Technology requirement analysis and self-modification method for combinatorial code grating Eddy current absolute-position sensor

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For the shortage of the low coarse positioning reliability of phase difference grating eddy current sensor (PDGECS), a combinatorial code grating eddy current sensor (CCGECS) is presented in this paper. A single-track code positioning method is adopted in CCGECS to realize the coarse positioning of grating eddy current sensor (GECS), which is replacement of the multi-track phase difference positioning method in PDGECS. The measurement principle of CCGECS is firstly introduced in this paper. Then the relationship of measurement accuracy and main characteristic parameters of sensor is obtained by mathematical and error analysis, which offers theoretical base for design of sensor and confirmation of technology requirement on processing and installation of sensor. At last, a simple and practical self-modification method is introduced. Experimental results show that adoption of a single-track code positioning method to realize the coarse positioning has greatly improved the coarse positioning reliability of GECS, resolved the contradiction between the coarse positioning reliability and the measurement range caused by the multi-track phase difference positioning, realized the absolute position measurement to larger range and at the same time reduced the demands on technology, which lays a solid foundation for mass production of CCGECS.

NOMENCLATURE

GECS=grating eddy current sensor
PDGECS=phase difference grating eddy current sensor
CCGECS=combinatorial code grating eddy current sensor

1. Introduction

The absolute measurement range of phase difference grating eddy-current sensor (PDGECS) is enlarged by adoption of the double-track phase difference value [1], however low coarse positioning reliability of PDGECS due to such reasons as non-linearity characteristic of the eddy-current, inaccuracy of processing and installation of sensors and so on makes possible the appearance of gross error of measurement results at particular locations, which is not allowed [2]. The coarse positioning reliability of sensors can be greatly improved in theory with three or more tracks, but on occasions of limitation of volume of sensors, increase of measurement tracks will inevitably reduce the size of conductors and coils which will lead to reduction of measurement sensitivity and further reduction of measurement accuracy and coarse positioning reliability. Thus, sometimes it makes no sense to resolve of low coarse positioning reliability of double-track PDGECS by increase of measurement tracks. Certainly, to have the problem resolved, optimization the parameters of sensors and improvement of the accuracy of processing and installation of sensors can be carried out, but have to be with the cost of increase of difficulty and cost of processing of sensors.

In view of characteristics of GECS mentioned above, to overcome low coarse positioning reliability of double-track PDGECS and to avoid large size or complicated structure of sensors, a CCGECS is presented in this paper. The method of having phase value of one track as precise positioning of PDGECS is adopted by CCGECS, but coarse positioning method is improved by adoption of single-track code to realize coarse positioning as a replacement of using phase value of multiple-track as coarse positioning of PDGECS[3-5]. Measurement principle of CCGECS is introduced in the second part. Technology requirement analysis is fully stated in the following part. A simple and practical self-modification method is introduced in the fourth part, experiment results are introduced in the fifth part and conclusion of the whole paper is drawn in the last part.

2. Measurement principle of CCGECS

The layout of CCGECS is shown in Fig.1 consisting of the reflection conductors arranged on the glass substrate and the

