Research on the Principle and Structure of Novel High-precision Linear Time Grating Displacement Sensor

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The existing grating type sensors such as optical grating sensor, have long been designed to rely on the precise mechanical spatial division technology, which is hard to develop without heavy investment. A theoretical concept, time-space coordinate transformation, was presented to realize measuring spatial displacement with time difference. Similar to the principle of circular time grating based on rotating electrical machine, linear time grating is designed based on the principle of linear motor, with which the physical and mathematical models of linear time grating are established. Based on these models linear time grating mechanical structure is designed, which has commercialization value. The resolution of linear time grating can achieve 0.1μm tested by National Institute of Measurement and Testing Technology.

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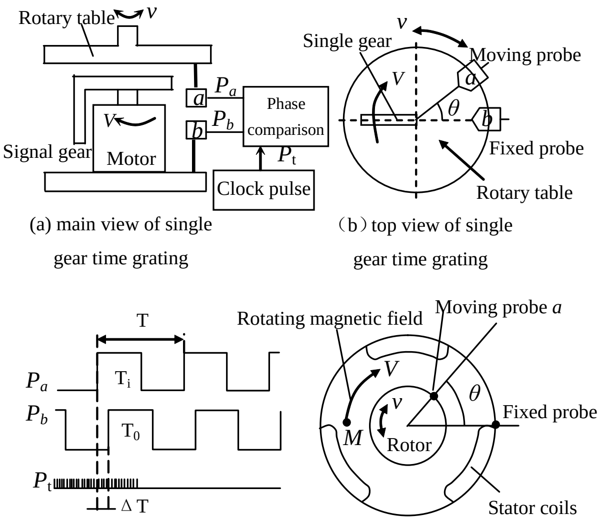
1. Introduction

The traditional grating type sensors such as optical grating, magnetic encoder and so on, have been designed to rely on the precise mechanical spatial division technology. Measurement accuracy of traditional displacement sensors equals their spatial division accuracy. Although measurement principle is regarded as "simple and sophisticated", design and production capacities of such traditional grating type sensors are lacked for many countries. Original time grating displacement sensor technology has been developed for decade, and several important breakthroughs have been made in angular measurement field. The measurement principle of time grating sensors is presented: establishing two different coordinate systems moving relatively at a uniform velocity, the space displacement in one of them can be expressed by the time difference observed by the other. Therefore, space displacement can be measured by means of time difference. The key point of measurement principle is to employ clock pulses with high accuracy as measurement standard instead of the precise mechanical spatial division technology, so the high accuracy spatial measurement can be obtained with simple machining technology, and the high resolution can be obtained without any signal subdivision devices. Consequently, time grating sensors have the characteristic of low cost , strong anti-interference capabilities and high degree of intelligence, and have much more commercial competitiveness for products and industrialization. In industrialization process, linear measurement and novel sensor development are much important and urgent. First of all, length (displacement) is one of international system of units like time, mass, temperature and so on. And angular measurement is only regarded as the part or special case of length measurement. Second, take example for machine tool industry, the amount of linear measurement requirement(along three axes such as X axis, Y axis and Z axis) is more than three times that of angular measurement. Therefore, research on linear time grating sensor has much more theoretical and realistic significance.

2. Physical and mathematical model of time grating

The principle of mechanical rotary angular displacement sensor is illustrated in Fig.1.a and Fig.1.b. In order to solve endless coordinate system problem, rotary movement is employed. According to closed circle principle, single gear for time grating is adopted to solve equal division for coordinate axis. There is no division error in theory, because there is only one slot for one circle. And The angular rocker-arm can be regarded as single gear which is drived by synchronous motor with velocity V . These two components constitute the most simple moving coordinate systems. When the gear passes the movable probe a and the fixed probe b successively, inductive signals are generated representing the observed time points T_i and T_0, which can be transformed into square waves.

