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Ultra Precise Position Estimation of Servomotor using Analog Quadrature Encoder

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ABSTRACT

This paper describes the ultra precise position estimation of a servomotor using a sinusoidal encoder based on Arcsine Interpolation Method for the cost reduction of circuit design. The amplitude and offset errors of the sinusoidal encoder output signals, from the encoder itself and analog signal processing procedures, are effectively compensated and on-line tuned by utilizing a low cost programmable differential amplifier without any special expensive equipment. For a theoretical evaluation of the practical resolution of this system, the relationship between the amplitude of ADC(Analog to Digital Converter) input signal errors and the anticipated resolution is also addressed. The performance of the proposed method is verified by comparing it with speed control characteristics of the servomotor driving system using a digital incremental 50,000ppr encoder in the experiments.

Keywords: sinusoidal encoder, interpolation, position estimation, analog rotor position, digital rotor position

1. Introduction

In order to achieve highly accurate servomotor control, it is essential to secure accurate position feedback in the related system, and this is considered to be one of the most important criterions to guarantee reliance of the system[1-3]. However, the price of a digital incremental encoder overwhelmingly increases according to its resolution, and it has the problem of bandwidth limitation. Although servomotor control using sinusoidal encoder has been researched for these reasons, there are few precedents to apply for the servomotor control system.

For the total cost reduction of highly accurate servomotor position or speed estimating system, this paper describes servomotor control using a sinusoidal encoder based on Arcsine Interpolation Method, which is optimized to the cost reduction of signal processing circuits. The performance of the proposed method is verified by the experiments. The test results show that, with a much cheaper sinusoidal encoder, the proposed method shows better performance than 50,000ppr digital incremental encoder in adjustable speed control characteristics.

2. Signal Processing Principles of Analog Quadrature Signals[1]

Analog rotor position is determined by output signals of a sinusoidal encoder, while digital rotor position can be acquired by counting comparator output signals of them.

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Fig.1 is the schematic diagram of typical decoding circuitry of a sinusoidal encoder quadrature decoding and phase interpolation.

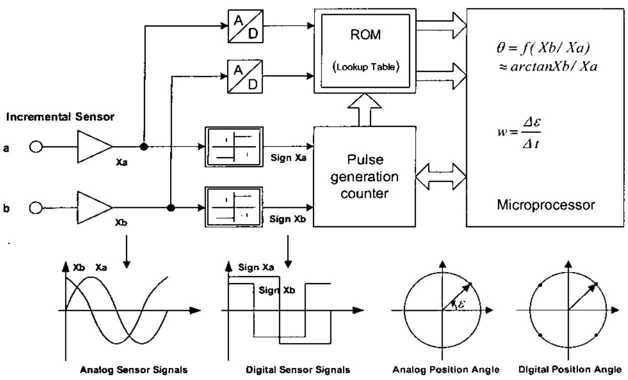

Fig. 1 Schematic diagram of typical decoding circuitry of a sinusoidal encoder incorporating quadrature decoding and phase interpolation

The total period numbers of analog incremental signals V_S and V_C per a revolution of mechanical rotor angle are different according to sinusoidal encoder models. The resolution of rotor angle guaranteed by digital rotor position is expressed by (1).

$$\theta_{digit} = 360° / M \quad (1)$$

Here, M: the period numbers of analog incremental signals per a revolution of mechanical rotor angle

θ_{digit} obtained by (1) represents a period of sinusoidal encoder output signals. They are converted to digital values throughout ADC, and the resolution of ADC determines rotor position control accuracy within each sector obtained by (1). From the above relationship, (2) can theoretically obtain the total resolution rotor angle.

$$\theta_{final} = \theta_{digit} \times K \quad (2)$$

Here, K is the resolution of ADC

Assuming that V_S and V_C are ideally sinusoidal and do not have offset and amplitude errors, they can be expressed by (3) and (4).

$$V_S = V_C \sin\theta \quad (3)$$

$$V_C = V_P \cos\theta \quad (4)$$

Here, θ : analog rotor angle, V_P : the amplitude of analog signals.

Analog rotor angle based on 'Arc-tangent method' can be obtained by (5).

$$\theta = tan^{-1}(\frac{V_S}{V_C}) \quad (5)$$

By using θ of (5) and counted numbers of V_S in Fig. 1, mechanical rotor angle can be obtained by (6).

$$\theta_{mech} = \frac{1}{M}[(N \times 360)] + \theta)] \quad (6)$$

Here, θ_{mech} : mechanical rotor angle, N : counted numbers of V_S after reference signal V_Z is generated.

