Analysis of Acoustic Noise Sources of FDB and ADB Spindle Motors Operating at BLDC Mode

Song Lin*, Chao Bi, Quan Jiang

Data Storage Institute, A*STAR, 5 Enineering Drive 1, Singapore 117608. *lin_song@dsi.a-star.edu.sg

Key words: Acoustic noise, PM motor, BLDC, fluid dynamic bearing, aerodynamic bearing, torque ripple

Abstract: The electromagnetic (EM) sources of the acoustic noise are very concerned in the spindle motor used in the hard disk drives (HDDs). Identifying the effects of these sources is important for high performance hard disk drive products. The electromagnetic analysis results in this paper show that, when the spindle motor is driven by brushless DC (BLDC) mode, the EM torque ripples can be categorized as intrinsic BLDC torque ripple and commutation torque ripple. A set of experiments were designed, tested and analyzed for identifying the effects of these ripples, and the results showed that the commutation torque ripple is the dominant EM source of the acoustic noise.

I. Introduction

The application of hard disk drives (HDDs) is increasing and the new applications are bringing much stricter requirements to the HDD products, among which the acoustic noise is greatly concerned. How to effectively reduce the acoustic noise generated by the motor is critical to HDD products.

The spindle motor used in HDDs is a 3-phase synchronous motor with surface mounted permanent magnet (PM) ring on the rotor. The PM ring made of bonded-NdFeB leads to small and almost constant inductance and very weak armature reaction. And the airgap field in radial direction is almost independent to the drive current. In addition, the spindle motor has multi magnetic-pole structure and the most common structures are 12-poles and 8-poles.

For the spindle motor, its acoustic noise sources can be categorized as mechanical and electromagnetic ones. The mechanical noises include the ones induced by the windage friction of rotor surface and the rolling of bearing balls rotating at high speed. In traditional electric machine analysis, the electromagnetic (EM) acoustic noise sources of the motor are considered to be formed by unbalanced magnetic pull (UMP) [3] and torque pulsations [4]-[7]. The acoustic noise caused by the motor deformation, which is induced by the radial magnetic field [8], can also be considered as the EM source.

Traditionally, the ball bearings were used in the spindle motors. In these years, for reducing the acoustic noise and non-repeatable-runout of the motor, fluid-dynamic bearings (FDB) have been used in the HDD spindle motors. The aerodynamic bearing (ADB) is also being tested in the high-end spindle motors. Using these two kinds of bearings, the acoustic noise caused by the mechanical source is much reduced so that the acoustic noise caused by the EM sources can be obviously revealed [1].

Although enormous research relevant to the acoustic noise reduction has been done, the acoustic noise in spindle motors is still very concerned in the HDD industry. As the acoustic noises induced by the EM sources are obvious in FDB and ADB motors, it is important to investigate the effects of each EM source on the acoustic noise of the motors.

Normally, the EM sources are considered to be formed by the UMP, torque pulsation, and deformation of motor parts. The UMP of the spindle motor is determined by the EM structure of the motor, the quality of the component, and the quality of motor assembling. Through careful motor design [2] and precision production technology, the UMP of the spindle motor can be reduced to a very small value.

Reference [1] points out that, as the torque ripples are related with drive current, changing the drive mode could change the acoustic noise caused by the torque ripples in the spindle motor operation. However, torque ripples are caused by different reasons. Knowing the effects of these reasons is very helpful to find out the effective drive modes, and is also helpful in optimizing the motor structure that can match the drive system to reduce the acoustic noise.

The torque ripples in the spindle motor consist of cogging torque and operation torque ripples. The cogging torque is normally very small in the qualified spindle motors because the frictional-slots are used [9]. Therefore, the effect of the cogging torque will be neglected in the following analysis.