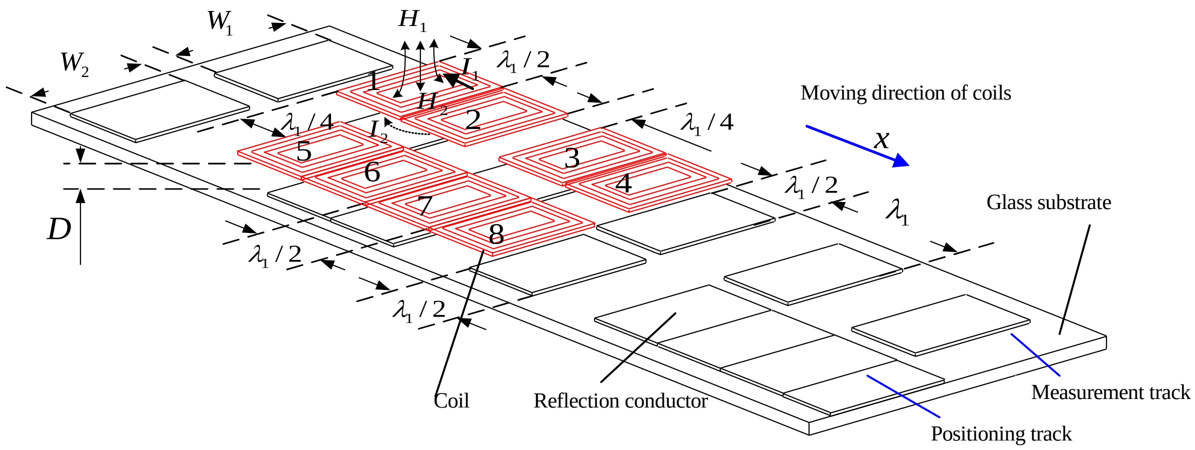

Fig.1 The layout of CCGECS

corresponding coils. The reflection conductors on the glass substrate are arranged on two tracks according to the specific rule, one is measurement track and the other is positioning track (or code track). The coils are arranged on two corresponding tracks as well according to the specific rule and which distance D to the reflection conductors is the same. The number of corresponding coils to measurement track is generally 4, while that to positioning track is dependent on the change of the absolute measurement range. When an alternating current I_1 flows through the coil, an alternating magnetic field H_1 will generate around the coil. Supposing that the reflection conductor is within the magnetic field H_1, then an eddy current I_2 will be produced on the surface of the reflection conductor and it will again generate a new magnetic field H_2 to weaken the effects of the magnetic field H_1 [6]. While a lateral displacement occurs between the coil and the conductor, the eddy current I_2 changes periodically[7]. The change in the magnetic field is sensed as a change of coil inductance, so the displacement of a coil can be converted into an inductance variation correspondingly and the inductance variation is finally converted to the frequency signals by connecting the sensor coils to an oscillator through analog multiplexers [1]. Each signal of coil is captured at different time. The multiple frequency signals captured from measurement track are used to calculate the decimal part of the value of coils' position, while those captured from positioning track are responsible for deciding within which wavelength λ_1 the coils' position is, that is to say, calculating the integer part of the value of the coils 'position. Coil 1 and coil 2, coil 3 and coil 4 of measurement track form two pairs of differential coils respectively. The central distance between coil 1 and coil 2 is half of the measured wavelength, so coil 1 and coil 2 form differential frequency output. Supposing the differential frequency signal is:

$$f_{12} = f_1 - f_2 = A\sin(\frac{2\pi x}{\lambda_1}) \tag{1}$$

Where λ_1 is the measured wavelength of measurement track; A is the amplitude of differential frequency; and x is the displacement. Because the central distance between coil 1 and coil 3 is 1/4 (or 3/4) wavelength, the differential frequency signal of coil 3 and coil 4 is:

$$f_{34} = f_3 - f_4 = A\cos(\frac{2\pi x}{\lambda_1}) \tag{2}$$

Then, the phase of measurement track is:

$$\varphi_1(x) = \arctan(\frac{f_{12}}{f_{34}}) = \arctan(\sin(\frac{2\pi x}{\lambda_1}) / \cos(\frac{2\pi x}{\lambda_1})) \tag{3}$$

In addition, there are four coils on the positioning track which also connect to the oscillator at different time, from which they output frequency signals. The numerical value of the frequency signals can be formed into a four-bit code after processed, which will become a positive integer N($0 \le N < 2^n$) after decoded. Here n is number of bits of code. Thus, the absolute-position is:

$$p(x) = \frac{\lambda_1}{2} N + \frac{\lambda_1}{2\pi}\varphi_1(x) \tag{4}$$

Here the former of the formula is the integer part of the value of the coils 'position, while the later is the decimal part of the value of coils' position.

