An Interpolation Error Measuring System Using a Tuning Fork Stage

S. Makinouchi[1], A. Watanabe[1], M. Takasaki[1], S. Wakui[2]
[1]*Nikon Corporation Japan*
[2]*Tokyo University of Agriculture and Technology Japan*

Makinouchi.Susumu@nikonoa.net

Abstract

In this study, we present a new concept interpolation-error-measuring-system for evaluations of high-resolution displacement sensors by using a tuning fork, which specialized for short-span repeatable position errors. A tested sensor is set facing one of the fork arms, and the tuning fork is excited by a low-distortion sound. Since the tuning fork has extremely high resonance, the fork-arm motion becomes a purely mono-tone sinusoidal waveform. However, the sensor output is contaminated by the interpolation error. A data process combined with a FFT and an inverse FFT extracts the interpolation errors. Repeatability of proposed measuring system was shown to be 0.33nm, sigma.

1 Introduction

The interpolation error is an avoidable error for displacement sensors which use periodic grating or laser wavelength as a scale. The error would cause uncorrectable alignment errors in semiconductor manufacturing, degradation of surface smoothness in precision machining, etc. The maximum value of interpolation error is one of the most importance specifications of displacement sensors, however, evaluations of the error is not simple because required error is less than one nanometer for precision tools. We developed a new simple interpolation-error-measuring system by focusing repeatability and space-periodicity of the error.

2. Concept

Figure 1 shows the concept of developed measurement system. Since the tuning fork has extremely high resonance, the fork-arm motion is a purely mono-tone sinusoidal waveform. A tested sensor which has a periodic interpolation error measures the fork arm motion, then, the error is transferred into harmonics distortions upon the tuning fork frequency. Therefore, the error can be extracted by using a FFT and an inverse FFT technique.

Equation (1) is the interpolation error of the sensor, Equation (2) is the fork motion, then, Equation (3) is interpolation error in time domain.

$$I_{err}(x) = \sum_{n=1}^{p} A_n \cos(n\omega_0 x) \tag{1}$$

$$x(t) = D\sin(\omega_f t) \tag{2}$$

$$\begin{aligned} I_{err}(t) &= \sum_{n=1}^{p} A_n \cos(n\omega_0 D \sin \omega_f t) \\ &= \sum_{n=1}^{p} A_n \left\{ J_0(n\omega_0 D) + 2\sum_{m=1}^{\infty} J_{2m}(n\omega_0 D)\cos(2m\omega_f t) \right\} \end{aligned} \tag{3}$$

where A_n is the amplitudes of the interpolation-error component, x is the displacement, ω_0 is first order spatial frequency of interpolation error, D is amplitude of the tuning fork arm motion, ω_f is the tuning fork frequency, and the function J_n represents Bessel's function of the first kind. Since J_0 is DC term, Equation (3) indicates that the interpolation error is composed of high-frequency terms over $2\omega_f$. Consequently, the interpolation errors can be reconstructed by using high-frequency components after removing the fundamental frequency ω_f from the tuning fork motion.

The process to extract these errors is carried out as follows: (1) Convert the encoder-position time-domain data to the frequency domain through a FFT (fast Fourier transform). (2) Eliminate the tuning fork frequency. (3) Reconvert the data from frequency domain to time domain through an inverse FFT. The resulting waveform represents the interpolation error.

3. The tool

Figure 2 is the frequency response of the fork used in our system. The data measured by LDM (Laser Doppler Meter) confirms a high-peak-resonance (ω_f =125.58Hz, Q = 6,250). Figure 3 is a photo of proposed interpolation error measuring system. An audio speaker is located near the tuning fork for effective excitation. A tested encoder head is installed on a micrometer stage, which can precisely adjust gap and the angles of yaw, pitch and roll between the head and the scale. The tuning fork is excited by a low-distortion 125.58-Hz sound. Since the tuning fork has extremely high resonance, the fork-arm motion becomes a purely mono-tone sinusoidal waveform. The tested encoder head is set facing one of the fork arms, on which small encoder scale had been glued. The system is placed in an acoustic chamber to isolate it from environmental noise. The amplitude of the fork motion is adjusted around 10 μm by the volume of the sound. A unique advantage of this method is its averaging capability. Since the tuning fork motion from acoustic excitation is quite stable, the data have a large number of cyclic waveforms, which can be averaged with respect to the encoder scale position. Since the interpolation error is position dependent, it can be clearly extracted by position averaging.

