Driving a High-Precision Multi-coils-motor by Reducing an Influence of Manufacturing Variations

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Abstract: One of the major challenges in the field of motors is to improve rotation ripples. There are several causes of rotation ripples. This paper focuses on variations of manufacturing of a stator coil and proposes a new technique called DTMM (dynamic multi-coils-motor three-phase matching) based on the conventional NSDEM (noise shaping dynamic element matching). With DTMM, all the moving elements are shuffled while a single moving element is shuffled with NSDEM. Results show that the proposed system reduces the rotation ripple by 30% compared to the conventional PWM driving technology.

Key words: Motor, multi coils motor, NSDEM, rotation ripple, torque ripple, delta sigma modulation.

1. Introduction

Motors are used in various devices. For example, they are used in painting machines and polishing machines. The motors used in these machines should have least vibrations to reduce unevenness of painting and glossing and the sound noise. The rotation ripple, which is equal to the motor vibrations is caused by manufacturing variabilities of coils. Manufacturing variabilities cannot be completely eliminated. To reduce the influence of manufacturing variabilities, a signal processing technique called NSDEM (noise shaping dynamic element matching) [1] has been proposed. This paper develops the NSDEM and proposes a new signal processing technique to reduce the influence of manufacturing variabilities, and confirms the reduction of rotation ripples.

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2. Issues of a Conventional Motor

2.1 Torque Ripple

The currents flowing through the stator coils of a PMSM (permanent magnet synchronous motor) are ideally equal in three phases. However, in reality, the values of impedance and length of stator coil vary due to manufacturing variabilities. To consider what kind of impact the current in U, V, and W phases has on the rotor, we assume that the direction of the magnetic flux of the rotor as a d -axis and the axis orthogonal to the d -axis as a q -axis.

In an ideal state in the case when all the elements of variabilities are the same values, I_q is constant. However, since the actual are not constant due to manufacturing variabilities, I_q vibrates at twice the frequency of the three phase current. Fig. 1 shows the I_q when the current flowing through the W-phase is large due to the variability (I_w is 1.3 times).

Fig. 1 Three phase current and I_q .

Since the equation of torque of PMSM is generated by I_q [2], the deviation of the alternating current by the element variation appears as torque ripple whose frequency is twice the fundamental frequency. A speed of rotation of the motor is modulated by this torque ripple, which causes rotation ripple. The rotation ripple causes various problems. For example, it would make uneven paint surface with the coating machine and shake the moving image of a video operated by a motor. Thus, the reduction of a rotation ripple is one of the important research themes.

2.2 Conventional Method to Reduce Torque Ripple

The relationship between a torque, rotor angular velocity, and angular acceleration can be represented by

$$J \frac{d\omega}{dt} = (T_e - T_L) - B_m \omega \quad (1)$$

where,

ω : Rotor angular velocity;

J : Moment of inertia;

B_m : Viscous friction;

T_e : Electricity torque;

T_L : Load torque.

This equation can be transformed by using the Laplace transform as follows:

$$\omega = \frac{1}{B_m} \times \frac{1}{\left(\frac{J}{B_m}s + 1\right)} (T_e - T_L) \quad (2)$$

where,

$K = \frac{1}{B_m}$: Gain;

$f_c = \frac{1}{\tau} = \frac{B_m}{J}$: Cut-off frequency.

This equation shows that the angular velocity of a motor is in proportion to the torque passed through the low-pass filter. The cut-off frequency of the low-pass filter is determined by the viscous friction coefficient and the inertia moment of the motor. Since the value of the cut-off frequency is reduced by increasing the moment of the inertia, the high-frequency torque ripple can be reduced. The use of a long diameter and heavy flywheel to increase inertia in the conventional PMSM reduces the high-frequency components of the rotation ripple. However, it cannot reduce the low-frequency components of rotation ripple when it is operated at a low angular velocity because the maximum inertia is limited by motor specifications. In addition, the motor is heavy and can have a slow response. Thus, this method is not suitable to realize the reduction of the rotation ripple of precise and small motors.