The measurement track of CCGECS has the same functions as that of whichever tracks of PDGECS introduced in reference [1]. The phase value of one track is adopted by both of the sensors to realize precise positioning, but coarse positioning is different from each other in nature. The phase difference value of two tracks is adopted by PDGECS to realize coarse positioning and obviously the phase difference value is related to both of tracks; however a special positioning track is used by CCGECS to enable coarse positioning which output value is only relevant to the positioning track. Besides, the absolute measurement range of PDGECS is decided on wavelength and wavelength difference of two tracks, when one track wavelength is fixed, if the wavelength difference of two tracks becomes less, as a result the absolute measurement range becomes more but the coarse positioning reliability becomes lower. However, the absolute measurement range of CCGECS is decided on the wavelength of measurement track and number of code bits, when the wavelength of measurement track is fixed, only number of code bits is needed to increase if the absolute measurement range is to extend with constant coarse positioning reliability. Thus, the contradiction between the coarse positioning reliability and the measurement range caused by adoption of phase value of multiple tracks to realize coarse positioning by PDGECS is well done by CCGECS, which technology requirement analysis and simple self-modification method are fully introduced as following.

3. Technology requirement Analysis

The absolute position of CCGECS is composed of two parts: the decimal part of the value of the coils' position from the measurement track and the integer part of that from the positioning track. Hence, it is not hard to conclude that the non linear error of sensor is dependent on phase error of the measurement track which is decisive to measurement accuracy of the sensor; however the signal from the positioning track is crucial to the coarse positioning reliability.

3.1 Influence of technology requirement on measurement accuracy

Measurement accuracy of CCGECS is dependent on the measurement track, the function of which is the same as that of single track of PDGECS. Error characteristic and error sources which influence measurement accuracy of PDGECS are analyzed in detail in reference [2]. Here technology demand is analyzed on sensor processing and installation on condition of satisfaction of measurement accuracy. When one error source is analyzed, the non linear errors to the system caused by other error sources are supposed as zero. These parameters needed to estimate include geometry parameter error and shape of conductors and coils, periodic error $\Delta\lambda$ of conductor distribution, center distance error Δs between coils, space error ΔD between conductor and coil and stability of oscillator. Among these, theoretical system error is decided by geometry parameter error and shape of conductors and coils. As expression formula of variation laws of differential frequency signal is hard to obtain, these relevant parameters are also difficult to confirm and estimate. Resolution of sensors is decided by stability of oscillator and variation range of differential frequency signal, which is not discussed here. The phase error caused by the three parameters which include the periodic error of conductor distribution, center distance error Δs between coils, space error ΔD between conductor and coil can be expressed as below formulas respectively.

$$\Delta\varphi_\lambda(x) = \tan^{-1}(\sin(\frac{2\pi x}{\lambda_1-\Delta\lambda})/\cos(\frac{2\pi x}{\lambda_1-\Delta\lambda})) - \tan^{-1}(\sin(\frac{2\pi}{\lambda_1}x)/\cos(\frac{2\pi}{\lambda_1}x)) \quad (5)$$

$$\Delta\varphi_s(x) = \tan^{-1}(\sin(\frac{2\pi}{\lambda_1}(x+\Delta s)/\cos(\frac{2\pi}{\lambda_1}x)) - \tan^{-1}(\sin(\frac{2\pi}{\lambda_1}x)/\cos(\frac{2\pi}{\lambda_1}x)) \quad (6)$$

$$\Delta\varphi_a(x) = \tan^{-1}((1+\Delta a)\sin(\frac{2\pi}{\lambda_1}x)/\cos(\frac{2\pi}{\lambda_1}x)) - \tan^{-1}(\sin(\frac{2\pi}{\lambda_1}x)/\cos(\frac{2\pi}{\lambda_1}x)) \quad (7)$$

As for $\Delta\lambda$, let x equal to λ_1 in equation (5) base on error characteristic, then we have the next equation.

$$\Delta\lambda_{\max} = \frac{\lambda_1\Delta\varphi_{1\max}}{2\pi+\Delta\varphi_{1\max}} = \frac{\lambda_1\Delta x_{\max}}{\lambda_1+\Delta x_{\max}} \quad (8)$$

As for Δs, let x equal to 0 in equation (6) and $\Delta s_{\max}$ is:

$$\Delta s_{\max} = \frac{\lambda_1}{2\pi}\sin^{-1}(\tan\Delta\varphi_{1\max}) = \frac{\lambda_1}{2\pi}\sin^{-1}[\tan(\frac{2\pi}{\lambda_1}\Delta x_{\max})] \quad (9)$$

Let x equal to $\lambda_1/8$ in equation (7) similarly and the next equation can be obtained.