4. Results

We evaluated the system by measuring a Nikon optical linear encoder which uses 2 micrometer pitch grating scale. Figure 4(a) is the interpolation error measured by proposed system, (b) is the same one measured by a capacitive sensor (Lion Precision DMT-22). We captured one-second-long time domain data with 10 kHz sampling for each measurement. Since the fork frequency is 125.58 Hz, we could use 125-time averaging in every evaluation. The repeatability of each measurement in our test was shown to be 0.33nm, sigma.

5. Conclusion

The proposed system is simple and reliable for interpolation-error evaluations of displacement sensors.

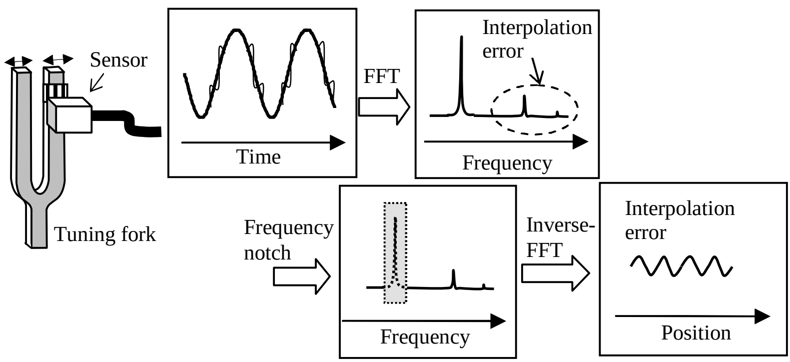


Figure 1: Concept of the system

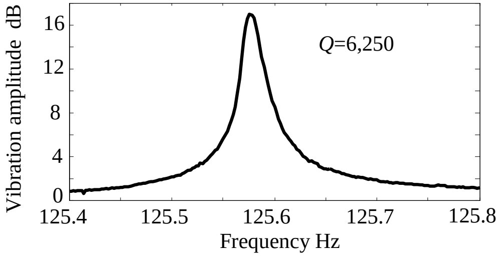


Figure 2: The tuning fork resonance

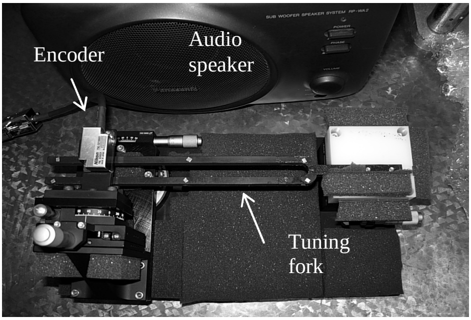
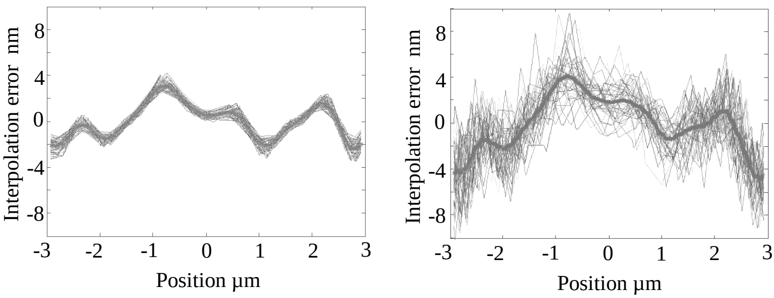


Figure 3: The test tool



(a) Proposed method (b) Capacitive sensor data

Figure 4: Interpolation error

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