measurement.

The measuring software is built based on C++. The Microsoft Foundation Class (MFC) Library provides an object-oriented wrapper over much of the Win32 and COM APIs. Although it can be used to create very simple desktop applications. It is most useful when more complex user interfaces with multiple controls is needed to develop. MFC is used to create applications with Office-style user interfaces. The individual hierarchy charts included with each class are useful for locating base classes. The MFC Reference usually does not describe inherited member functions or inherited operators. For information on these functions, refer to the base classes depicted in the hierarchy diagrams.

The main work of the software is to read the laser parameters from the sensors and perform the calculation. The function structure is as below.

```
// runLaser.h
//read light intensity from light sensor
double read LightIntensityFromDLL(…)
//read humidity from humidity sensor
double readHumidityFromDLL(…)
//read temperature from temperature sensor
double readTemperatureFromDLL(…)
//read atmospheric pressure from atmospheric pressure sensor
double readAtmosphericPressureFromDLL(…)
//use all the parameters to calculate air refractive index
double calculateAirRefractiveIndex (…)
```

Connect the data lines and connect the laser head to the power cord. After the connection is confirmed correctly, the power is turned on to warm the laser head. The sensor cable is connected to the respective material capture card position. The air measurement sensor is placed properly upright on the material of workpiece. The measuring software is run. The parameters are set before the measurement.

QUINDOS software is used to control the coordinate measuring machine.QUINDOS software has a unique detection function based on the pointing function and intuitive program editing function. It is one of the most powerful measurement software in the world. Automatic positioning is controlled by QUINDOS software and different parameters can be selected according to different measuring range and step size.

The cycle program of the coordinate measuring machine QUINDOS is programmed as follows:

```
USEPRB (NAM=PRB(1))
TMPCOMP (TEW=20,COE=0.0000115
MEPLT (NAM=PLANE(1))
MEAXI (NAM=AXIS(1))
MEPNT (NAM=POINT(1))
BLDCSY (NAM=CSY(1))
LENGTH=4
DO (NAM=I.BGN=1,END=LENGTH)
MEPNT (NAM=POINT(I))
TRAOBJ (NEW=PNT(I+1),X=152.4)
ENDDO
ADDEVA (NAM=POINT(I))
```

The cord sensor was placed on the measuring chamber and the measurement began after a sufficient time. The environmental parameters collected by the dual-frequency laser interferometer sensor was: ambient temperature 20.42℃, air humidity 50%, pressure 100814.458 pa . The environmental parameters was substituted into the modified Edlen formula to calculate the air refractive index, which was 0.99973. The material temperature was 20.46°C, and temperature differences lead to block length change expansion coefficient is 11.5 μm / °C. When the laser intensity was sufficient and the laser signal was stabilized, the average value of the three measurements of the linear displacement sensor was shown in Table 1.

Table 1.measurement data of linear displacement calibration system

Unit: mm

Measuring cycle	Standard displacement value Y_i	Instrument display y_i	Basic error δ_i
forward	0.0000	0.0000	0.0%
forward	62.8000	62.7866	-0.06%
forward	122.0000	121.8872	0.04%
forward	182.4000	182.3492	0.04%
forward	241.9000	241.7455	0.03%
forward	304.8000	304.7398	0.11%
reverse	304.8000	304.7388	0.11%

reverse	241.9000	241.7445	-0.03%
reverse	182.4000	182.3372	0.03%
reverse	122.0000	121.8842	-0.06%
reverse	62.8000	62.7796	-0.01%
reverse	0.0000	0.0000	-0.03%
reverse	-62.8000	-62.7850	-0.05%
reverse	-122.0000	-121.8865	0.01%
reverse	-182.4000	-182.3888	-0.14%
reverse	-241.9000	-241.7476	-0.03%
reverse	-304.8000	-304.3754	0.20%
forward	-304.8000	-304.3784	0.20%
forward	-241.9000	-241.7480	-0.03%
forward	-182.4000	-182.3898	0.14%
forward	-122.0000	-121.8875	0.01%
forward	-62.8000	-62.7860	-0.05%
forward	0.0000	-0.0305	0.01%