$$\Delta A_{\max} = \tan(\frac{\pi}{4}+\Delta\varphi_{1\max})-1 = \tan(\frac{\pi}{4}+\frac{2\pi}{\lambda_1}\Delta x_{\max})-1 \quad (10)$$

Of course, sensitivity of differential frequency signal is has to be known to obtain $\Delta D_{\max}$. Here let $\Delta D_{\max}$ = $5\Delta A_{\max}/12$ for discussion facility and according to reference [2]. Processing and installation accuracy of sensors can be estimated quantitively according to relationship between such parameters and non linear error. Processing and installation accuracy requirement of each parameter to meet different measurement accuracy is shown in Fig.2 and it can be concluded that $\Delta\lambda_{\max}$ and $\Delta x_{\max}$ is in linear relation by 1:1 ratio as that of $\Delta s_{\max}$ and $\Delta x_{\max}$. It can also be shown that periodic error $\Delta\lambda$ of conductor distribution and center distance error Δs between coils can cause the coequal measurement error. The technology requirement to ΔD is less severe under the same measurement accuracy compared to $\Delta\lambda$ and Δs.

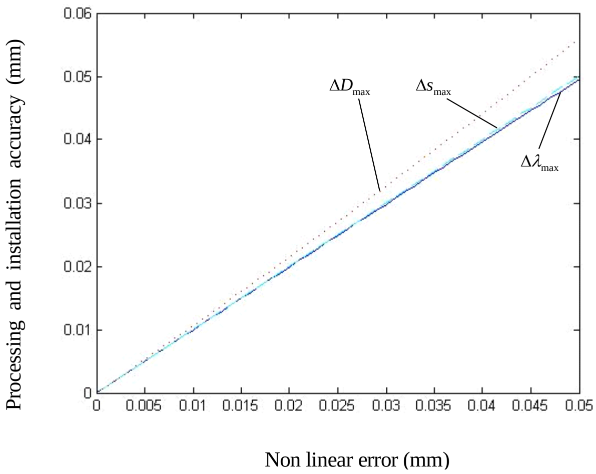

Fig.2 Processing and installation accuracy requirement of each parameter to meet different measurement accuracy

3.2 Analysis of coarse positioning reliability

Theoretical output curve within one wavelength should be folding line as shown in Fig.3 to single coil and single conductor of positioning track, however in fact frequency signal changes close to the law of sine line instead of that of folding line. Here the actual characteristic curve of frequency signal within one track wavelength is supposed as sine curve, and then the frequency error is as below:

$$\Delta f_t = -\cos(\frac{2\pi}{\lambda_1}x) - \frac{4}{\lambda_1}x + 1 \quad (11)$$

Likewise, such error is defined as theoretical system error.

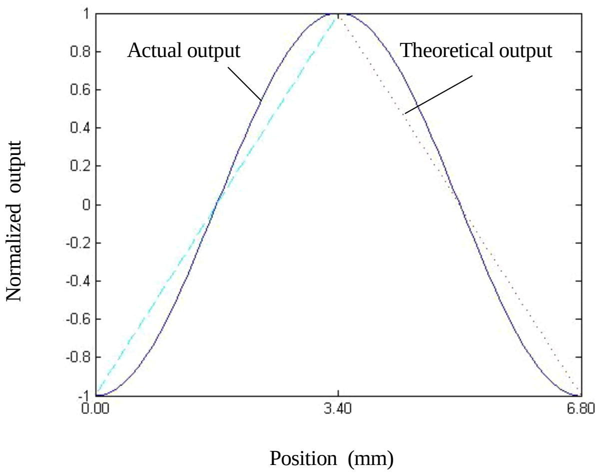

Fig.3 Characteristic curves of positioning track

Besides theoretical system error, below reasons can also cause errors: 1. positioning and geometry size errors of conductors; 2. positioning and geometry size errors of coils; 3. space error between the coil and the corresponding conductor; 4. Dispersiveness of electronic component parameters; 5. measurement error of output signal of sensor. According to analysis of error of measurement track, it can be concluded that errors caused by reason 1, 2 and 5 total of three reasons are not great and can be neglected; and error by reason 4 may not be regarded, as it can be eliminated by modification of differential frequency. The error by reason 3 is as

$$\Delta f = \Delta f_A + \Delta f_t = -(1+\Delta A)\cos(\frac{2\pi}{\lambda_1}x) - \frac{4}{\lambda_1}x + 1 \tag{12}$$