As shown in Fig. 1, mechanical rotor angle θ_{mech} of a servomotor control system using a sinusoidal encoder can be calculated by either look-up table method or microprocessor calculation.

3. Implementation of the Proposed Method

The proposed method basically depends on both analog and digital rotor position information. Analog rotor position is obtained by (7), and sector distinction over the symmetrical output is performed by zero-crossing V_S. Digital rotor position is acquired by counting comparator outputs of V_S. From the obtained analog and digital rotor position, mechanical rotor position of servomotor can be calculated by (6)[1]. Main hardware configuration for the proposed method represents Fig. 2.

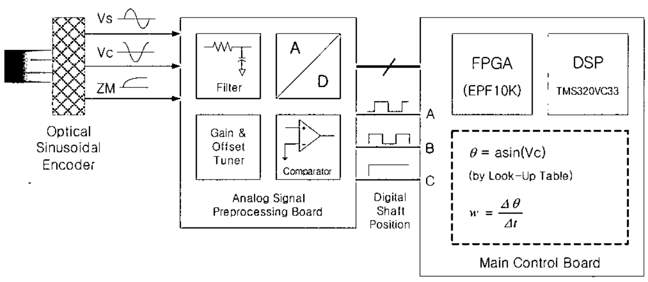

Fig. 2 Hardware configuration for the proposed method

For the accurate calculation of analog rotor position, V_C is tuned to full input range of ADC, and offset errors are compensated by controlling programmable differential amplifiers. The compensated analog output is converted to digital values throughout ADC, and matched with an analog rotor angle value within the arcsine lookup table. The Arcsine lookup table can be configured by(7), and the sector is determined by zero-crossing signal of V_S.

$$\theta_{a\,sine} = sin^{-1}(V_C) \tag{7}$$

For the calculation of digital rotor position, comparator output signals of the compensated V_S and V_Z are applied to the inner counter of FPGA. The digital rotor position is obtained by counting the numbers of V_S comparator output, and this value is reset by reference signal V_Z. Fig. 3 represents the path and errors of sinusoidal encoder outputs.

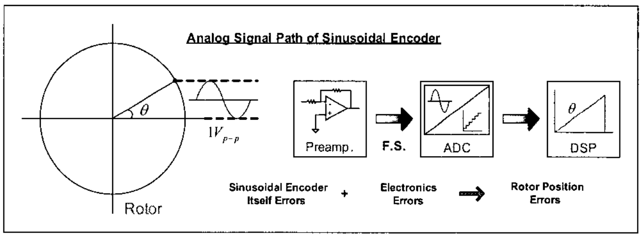

Fig. 3 Analog signal path and errors

The errors of sinusoidal encoder output signals can be divided into sinusoidal encoder errors and electronics errors for signal processing when amplitude and offset errors are completely compensated. For the convenience of analysis, ignoring the encoder itself and electronics errors, output signals of a sinusoidal encoder are satisfied with the following conditions:

(1) ADC input signals should be adjusted to full scale input range of ADC.
(2) Input signal errors of ADC should be satisfied with (8).

$$V_{error} \le \frac{A_K}{(2^n - 1)} \tag{8}$$

Here, V_{error}: input signal errors of ADC, A_K: adjusted ADC input full scale range, n : bits of ADC.

The proposed method for amplitude and offset error compensation of sinusoidal encoder output signals represents Fig. 4. The compensation sequence is as follows:

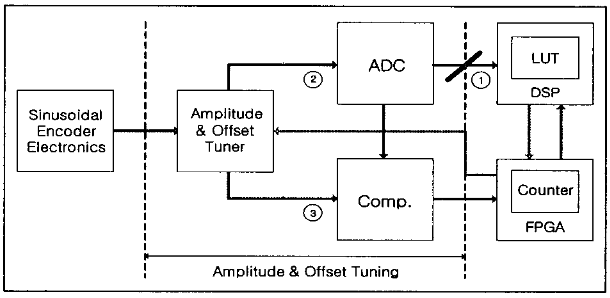

Fig. 4 Signal flow diagram about the proposed gain & offset compensation

(1) Adjust the amplitude of V_C to full-scale input range of ADC, observing the output signal V_C of ADC. (This procedure includes offset elimination processing).

(2) Control the amplitude and offset errors of V_S, observing the tuned input signal V_C amplitude of ADC.

(3) Confirm whether or not V_S and V_Z are synchronized. If not, synchronize them by using logics in FPGA.