In the stable operation, the motor torque and torque ripple are determined by the waveforms of the back-EMF and the drive current in the windings. The former is related with the EM structure of the motor, the later with the drive mode used. For the spindle motors used in HDDs, the sensorless constant-voltage BLDC mode, CV-BLDC mode in short, has been widely used to realize high efficiency and accurate speed control. In using the CV-BLDC mode, the DC-link voltage is kept constant. The operation of the armature winding on the stator is formed by two states, silent state and energized state as shown in Fig. 1.

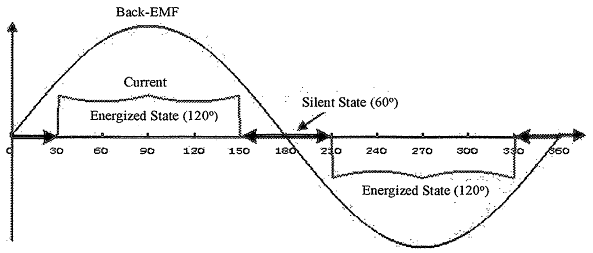


Fig. 1 Optimal status in CV-BLDC mode

In the optimal operation of the CV-BLDC mode, the drive current is applied after 30 degrees from the zero-crossing positions of phase back-EMF and lasts 120 degrees. And one CV-BLDC drive cycle is formed by six steps, (A+)(B-), (A+)(C-), (B+)(C-), (B+)(A-), (C+)(A-) and (C+)(B-), where (A+), (B+), (C+), (A-), (B-) and (C-) refer to the "on" state of upper and lower transistors of phase A, B and C.

II. Analysis of the motor deformation in the spindle motors

The acoustic noise caused by the motor deformation has been a great concern in the study of electric machine noises. The motor deformation is caused by the radial airgap fields, and when the drive current changes, the radial fields could also change, which deforms motor parts. However, whether the acoustic noise caused by the deformation is still obvious in the spindle motor is questionable as the airgap field of the spindle motor is dominated by the PM ring on the rotor.

To clarify the effects of the drive current on the motor deformation in the spindle motors, the magnetic fields in one FDB and one ADB motors that were used in the experiments were calculated with FEM. To make the difference clearer, a drive current that is 5 times of the rated one, which is not likely to happen in practical cases, was used to illustrate the variation of the radial field in the FDB motor, and the FEM results are shown in Fig. 2.

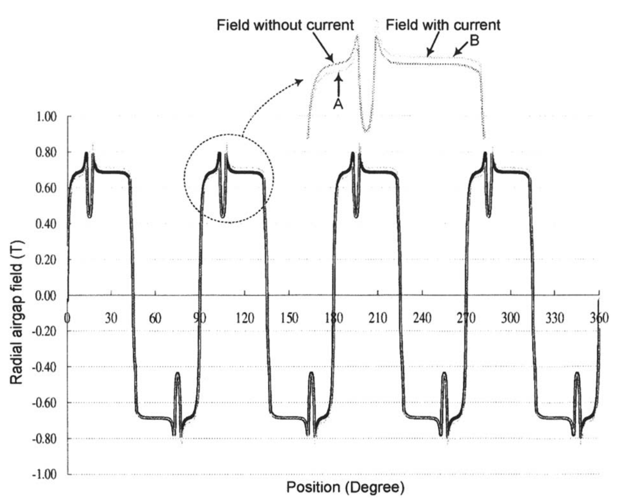


Fig. 2 Distribution of the radial airgap field in the FDB motor

It can be found that the filed changed very little even with such a high current. For example, at positions A and B, the fields change only 4.22% and 3.66% separately. When the rated drive current is used, the changes reduce to 0.83% and 0.74% separately. Similar results can also be obtained in the ADB motor. Therefore, the influence of the drive current to the radial airgap field is very weak. Moreover, for these two motors, as their magnetic pole-pair are 4 and 6 separately, the lowest order of the stator deformations, if there is any, should be 4 and 6 respectively, which is known difficult to occur. Consequently, the deformations of the two spindle motors caused by the drive current can be neglected.