The phase of signal P_b is fixed, and the phase of signal P_a shifts s ynchronously with the table rotation at a variable velocity V. Becaus e it is a single gear with its circular pitch being W=360°, its correspon ding electrical angle, i.e. the signal phase angle θ=360°. After compar ing the phases of these two signals, the phase difference can be expres sed with time difference. Therefore, the space displacement between t he fixed probe and the movable probe, (i.e. space displacement betwe en the rotor and the stator of the rotary table) $\theta = V\Delta T = V(T_i - T_0) = V\sum P_t$,can be obtaine. Where $\sum P_t$ repre sents time difference ΔT. Note: angular displacement of moving obj ect with random velocity V can be obtained with this method.

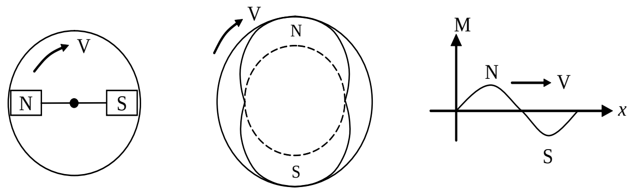


(c) Signal chart of time grating (d) Schematic diagram of field-type time grating

Fig.1. Measurement principle of time grating

The aims of “Angular measurement with graduator without slot” and “Spatial measurement with time difference” are carried out for m echanical time grating. Later, a field-type time grating sample with the principle of “moving coordinate system formed by moving magnetic field” was designed as shown in Fig.1.d. The principle of fie ld-type time grating is similar to general ac motor. Rotating magnetic field replaces single gear, and two embed wires replace prob es. Obviously there exists a kind of corresponding relationship betwee n Fig.1.b and Fig.1.d. In Fig.1.b, rotary machinery (single gear)cuts fi xed magnetic field (magnet coil).But in Fig.1.d, rotating magnetic fiel d M cuts fixed machinery (embed wire). Experiment results prove tha t time grating displacement sensor is an important invention. First, ste ady coordinate systems with uniform velocity has been obtained, mec hanical friction and air resistance are eliminated. So the accuracy of s ensors is improved. Second, mechanical rotary machinery can be rem oved to decrease its volume and weight. consequently, it is easy to ins tall. Last, according to the principle of linear motor, endless moving c oordinate system with equal division can be obtained(such coordinate system can not be obtained in mechanical way) and applied into line ar time grating displacement sensor.

Rotating magnetic field play an important role to develop from mechanical time grating to field-type time grating. Rotating magnetic field which is norm knowledge in electromechanics, sometimes is called traveling wave of magnetic potential. Rotating magnetic potential as shown in Fig.2.b has an equivalent effect as rotating permanent magnet as shown in Fig.2.a. According to aforementioned



(a) rotary permanent magnet (b) rotating magnetic potential (c) magnetic potential in linear motion

Fig.2. Magnetic potential in motion

time-space transformation method, a endless coordinate system of evenly divided scale moving with uniform velocity is needed to scan fixed probe and moving probe. Moving magnetic traveling wave along a line as shown in Fig.2.c. can be regarded as continuous movement without start and end. So combining the principle of linear ac motor, motor shell can be expand along the line as shown in Fig.3.to obtain the structure of linear field-type time grating. Once the power is on, the traveling-wave magnetic field starts at point c, ends at point d and travels the distance of W every time period T. And the whole process is repeated again and again. When the magnetic field passes by the fixed probe b and the movable probe a successively, induced electrical signal can be obtained and the instantaneous arriving time point T_0 and T_i can be obtained. For linear time grating, the same signal waveform and processing system can be used as circular time grating, and the measured quantity is changed to linear value W i.e. a linear pitch. All these mentioned structure and technology constitute the principle of linear time grating displacement sensor.