This paper proposes a novel rotation ripple reduction method with multi-coils-motor [3] using a digital direct drive technology and a DTMM (dynamic three-phase multi-coils-motor matching) [4, 5].

3. Proposed Method

This paper proposes DTMM [5] that can reduce the influence of variations of manufacturing of motors based on the novel signal processing method called NSDEM (noise shaping dynamic element matching) [1], before describing DTMM, we explain a digitally direct driven technology and multi-coils-motor in this section, which are important technology to realize DTMM. The digitally direct driven technology is a system that combines a $\Delta\Sigma$ modulator [6] and NSDEM shown in Fig. 2. This system is capable of high output at low voltage and is used in speakers [7] and motor drives [3, 8].

3.1 Multi Bit $\Delta\Sigma$ Modulator

The $\Delta\Sigma$ modulator is composed of a loop filter and a quantizer as shown in Fig. 3. An input signal that

Fig. 2 Digitally direct-driven system.

Fig. 3 $\Delta\Sigma$ modulator.

passed through the loop filter is quantized by the quantizer. The transfer function of $\Delta\Sigma$ modulator can be represented by

$$Y_{(z)} = z^{-n}X_{(z)} + (1 - z^{-1})^n Q \quad (3)$$

where,

Input: $X_{(z)}$;

Output: $Y_{(z)}$;

Quantization error: Q ;

The order of the loop filter: n .

From this equation the quantization error is multiplied by $(1 - z^{-1})^n$. This equation is converted to a frequency domain expression by using $z^{-1} = e^{-\frac{j\omega}{f_s}}$.

Thus $(1 - z^{-1})^n$ is converted to

$$\begin{aligned} (1 - z^{-1})^n &= \left(1 - e^{-\frac{j\omega}{f_s}}\right)^n \\ &= \left(j2 \sin\left(\frac{\omega}{2f_s}\right) e^{\frac{-j\omega}{2f_s}}\right)^n \end{aligned} \quad (4)$$

Q is multiplied by $\left(2 \sin\left(\frac{\omega}{2f_s}\right)\right)^n$.

For the DC current, $\left(2 \sin\left(\frac{\omega}{2f_s}\right)\right)^n = 0$ because of $\omega = 0$. The amplitude of the transfer function has a peak at the half of the sampling frequency from the equations,

$$\omega = 2 \times \pi \times \frac{f_s}{2} = \pi f_s \text{ and } \left(2 \sin\left(\frac{\omega}{2f_s}\right)\right)^n = 2^n.$$

The signal processing that shifts the quantization error to the higher band is called noise shaping as shown in Fig. 4. The noise shaping characteristics can be strengthened by increasing the order- n of the loop filter. In addition, it is possible to reduce the quantization error by increasing the bit length of the quantizer as shown in Fig. 5. Thus, $\Delta\Sigma$ modulator achieves a highly accurate A/D conversion by the noise shaping and multi-level quantization. The $\Delta\Sigma$ modulator generates the multi-level-PDM signal and energy conversion elements such as coils that are driven by the signal. In the conventional method, the multi-level-signal was added in a circuit to get an output. However, this method has disadvantages that the driving voltage becomes high and the noise occurs when an addition is taken place in the circuit. We thus employ a drive method that does not add the multi-level signals in the circuit but directly outputs the signals. Consequently, the number of coils to be driven using a digitally direct driven technology is plural.

Fig. 4 Noise shaping.

Fig. 5 Multi-level-PDM.

3.2 MCM (Multi-coils-motor)

An MCM is a motor that is driven by a digitally direct driven technology as described above. For driving a plurality of signals by the multi-bit PDM signal, it is necessary to provide a plurality of energy conversion elements such as coils in one phase. MCM is based on the PMSM. For example, a U-phase PMSM stator coil with 15-turn is divided into three, each has 5-turn. The three coils are named U1, U2 and U3. They are wound so as to overlap the same core as shown in Fig. 6. The same is done in the V-phase and the W-phase. As a result, the PMSM becomes MCM. The structure of MCM used in this paper is formed by winding three coils in each phase whose structure of one phase is shown in Fig. 6. By connecting the coils in parallel, it is possible to drive with a low supply voltage. Thus, it enables the use of high speed and low-breakdown-voltage MOS transistors in a driver stage.