III. EM torque generated in constant-voltage BLDC operation

In section I, it has been mentioned that the inductances of the spindle motor armature windings are very small. Neglect the effects of these inductances and the EM torque of the spindle motor can be expressed as,

$$T_e(t) = \frac{e_A(t)i_A(t) + e_B(t)i_B(t) + e_C(t)i_C(t)}{\Omega} \quad (1)$$

where e_A, e_B, e_C are the phase back-EMFs, and Ω is the mechanical angular speed of the rotor.

First, the EM torque performance in the state (A+)(B-) is analyzed because other states just repeat the pattern. From **Error! Reference source not found.**, the line current i_{AB} in this state can be simplified as,

$$i_{AB}(t) = i_A(t) = -i_B(t) = \frac{U(t) - [e_A(t) - e_B(t)]}{R_A + R_B} = \frac{U(t) - e_{AB}(t)}{R_{AB}} \quad (2)$$

where, R_A and R_B are the total resistances of A-phase and B-phase circuit, respectively.

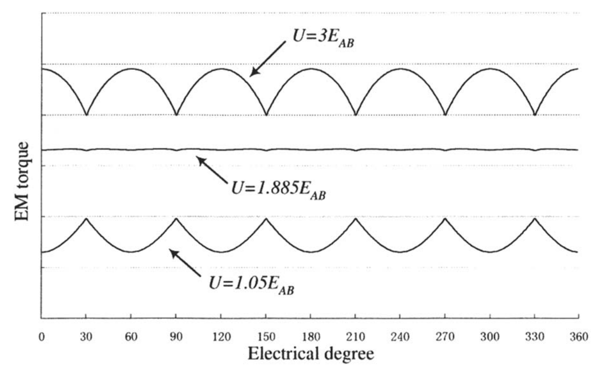


Fig. 3 The EM torque generated in the CV-BLDC operation

When the CV-BLDC drive mode is used, the DC-link voltage $U(t)$ is constant, so it is replaced by U and equation (1) can be rewritten as

$$T_e(t) = \frac{e_A(t)i_A(t) + e_A(t)i_A(t)}{\Omega} = \frac{e_{AB}(t)[U - e_{AB}(t)]}{\Omega \cdot R_{AB}} \quad (3)$$

It is clear that the torque expressed in (3) varies with time. This torque ripple is caused by the CV-BLDC drive mode itself, so it is named as intrinsic torque ripple. Also, from (3), changing the voltage U will change the waveform of $T_e(t)$.

Fig. 3 shows three typical waveforms of the torque in the CV-BLDC operation, where E_{AB} is the amplitude of $e_{AB}(t)$ in (2) and (3).

As the existence of intrinsic torque ripple, the rotor will vibrate in the rotation and thus the acoustic noise will be induced. Now the questions are,

(1) Is the intrinsic torque ripple the major EM source in the acoustic noise?
(2) How can the noise effects of the intrinsic torque ripple be identified?

IV. Minimal intrinsic torque ripple with CT-BLDC mode

For identifying the effects of the intrinsic torque ripple, the logic way is to keep all the operation conditions unchanged, e.g., the operation speed and load condition, while operating the motor in different modes where the intrinsic torque ripple appears in one and disappears in the other.

Several technologies could be considered to reduce the intrinsic torque ripple. Here, a simple and effective way is introduced. From Fig. 3, it can be known that, when the motor speed and load are unchanged, changing the DC-link voltage U can change the EM torque waveform, so the next step is to find the optimal value of U that can minimize the intrinsic torque ripple.