4. Experimental Results

Fig. 5 represents laboratory experimental set-up. Digital incremental 50,000ppr encoder used in the experiment is TS5178N60 model, a product of Damagawa Corporation. The sinusoidal encoder is ERN1387 model, a product of Heidenhain Corporation. Fig. 6 shows 50,000ppr encoder attached to PMSM and a sinusoidal encoder to IM.

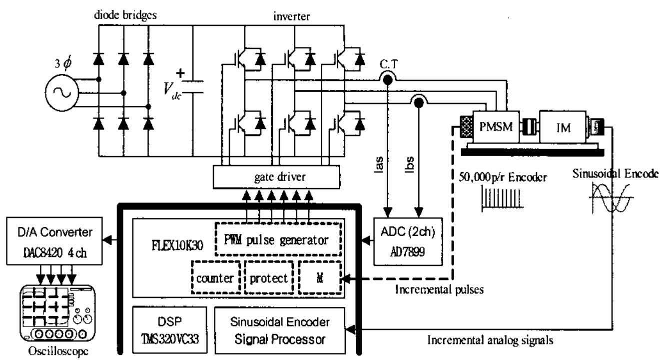

Fig. 5 Laboratory experimental set-up

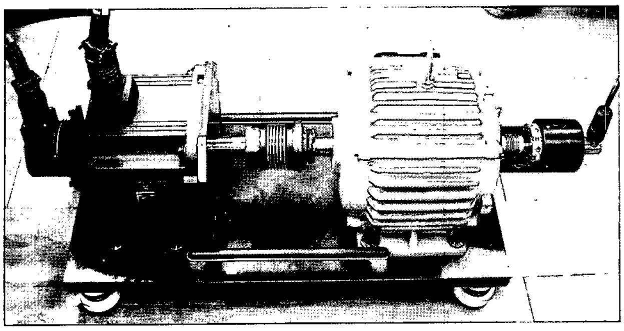

Fig. 6 Experimental M-G set

Fig. 7 shows the output signals of differential amplifiers V_S and V_C still affected by inverter switching noise. In this experiment, the current sampling time is 100[us].

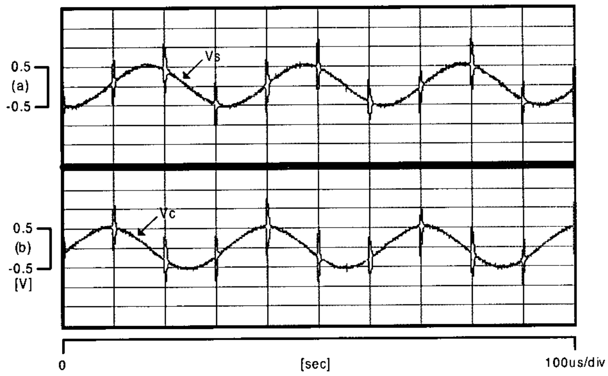

Fig. 7 Analog output signals of a sinusoidal encoder

Fig. 8 shows almost completely amplitude and offset tuned incremental signals. In addition, the noise effect is completely eliminated by designed analog filter circuit. The full scale input range of ADC is set up to guarantee the maximum resolution over analog signal conditions.

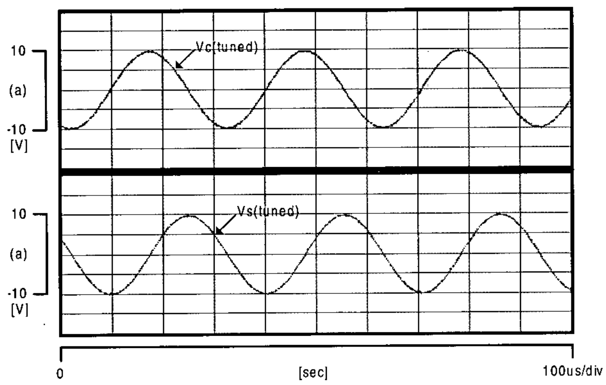

Fig. 8 Tuned analog signals of a sinusoidal encoder

Fig. 9 shows the outputs of ADC and analog rotor position θ sampled and calculated at intervals of the current sampling time when the motor speed is 100[rpm] and direction is clockwise. This analog rotor position θ is used for the position error compensation between digital incremental pulses.