3.3 H-Bridge Circuits

MCM is driven by controlling individual coil. Thus, the H-bridge circuit is used for driving MCM circuit. As shown in Fig. 7, there are three patterns to control the H-bridge circuit. Since each coil connected in parallel is independently driven by the H-bridge circuits, the number of driving coils can be reduced in the case of low output as shown in Fig. 8. Therefore, it is possible to suppress the switching loss in the driver circuit, when the number of the driven coil is reduced at low output.

3.4 NSDEM

It is possible to output multi-level signals without using an adder circuit by combining the $\Delta\Sigma$ modulator, MCM and H-bridge circuits. This is because MCM has a structure that can mount a plurality of coils. However, the coil has a characteristic variation due to manufacturing variabilities, which causes nonlinear characteristics between the number of coils used and output power (Fig. 9). This causes the vibration of the

Fig. 6 Parallel connections of three coils.

Fig. 7 H-bridge circuit.

Fig. 8 Number of coils to be used.

motor. NSDEM [1] can improve this degradation. NSDEM, which counts the usage of coils by counters, selects coils according to the descending order of usage of coils. The number of times the coils are used is

Fig. 9 Manufacturing error.

Fig. 10 Linearization.

averaged by this selection, which linearizes the characteristics between the number of coils used and output power as shown in Fig. 10. Thus, it is possible to drive the system precisely with multi-bit PDM signal generated by $\Delta\Sigma$ modulator and NSDEM. In addition, the more the patterns to choose coils, the higher the performance of NSDEM is. One phase of MCM is equipped with three coils. Therefore, the output of the U-phase stator coil is an average value of the three coils. Without changing the number of coils, we will propose a method of increasing the pattern of a coil used in NSDEM.

3.5 DTMM

Based on the foregoing description, we now describe the DTMM, a method proposed in this paper. Although an MCM can have an unlimited number of coils for each phase as much as structurally possible, we assume three coils to start with, as follows. The three coils of the U-phase of MCM are named U1, U2, and U3,

respectively, and V and W-phase also has three coils named V1 to V3 and W1 to W3. NSDEM is used in the U, V, and W-phases to suppress the influence to the variation of the coil in each phase. The combinations of U1, U2, and U3 is used to make the magnetic field of the U-phase component. The shuffling of the U1, U2, and U3 combinations can reduce the influence of the variation due to manufacturing variabilities in the U-phase. NSDEM reduces the influence of the element variation more when the combinations to shuffle are more. One way to increase the combinations is to increase the number of the stator coils of MCM. However, there is a limit in winding a plurality of coils in one phase. Therefore, it is more effective to increase the combinations of the generation of U-phase magnetic field without changing the number of stator coils.

Fig. 11 shows vector diagrams of magnetic field generated when a current flows to each coil of the MCM. The vector of the red dashed arrow is a magnetic field vector generated when the plus current flows in the U phase. Vectors of blue and green dotted arrows are the magnetic field vector generated when the minus current flows in the V and W phase. The black arrow is the synthesized magnetic vector. NSDEM averages the output from the vector of red dashed arrow of U1, U2 and U3. We focus on the new synthetic magnetic field generated by the vectors of the blue, green and the dashed arrow. The generated synthetic magnetic field has the same direction and magnitude as the U-phase component vector of red dashed arrow (Fig. 11). Thus, by driving the two coils of the V-phase and W-phase at the same time, a magnetic field can be generated in the U-phase components without the stator coils of the U-phase.

In this MCM, 12 combinations have been used to reproduce the magnetic field of the U-phase component as shown in Fig. 12. Each of the output values has variations compared to the ideal output value. The output value is averaged by switching the combination of coils at high speed. This method can

Fig. 11 The magnetic field of the U-phase component.