So only the ΔD is need to be estimated on positioning track, let $x = \frac{\lambda_1}{2\pi}\arcsin(2/((1+\Delta A_{\max})\pi))$ in equation (12), then $\Delta f_{\max}$ is:

$$\Delta f_{\max} = 1 - \frac{\sqrt{\pi^2(1+\Delta A_{\max})^2 - 4}}{\pi} - \frac{2}{\pi}\arcsin(\frac{2}{\pi(1+\Delta A_{\max})}) \tag{13}$$

Likewise, let $\Delta D_{\max} = 5\Delta A_{\max}/12$, then the curve can be drawn as Fig.4. It can be known from code recognition that as long as Δf of any position is no more than 0.4, the requirement of code recognition at the location can be satisfied. It is known from the Fig.4 that $\Delta D_{\max}$ is approximate to 0.095 mm and from reference [2] it is known that when the absolute position is made by the phase error of two tracks, even if $\Delta D_{\max}$ is only equal to 0.05 mm it is unable to meet the requirement of coarse positioning. So coarse positioning reliability is improved by use of single track to realization of coarse positioning and that means technology requirement is reduced accordingly.

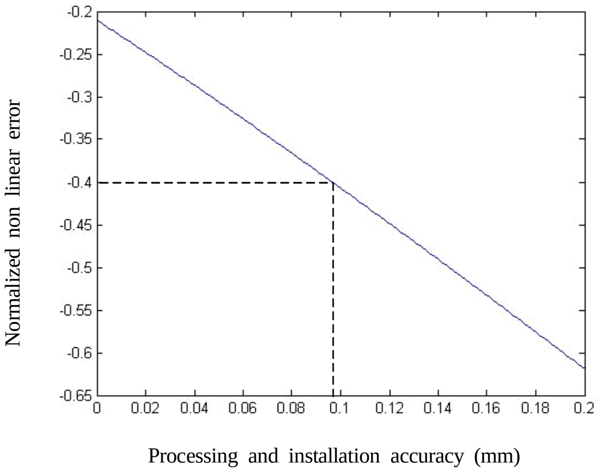

Fig.4 Processing and installation accuracy requirement of space D to meet different measurement accuracy

4. Self-modification method

Even if measurement accuracy meets the requirement, gross error still possibly arises at particular locations due of low coarse positioning reliability of PDGECS and so the phase error has to be modified by the method of least square segmental line fitting as reference [2]. The shortage of error compensation method in reference [2] is based on raster, that is to say that special equipment is needed to measure the sensor in full range to obtain the error compensation data, which reduces efficiency of industrialization of GECS. It is known from above analysis that coarse positioning reliability can still be fully guaranteed even if measurement system error comes up to error limit of 0.04 mm when single-track code is adopted to enable coarse positioning. So when sensor is designed, only measurement accuracy is necessary to be regarded whether to meet the requirement because the same technology is used to processing the measurement track and the code track, if the measurement accuracy meets the requirement, the coarse positioning will be out of problem definitely. Thus according to reference [2], measurement system error is only relative to that caused by dispersiveness of electronic component parameters if processing and installation accuracy of sensor can be controlled under range that meets requirement of measurement accuracy. In reference [2] error modification data is acquired by modification of $\Delta\varphi_b$ by minimum square error approach method based on the measurement data of sensor in full range. Here a simple self-modification method to modify $\Delta\varphi_b$ is introduced without based on the raster.

It is known to us that modification of $\Delta\varphi_b$ of measurement track is mainly to obtain amplitude and biased value which is then used to calculate normalization coefficient of each differential frequency signal. As for code track only the maximum and minimum of each frequency signal is needed which likewise is used to calculate the normalization coefficient of each frequency signal. Such step for self-modification method is: the sensor is powered up and into self-modification mode and then the moving grating which is made up of coils is pulled. As for measurement track, the maximum and minimum of differential frequency is automatically recorded during each period when pulling; however as for code track, that of output frequency of each coil is automatically recorded in full range. The amplitude value of differential frequency is half of the result of the average of all maximum minus that of all minimum from measurement track, while the biased value is half of what the average of all maximum plus that of all minimum. Finally the amplitude and biased value is adopted to calculate the normalization coefficient of each differential frequency signal. In the same way, the maximum and minimum of each frequency from code track is directly put in use to calculate the normalization coefficient of each frequency signal to finish self-modification of CCGECS, which is shown in Fig.5.