Still consider the state (A+)(B-), and use the H_{AB} (U, T) defined by (5) as the objective function in determining the optimal U,

$$H_{AB}(U,T)=\int_{\pi/3}^{2\pi/3}\left[\frac{E_{AB}Sin(\theta)[U-E_{AB}Sin(\theta)]}{\Omega\cdot R_{AB}}-T\right]^2 d\theta \quad (4)$$

where T is a constant EM torque required to drive the motor that can be determined by the average torque in the cycle,

$$T=\frac{3}{\pi}\int_{\pi/3}^{2\pi/3}\left[\frac{E_{AB}Sin(\theta)[U-E_{AB}Sin(\theta)]}{\Omega\cdot R_{AB}}\right]d\theta \quad (5)$$

Calculate $dH_{AB}(V)/dV$ and let the derivative be zero, and the optimal ratio V_{op} can be obtained,

$$V_{op}=U/E_{AB}\approx 1.885 \quad (6)$$

The result of (6) means that, the intrinsic torque ripple can be minimum in the CV-BLDC mode when $U=V_{op}\cdot E_{AB}$. The EM torque waveform in this state is shown in Fig. 3, and it is clear that the intrinsic torque ripple is much reduced and the EM torque generated in the motor operation can be considered as a constant.

However, the DC-link voltage shown in (6) is higher than the normal value. To keep the same average EM torque when U is increased, R_{AB} should be increased too, which can be realized by using external resistors.

Use r and R to express the external and armature resistors, and V_N to express the ratio between U and E_{AB} in normal CV-BLDC operation. When the voltage is adjusted to $V_{op}\cdot E_{AB}$, the EM torque will not change if the external resistor meets the following equation,

$$r=\frac{12(V_{op}-V_N)}{3(4V_N-\sqrt{3})-2\pi}R \quad (7)$$

Therefore, the intrinsic torque ripple would be the smallest in the CV-BLDC mode while the average EM torque is kept the same as in normal operation by adjusting U and r. This BLDC mode with the DC-link voltage and external resistors described by (6) and (7) is defined as the constant-torque BLDC (CT-BLDC) mode.

V. Identify the effects of intrinsic torque ripple on the acoustic noise

Using the CV-BLDC mode to drive the motors, the current commutating induces current spikes as shown in Fig. 4. Therefore, for a practical spindle motor driven by the CV-BLDC mode, besides the intrinsic torque ripple, the torque ripples caused by the commutation current spikes also exist, which will be called commutation torque ripple.

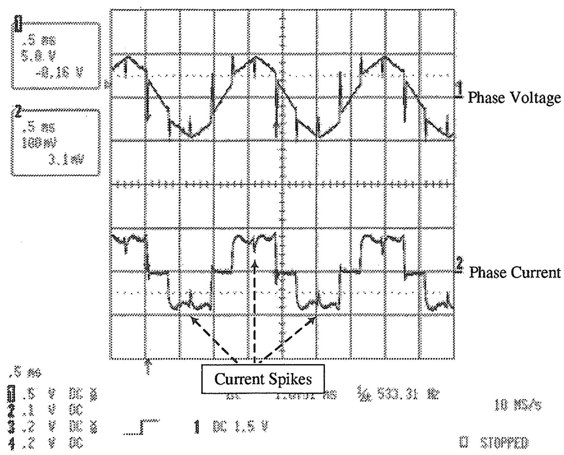


Fig. 4 Phase voltage and current of a FDB motor in normal CV-BLDC operation

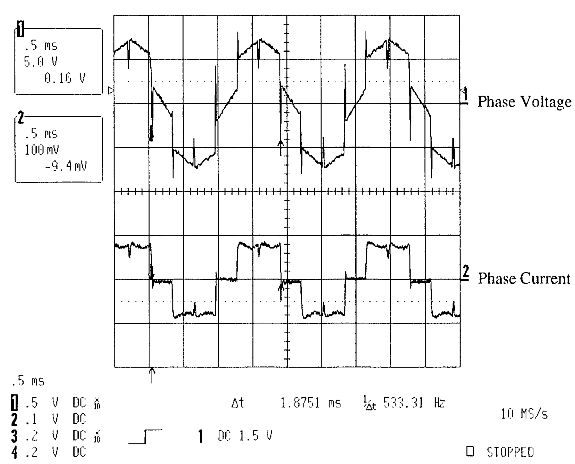
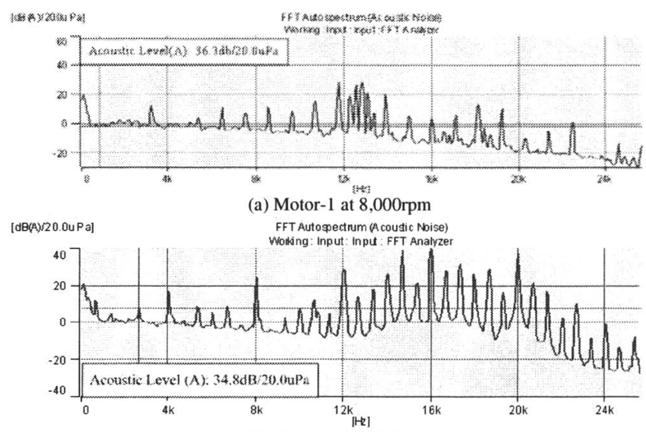