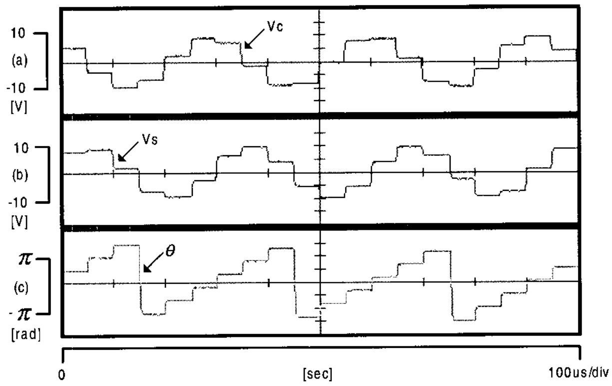

Fig. 9 output signals of ADC and analog rotor position θ

Fig. 10 shows comparator output signals called 'digital rotor position' when the motor speed is 100[rpm]. These signals are transferred from the sinusoidal encoder board to FPGA in the main control board throughout the parallel port. Digital rotor position detection and zero-crossing is performed logistically in FPGA.

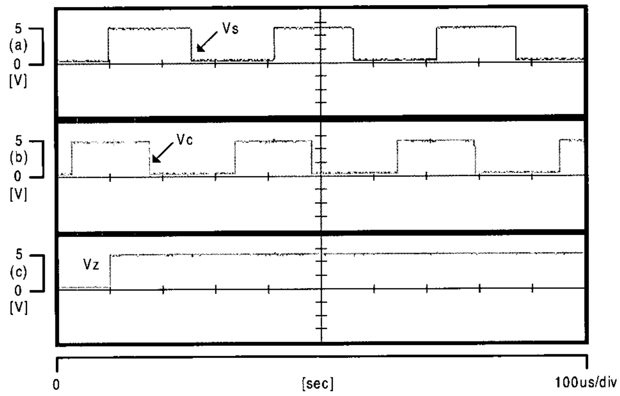

Fig. 10 comparator output signals

Fig. 11 shows electrical angles acquired by the 50,000ppr encoder and a sinusoidal encoder when the motor speed is 100[rpm] and the direction is clockwise. Fig 12 shows electrical angles acquired by the 50,000ppr encoder and a sinusoidal encoder when the motor speed is changed from 100[rpm] to -100[rpm].

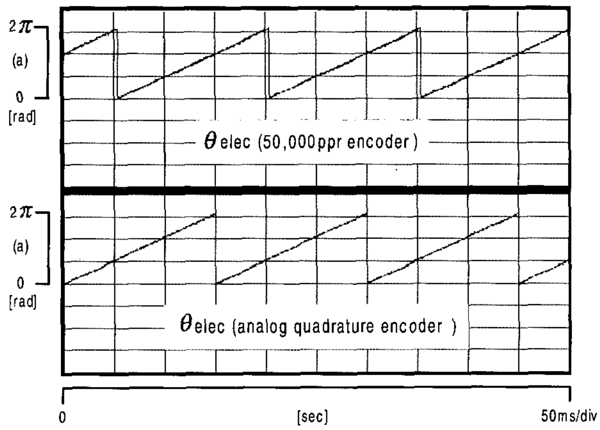

Fig. 11 electrical angle comparison (clockwise)

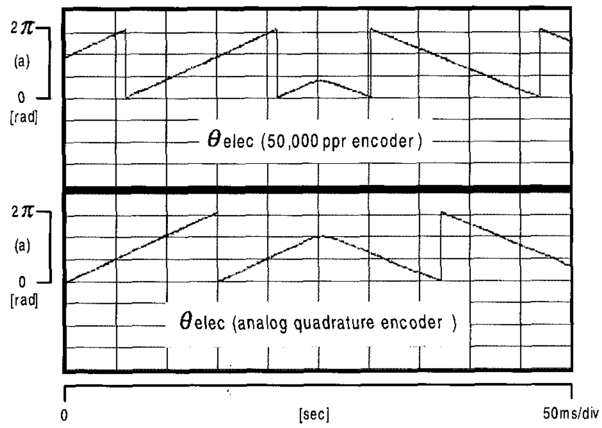

Fig. 12 electrical angle comparison (clockwise to counterclockwise)

Fig. 13, 14, 15, and 16 shows speed ripple characteristics acquired by M method (a), M/T method (b), and the proposed method (c) when the motor speed is 200[rpm], 100[rpm], 50[rpm], and 30[rpm], respectively. The waveforms show that the speed ripples acquired by M method is highest in this experiment. This method basically depends on just the pulses called digital rotor position so that it cannot compensate the position error between each pulse.

The test results show that the characteristics of speed ripple acquired by M/T method exhibits better performance than the M method. This is because the M/T method compensates for the rotor position errors generated between each pulse by using system clocks. The accuracy of this method basically depends on the clock frequency, and it should be synchronized to the digital pulses. For this reason, this method has a weak point in that the sampling time is not constant.