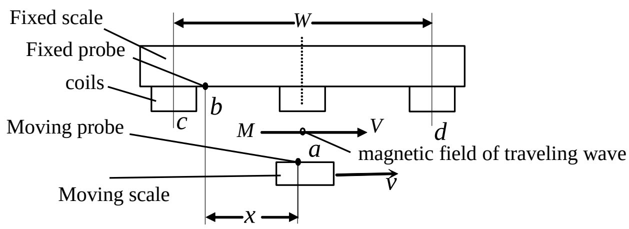


Fig.3 Schematic diagram of linear field-type time grating

3. Mechanical structure

The structure of linear time grating requires a row of slots along t he framework with equal spatial interval. Furthermore, easy processin g, high accuracy, small size are essential. Coils of linear time grating are wound as that of the ac motor. Four technical schemes are illustrat ed as following:

(1) Series of slots are cut directly in a framework with machining (machining centre, milling machine, gear shaping machine, wire cutting machine and so on) as shown in Fig.4.

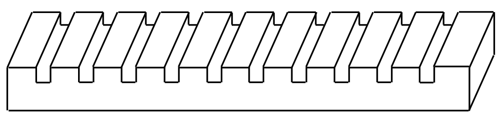


Fig.4. Three-dimensional diagram of equal spatial division by machining

(2) Two kinds of bearing needle roller with different diameter are arranged in two rows as shown in Fig.5. Slots with equal spatial interval can be obtained between the two neighbouring bearings needle roller with small diameter.

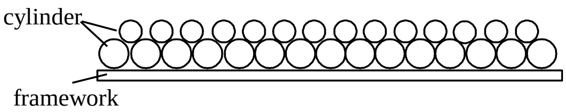


Fig.5. Side view of equal spatial division by double row needle roller

(3) Two kinds of bearing needle roller with different length and same diameter are arranged in one row ,and bearing needle rollers

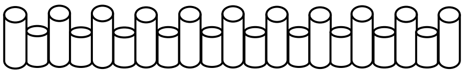


Fig.6.Three-dimensional diagram of equal spatial division by needle rollers in different length

should be aligned to the one end as shown in Fig.6. Slots with equal spatial interval can be obtained between the two neighbouring bearing needle roller. Similarly, slots with equal spatial intervals can be obtained by arranging bearing needle rollers and steel balls.

(4) Similar to the structure in Fig.6, the diameter of straight flute should be somewhat bigger than that of bearing needle roller. Two screws of the end of straight flute force bearing needle rollers reorder into two rows as shown in Fig.7. So slots with equal spatial intervals can be obtained.

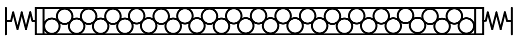


Fig.7. Top view of equal spatial division by interlaced needle rollers of different length

Note, uniformity quantities of pursued grooves in four ways are at least less than one order of magnitude than that of optical grating. For optical grating, grooves with equal spatial intervals are used as measurement standard. So the accuracy of grooves is very important. But for linear time grating, magnetic field of traveling wave is required to be as uniform as possible. And measurement standard depend on the accuracy and resolution of time pulses.

4. Incremental time grating

According to aforementioned measurement principle of time grating, position information is sampled for every equal time interval. In other word, discrete absolute position information is obtained for equal time interval. Although absolute sensors are the trend of sensor development, incremental sensors have been widely applied to numerical control systems. For example, incremental sensors are employed for siemens and fanuc numerical system in Chongqing machine tool factory. Only a few advanced numerical systems adopt absolute sensors. In order to meet the requirement of market, incremental time gratings should be designed. The key technology for incremental time grating is to transform absolute time grating into traditional continuous pulses, i.e. original absolute angular displacement signal sampled during equal time interval should be transformed into incremental continuous pulses which enable time grating applied for numerical control system. This technology is called “spatial position predicting method”[4].

Spatial position predicting method for numerical rotary table is illustrated in Fig.8. Suppose series of measured displacement value can be expressed as: $\theta_1 \ldots \theta_{i-n-1}$, $\theta_{i-n}, \ldots \theta_{i-1}$, θ_i, and the next incremental angular displacement $\Delta\theta_i$ for next measurement period (between T_i and T_{i+1}) can be predicted, then continuous pulses representing $\Delta\theta_i$ should be send out for the next measurement period T. In this way, discrete measured angular displacement can be transformed into continuous pulses. The incremental angular displacement for the N-th measurement period:

$$\Delta\theta_i = \theta_{i+1} - \theta_i \tag{2}$$

Series of incremental angular displacement for past measurement periods are $\Delta\theta_{i-N+1}$, $\Delta\theta_{i-N+2}, \ldots \Delta\theta_i$. According to time series theory, the next incremental angular displacement $\Delta\theta_i$ for next measurement period (between T_i and T_{i+1}) is :

$$\Delta\hat{\theta}_{i+1} = L(\Delta\theta_{i+1} | \Delta\theta_i, \Delta\theta_{i-1}, \cdots, \Delta\theta_{i-N+1}) \tag{3}$$