Fig. 5 Phase voltage and current of a FDB motor in CT-BLDC operation

It is clear that both the intrinsic and commutation torque ripples exist in the motor operation, but which one is the major EM source inducing the acoustic noise? As it was analyzed, the CT-BLDC mode can eliminate the intrinsic torque ripple, and thus eliminate the acoustic noise caused by this kind of torque ripple. However, for a practical motor, even if the CT-BLDC mode is used, the current spike also exists as the experimental result shown in Fig. 5, which means the commutation torque ripple still exists in the CT-BLDC mode.

In the experiment, the motor was driven with the normal CV-BLDC mode and CT-BLDC mode separately while keeping the load and motor speed unchanged. If the intrinsic torque is the major source, the acoustic noise produced in the CT-BLDC operation should be obviously weaker than that in the CV-BLDC operation. Two motors were used in the comparison. Motor-1 is a FDB motor and motor-2 is an ADB motor. In the measurements, both motors operated in no-load state, i.e., no disk was assembled on the rotor.

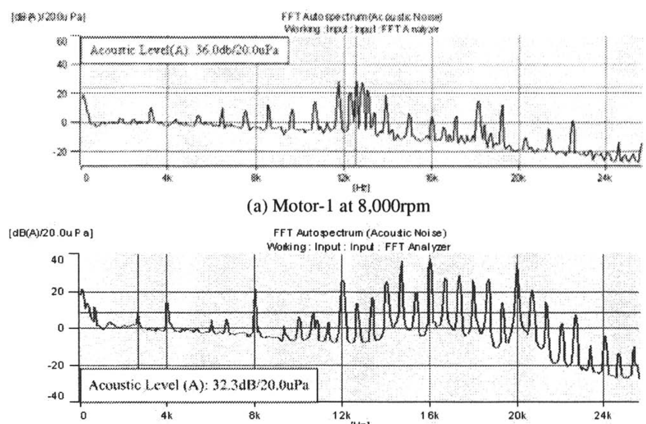
Fig. 6 and Fig. 7 show the acoustic noises of Motor-1 and Motor-2 driven in normal CV-BLDC mode and CT-BLDC mode, separately.



(a) Motor-1 at 8,000rpm

(b) Motor-2 at 10,000rpm

Fig. 6 The acoustic noise spectrum at normal CV-BLDC mode



(a) Motor-1 at 8,000rpm

Fig. 7 The acoustic noise spectrum in CT-BLDC mode

Comparing these two figures, it is difficult to find the difference in the noise spectrums of CV-BLDC mode and CT-BLDC mode, though the noise level is reduced a little in the latter. It can thus be concluded that the intrinsic torque ripple contribute only a little in generating the acoustic noise, and this kind of torque ripple is not the major EM source of the acoustic noise.

Then, is the commutation torque ripple the major EM source? Because the commutation torque ripple caused by the current spikes exists in both the CV-BLDC and CT-BLDC modes, its influence on the acoustic noise cannot be disclosed clearly in the above tests. The drive modes that can eliminate the current spikes should be investigated to disclose the effects of the commutation torque ripple, and using sinusoidal drive current is a reasonable choice.