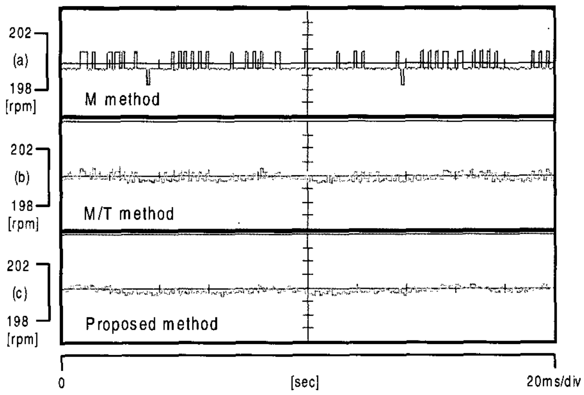

Fig. 13 Speed ripple comparison (200[rpm])

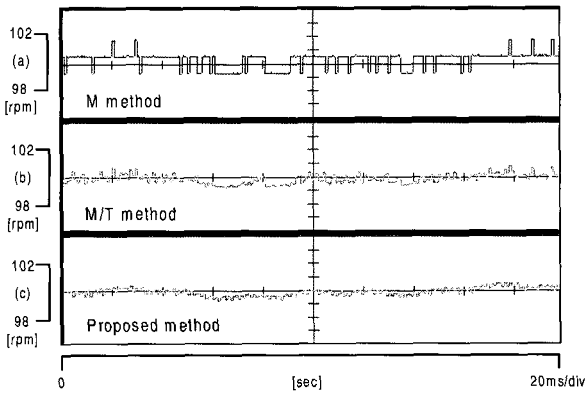

Fig. 14 Speed ripple comparison (100[rpm])

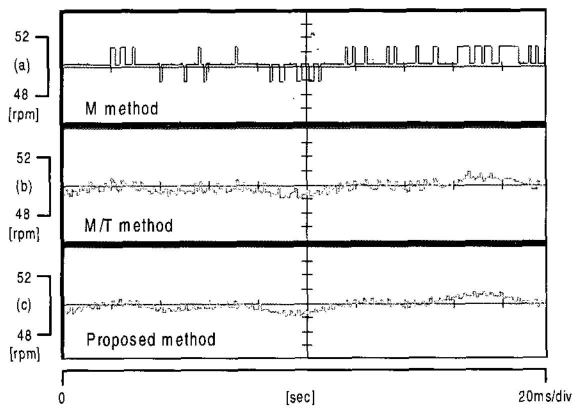

Fig. 15 Speed ripple comparison (50[rpm])

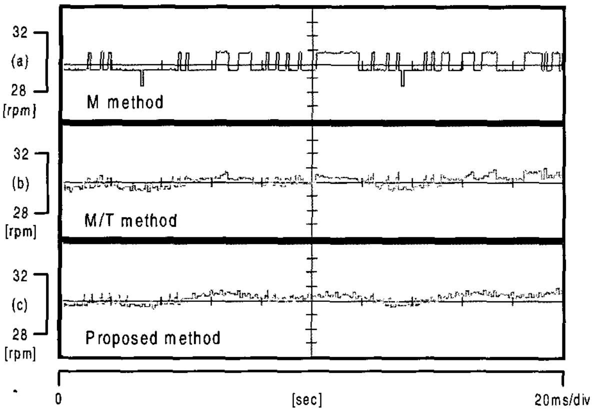

Fig. 16 Speed ripple comparison (30[rpm])

The test result shows that the characteristic of speed ripple acquired by the proposed method demonstrates better performance than both M method and M/T method. This is because the proposed method more accurately compensates the rotor position errors generated between each pulse by using ADC with high resolution. The theoretical resolution calculated in terms of a digital incremental encoder is more than 2,000,000 pulses.

5. Conclusions

This paper suggests a new method of the ultra precise position measurement using the sinusoidal encoder based on Arcsine Interpolation Method, optimized to the cost reduction of interpolation circuits. To evaluate the practical resolution of this system theoretically, the relationship between the amplitude of ADC input signal errors and the anticipated resolution is addressed. The performance of the proposed system is verified through the experiments. The test results show that the proposed method shows better performance not only in rotor position estimation but also in adjustable speed control characteristics more than 50,000ppr in the digital incremental encoder.

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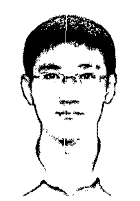

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