The incremental pulses should be send out between T_i and T_{i+1} and the number of incremental pulses can be determined with pulse-width modulation technology.

$$P_i = (\Delta\hat{\theta}_i - e_{i-1}) / \mathrm{Q} \tag{4}$$

Where, Q is pulse equivalent, e_{i-1} is prediction error for last measurement period. When sample time point T_{i+1} is coming, a measured value θ_{i+1} can be obtained by time grating. And last prediction error can be obtained. So last prediction error can be corrected using current measured value. As a result, prediction error will not accumulated, and high accuracy of measurement can be improved.

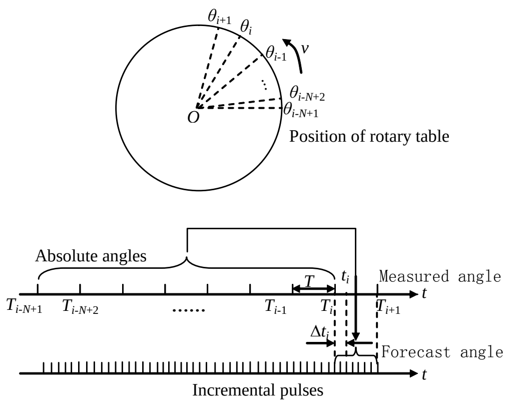


Fig.8. Forecast measurement principle

In a word, there is no difference between mathematical model of linear measurement and that of angular measurement. So aforementioned measurement methods can also be applied to incremental linear measurement.

5. Analysis on Abbe error and temperature variation problem

Temperature variation has much more affects on linear measurement than angular measurement because of the lack of closed circle principle for linear measurement. Furthermore, linear measurement devices size is limited by measurement space. So probes and main scale are only installed in parallel. But this install method is against Abbe principle. Any linear sensors should confront these two problems. Linear time gratings do not eliminate effects caused by these two problems too,. So the feasible method is to limit these negative effects as little as possible to meet engineering accuracy in production environment.

But in lab, constant temperature and Renishaw laser interferometer are adopted to meet requirement of Abbe principle which ensures that trajectory path of moving lies in scale laser beam extension line of laser interferometer.

Moving scale and fixed scale of linear time grating sensor are made from the same metal materials whose thermal expansion coefficient equals that of metal shell of measured objects (such as machine tool).

6. Experiment results

Aforementioned four kind of mechanical structure have been researched to realize linear measurement. Three structure samples have been developed as shown in Fig.9. These structures all have advantages and disadvantages. Mechanical slots method is simple but dull. Needle roller bearing method is smart but hard to realize. For example, cementation and fixation are complicated to realize for two rows method in Fig.9.b. Bearing needle roller with different length and same diameter method does not need cementation, but machining thin and long bars problem caused by strake forcing board , size and weight problems are hard to solve. All these problems are not impossible to overcome, the key point is to make a mass of experiments and comparisons, and choose the best structure. First, in order to control accuracy, a linear time grating with length 1.5 meters is designed as shown in Fig.10. The accuracy of linear time grating is ±0.5μm/m tested by National Institute of Measurement and Testing Technology, an institute of legal verification of China, in 2010.

(a) sample in machining structure (b) sample in two row needle roller structure (c) sample in needle roller in two different length structure

Fig.9. linear time grating samples in three different structure

Fig.10. Experiment table for 1.5 meters long linear time grating

This paper mainly introduce the principle and structure of linear time grating. Experiment method and other aspects of research will be introduced in other paper.

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