VI. The effects of sinusoidal drive mode on the acoustic noise

The back-EMF of the spindle motor is well-shaped sinusoidal. For this kind of AC PM motor, it is not difficult to approve that the sinusoidal current is a better choice in generating constant torque [1]. The Motor-1 and Motor-2 were again tested using the sinusoidal drive mode, which is named as PSIN mode hereinafter. And it is clear that both the intrinsic and commutation torque ripples can be eliminated in the PSIN mode.

The acoustic noises results of the Motor-1 and 2 driven by the CV-BLDC and PSIN modes are shown in Fig. 8 using the waterfall format, where the influence of the motor speed is also included, and the effects of different noise sources can thus be disclosed more clearly.

In the section V, it was proved that the acoustic noise caused by the intrinsic torque ripple takes very small ratio in the total noise, but the results there cannot distinguish the effects of the commutation torque ripple because it exists in both the CV-BLDC and CT-BLDC drive modes. Comparing Fig. 6, Fig. 7 and Fig. 8, because most of the noise spectrum spikes produced by the CV-BLDC and CT-BLDC modes disappear in the PSIN mode, it is clear that commutation torque ripple is the major EM reason inducing the acoustic noise.

In the above experimental results, it can also be concluded that the acoustic noise caused by the motor deformation is very weak in the motor operation. As the radial force in the motor is independent to the drive mode, if there was any deformation, the related acoustic noise peaks should have appeared in the spectrums of both the BLDC mode and the PSIN mode. However, most of the spectrum peaks in CV-BLDC mode disappear in PSIN mode, which proves that the deformation, if it exists, is very small.