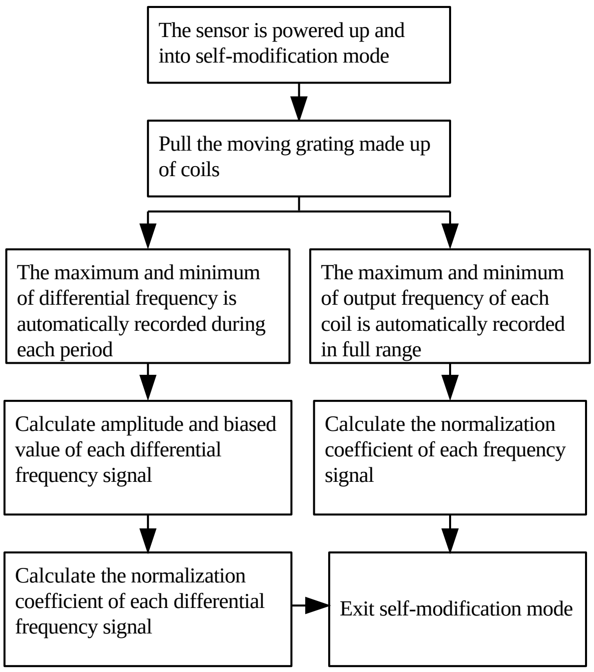

Fig.5 Self-modification method for CCGECS

5. Experiment results

Processing and installation accuracy of sensor is firstly tested before the experiment. As for the conductor on the fixed grating, periodic error $\Delta\lambda$ of conductor distribution in full range is no more than 0.005 mm and as for the coil on the moving grating, center distance error Δs between coils is no more than 0.005 mm either. Space error ΔD is no more than 0.03mm when the moving grating moves. The actual and theoretical output curve of single coil of code track measured in the experiment is shown in Fig.6 and its normalized error curve is as Fig.7. From the figures, it is known that normalized error value at any location is no more than 0.3 and is less than 0.4 which is the requirement of code recognition. From the test result of PDGECS, it is known that the phase error of two tracks before modification of differential frequency can not match the requirement of coarse positioning; however requirement of coarse positioning of CCGECS is easily satisfied even by use of frequency signal instead of differential frequency signal and without any modification. That is to say, coarse positioning reliability of CCGECS is greatly improved by