Fig. 12 The combination of coils.

Fig. 13 DTMM.

also be applied to the V-phase and W-phase. We propose DTMM as a method to decrease effects of manufacturing variations of elements by shuffling coils among U, V and W phases. Next, we describe an algorithm of DTMM.

DTMM is roughly composed of three modules. One is a model to count the number of times each coil is used. Another module is to select a phase to drive based on the number of use of each coil. The last one is an NSDEM module that selects coils of each phase that are not used frequently. The combination of these modules realizes DTMM (Fig. 13).

Fig. 14 shows a PDM signal generated by $\Delta\Sigma$ modulator. In these figures, only the U-phase is focused. +U1 and -U1 used in the figure should be

referred to the signals in Fig. 7. If signal is not processed, the signal is outputted from the U1 coil. By mounting NSDEM, it is possible to distribute the output from U1, U2, and U3 (Fig. 15). Furthermore, by mounting DTMM, coils other than in the U-phase can output signals as shown in Fig. 16. Figs. 14-16 show that although the driving coils are different from the original, the generated magnetic field has ideally the same size and same direction. NSDEM can generate the averaged variations of three coils as U-phase magnetic field (Fig. 15); however, DTMM can generate the averaged variations of twelve coils as U-phase magnetic field (Fig. 16). As a result, variations of each coil can be averaged more than NSDEM as in Fig. 12 and more precise driving can be performed.

Fig. 14 1bit PDM signal.

Fig. 15 NSDEM (DWA) signal waveform.

Fig. 16 DTMM signal waveform.

4. Implementation

We conducted a measurement to confirm the reduction of rotation ripple using the proposed method. The measurement compares the conventional PWM drive and the proposed DTMM. The measurement environment is shown in Fig. 17. A driver circuit for driving MCM and the FPGA are mounted on the blue board as shown in Fig. 17.

The block diagrams in Fig. 18 show the experimental circuit of the electrical circuit in Fig. 17. By connecting stator coils of the multi-coils-motor in series as shown in right Fig. 18, the measurement of PWM driving can be performed as same construction as of the conventional motors. The algorithm is translated into hardware description language and written into FPGA and the reduction of rotation ripple is performed. The three-phase alternating signal is provided in the table within the FPGA board. This signal is converted to a PWM signal and PDM signal. PDM signal is shuffled beyond the phase by DTMM. The supply voltage to the driver circuits is set to 6 V, and the motor is unloaded. The target rotation speed is 120 rpm. The changes in the rotational speed (rotation ripple) are compared by measuring the rotational speed using an encoder. The results are shown in Fig. 19 and Table 1. The amplitude of the rotational speed of the proposed DTMM method is more reduced compared to the conventional PWM driving as shown in Fig. 19. Table 1 is a summary of the results shown in Fig. 19. The difference between the maximum value and the minimum value of the amplitude is reduced to 32.86 rpm from 46.84 rpm.

The amplitude of the rotational ripple was confirmed to be reduced about 30% with DTMM.

Fig. 17 Measurement environment.

Fig. 18 Measurement environment, (a): DTMM (b): PWM.

Fig. 19 Measurement result of RPM.

Table 1 Compare PWM and DTMM.

(rpm)	Max	Min	P-P
PWM	140.98	94.14	46.84
DTMM	135.94	103.7	32.86

5. Conclusions

This paper proposed a new method to reduce the rotation ripple caused by manufacturing variabilities of the stator coil. We actually confirmed the reduction of rotation ripple by using DTMM and MCM. Unlike the conventional motor, the proposed method can realize a

small, lightweight and high-precision motor system without a flywheel and sensors. Thus, it can contribute to the production and development of high-quality works and products using video recording camera and painting instrument. The MCM presented in this paper uses three coils for each phase in parallel. By increasing the number of coils to more than three and connecting them in parallel, combinations of DTMM can be increased, the variabilities of each element can be reduced, and more precision motors can be expected.

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