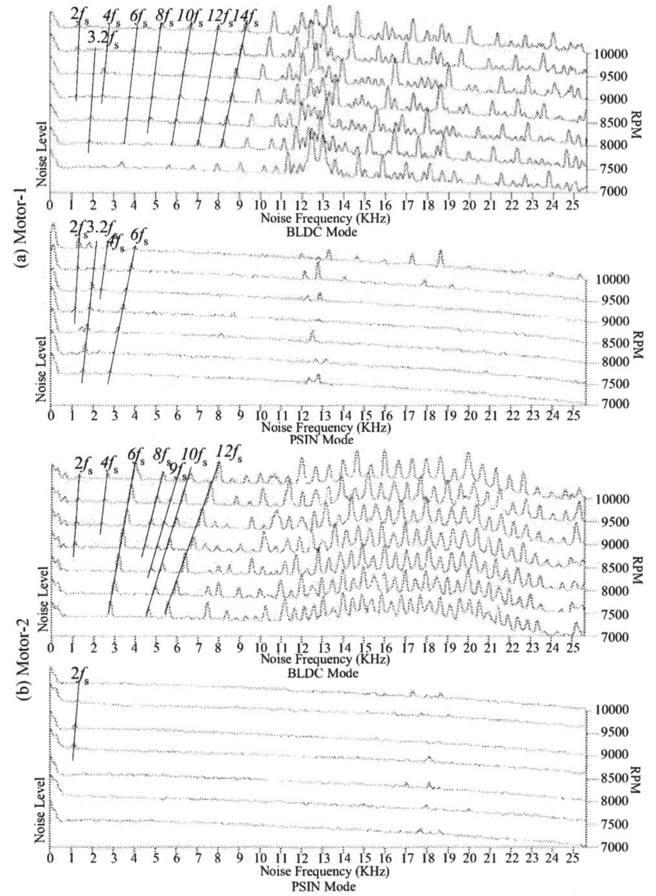


Fig. 8 The acoustic noise spectrum waterfalls generated in BLDC and PSIN mode

VII Conclusion

The reduction of acoustic noise generated by the motor is critical to HDD products. The spindle motors are now mainly using FDB to reduce the non-repeatable-runout and acoustic noise caused by ball bearing, and may also move to ADB in the future. Using these two kinds of bearings, the effects of the EM sources on the acoustic noise become obvious. Therefore, it is important to find out the major EM reason inducing the acoustic noise in FDB and ADB spindle motors. In this paper, the EM sources of the acoustic noise generated in spindle motor at CV-BLDC mode are analyzed. It is proved that motor deformation is negligible in producing acoustic noise and the major EM source is considered to be the operation torque ripples that are formed by the intrinsic torque ripple and commutation torque ripple. To identify the effects of the intrinsic torque ripple, two special drive modes, CT-BLDC mode and PSIN mode, were developed and analyzed. The analysis shows that the CT-BLDC mode, compared with CV-BLDC mode, can reduce the intrinsic torque ripple obviously but leave the commutation torque ripple almost unchanged. In contrast, PSIN mode can eliminate both the intrinsic torque ripple and commutation torque ripple. Comparing the experimental results of the CV-BLDC, CT-BLDC and PSIN modes, it can be concluded that the major EM source of the acoustic noise is the commutation torque ripple, and the intrinsic torque ripple contributes very little to the acoustic noise. Therefore, it can also be concluded that future research work to reduce the noise caused by EM source in the FDB or ADB motors should be focused on the ways in reducing the commutation current jump. These results are very helpful in guiding the research in future to develop advanced and effective spindle motor drive systems for the high performance applications, especially for hard disk drive products.

Reference

[1]. S. Lin, Q. Jiang, A. A. Mamun, C. Bi, "Effect of drive modes on the acoustic noise of fluid dynamic bearing spindle motors", IEEE Transactions on Magnetics, Vol. 39, No. 5, pp. 3277 - 3279, September 2003.

[2]. Bi Chao, Z.J. Liu, "Unbalanced-Magnetic-Pull in PM Synchronous Motors-- Its relation with stator tooth number and armature winding", Proceedings of 25th Annual Symposium on Incremental Motion Control Systems and Devices, IMCSD' 96, June 11-14, 1996, San Jose, US, pp. 79-84;

[3]. T. S. Low, C. Bi, and Z. J. Liu, "A hybrid technique for electromagnetic torque and force analysis of electric machines", International Journal for Computation and Mathematics in Electrical and electronic Engineering, Vol. 16, No 3, pp. 191 - 205, 1997.

[4]. T. M. Jahns and W. L. Soong, "Pulsating torque minimization techniques for permanent magnet AC motor drives – a review," IEEE Trans. on Industrial Electronics, Vol. 43, pp. 321 - 330, April 1996.

[5]. J. De La Ree and N. Boules, "Torque production in permanent-magnet synchronous motors", IEEE Trans. on Industry Applications, Vol. 25, No. 1, pp. 107 - 112, January - February 1989.

[6]. S. J. Park, H. W. Park, M. H. Lee and F. Harashima, "A new approach for minimum-torque-ripple maximum-efficiency control of BLDC motor", IEEE Trans. on Industrial Electronics, Vol. 47, No. 1, pp. 109 - 114, February 2000.

[7]. B. H. Kang, C. J. Kim, H. S. Mok and G. H Choe, "Analysis of torque ripple in BLDC motor with commutation time", IEEE International Symposium on Industrial Electronics, Vol. 2, pp. 1044 - 1048, June 2001.

[8]. Z. Q. Zhu and D. Howe, "Electromagnetic noise radiated by brushless permanent magnet DC drives", Sixth International Conf. on Electrical Machines and Drives, pp. 606 - 611, September 1993.

[9]. J.R. Hendersshot, T.J.E. Miller, Design of Brushless Permanent-Magnet Motors, Magna Physics Publishing & Oxford University Press, 1994.

[10]. Q. Jiang, C. Bi, and R. Y. Huang, "A new phase-delay free method to detect back emf zero-crossing points", APMRC'04, Seoul, Korea, August 16-19, 2004.