3.1 Basic error

The calibration value of the linear displacement calibration system at the calibration point is the standard value, and the formula of the basic error measurement results is shown as follows (5) [2]

$$\delta_i = \frac{y_i - Y_i}{Y_{FS}} \times 100\% \quad (5)$$

$$Y_{FS} = Y_M - Y_N \quad (6)$$

Formula (6): Y_{FS} — Full scale output

Y_M — Displacement output at the time limit

Y_N — The output of the displacement to the lower limit

3.2 Return error

The return error of each calibration point of the linear displacement calibration system, taking the largest of each point as the return error measurement result[2].

$$h_i = g_i - b_i$$

g_i — The linear displacement measuring system is at i calibration point, the forward stroke output

b_i — The linear displacement measuring system is at i calibration point, the reverse stroke output

When the data is processed, The error of return error is 0.089mm.

The measurement characteristics of the displacement sensor are composed of basic error, linearity, return error and repeatability. The calibration work only gives the measurement result. The design of the system fully meets the requirements of the calibration specification.

3.3 repeatability

According to the measurement data of the three cycles, the output value is measured three times by the i calibration point of the forward and reverse directions. The maximum difference between the same direction is obtained. The maximum difference is get by the point of the same direction of the difference between the maximum Δ_i . The repeatability is calculated according to formula below.

$$r_i = \frac{0.61\Delta_i}{Y_{FS}} \times 100\%$$

4 Uncertainty analysis of calibration system

4.1 Mathematical mode

The measurement uncertainty is used to characterize the dispersion of the measured values[4]. Uncertainty is used to describe the calibration level as a basis for traceability and to characterize the quality of the measuring equipment.

In the linear displacement sensor calibration system, the displacement of sensor could be expressed as (7) [1]

$$l_W = l_{WJ} - L\alpha_W \Delta t_W + \delta_{MB} + \delta_{AW} + \delta_{AJ} \quad (7)$$

l_W — The string sensor displacement at a reference temperature of 20℃

l_{MJ} — Displacement displayed by a laser interferometer

L —The nominal value of linear displacement sensor

α_W — The linear thermal expansion coefficient of string sensor

Δt_W —The difference of temperature between sensor and reference temperature 20℃

δ_{MB} —The expected value is zero correction value, which reflects the influence of coordinate measuring machine's yaw error during measurement

δ_{AW} —The expected value is zero correction, which reflects the sensor's directional error

δ_{AJ} —The expected value is zero, which reflects the directional error of the laser

4.2 Uncertainty analysis of calibration system

The uncertainty analysis procedure of the calibration system is mentioned in the paper[8]. Based on experience, the uncertainty components are listed in table 2:

Table 2.uncertainty components

component u_i	influence factor	sensitivity coefficient C_i	standard uncertainty (μm)
u_1	Laser measuring length	1	0.3L
u_2	thermal expansion coefficient	1	0.4L
u_3	angular component of machine	1	0.2L
u_4	String sensor direction	1	0.3L
u_5	laser orientation	1	0.1L

4.3 Standard uncertainty of synthesis

The standard uncertainty synthesized by the above uncertainty components is as follows.

$$u_c = \sqrt{\sum (c_i u_i)^2} = \sqrt{0.39L^2} \approx 0.7L(\mu m)$$

$$U = ku_c = 2\times 0.9L \approx 2L(\mu m),\ (k=2)$$

$$U_{rel} = 0.0002\%$$

5 Conclusion

This paper mainly deals with the calibration of linear displacement sensors with measuring range between 200mm and 1000mm. The calibration system of line displacement based on coordinate measurement and dual frequency laser interference is developed. A measuring Software of this calibration system is developed to control the movement, collect and process data. It is known that the measurement uncertainty of the measurement using the dual-frequency laser interference coordinate measurement system is $U_{rel} = 0.0002\%$ and maximum measurement characteristics of linear displacement measurement system is $\pm 0.01\%$. The result meets the requirements of the JJF 1305-2011 Calibration Specification for Linear Displacement Sensor.

The linear displacement sensor is a one-dimensional sensor which is widely used in length measurement. There are many types such as inductors, differential pressure, grating, cord, magnetostrictive, wavelength-coded fiber, etc. The solution of various linear displacement calibration represents the measurement ability of a metrological testing organization. The development of linear displacement calibration system solves the problem of inaccurate displacement in real work.

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