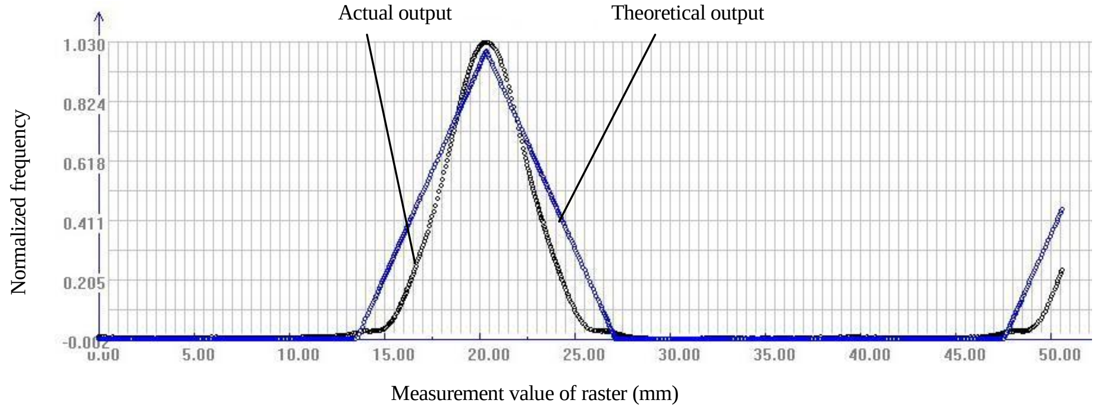

Fig.6 Characteristic curves of positioning track

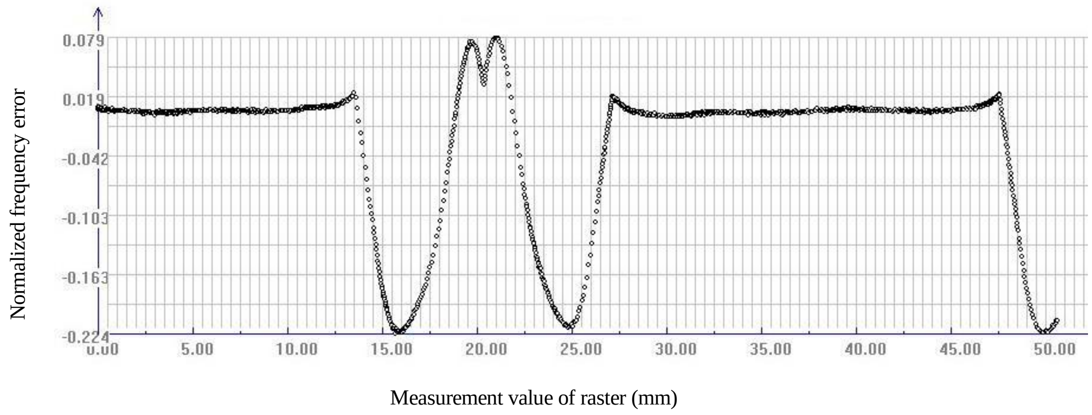

Fig.7 curve of normalized frequency error of positioning track

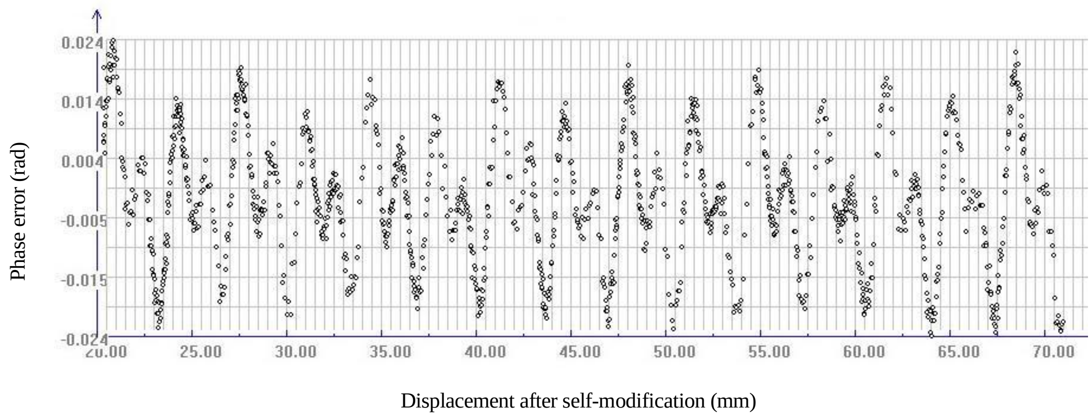

Fig.8 Curve of phase error after self-modification

adoption of single-track code. Besides, to enlarge the measurement range only the number of coil of code track is needed to add while measurement accuracy of sensor remains instant. The curve of phase error measured during the experiment is shown as Fig.8 from which it is known that phase error comes up to ±0.025 rad after simple self-modification and the error is mainly made up of $\Delta\varphi_a$ and $\Delta\varphi_t$, here the $\Delta\varphi_t$ is indicated as theoretical system error in reference [2].

6. Conclusion

In view of shortage of high technology demand on processing and installation of PDECS, a CCGECS is proposed in this paper in which coarse positioning is realized by single-track code with replacement of coarse positioning realized by phase difference value of multiple tracks in PDGECS. It begins with measurement principle of CCGECS, followed by full statement of analysis of technology demand on processing and installation of CCGECS. The factors affecting measurement accuracy and coarse positioning reliability are illuminated theoretically and at last one simple self-modification method is proposed to enable self-modification of sensor with improvement of productivity of such sensors. It is known from the later experiment results that single-track code is adopted in CCGECS to enable coarse positioning as a result coarse positioning reliability is improved and technology on demand is reduced as well.

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