Hard Disk Drive Spindle Motor System Design For Data Recording With Ultrahigh TPI

Bi Chao

Data Storage Institute, A*Star, 117608, Singapore

The performance of spindle motor system is crucial to that of the hard disk drive (HDD). The spindle motor system faces tremendous challenges as the HDD industry keeps pushing up magnetic recording areal density. This paper analyzes several attributes of the spindle motor system which affect the recording density of the hard disk drive. Some of the attributes have not been highlighted and studied before. The present analysis shows that the performance of spindle motor system can be improved through the integration of optimal electromagnetic design, mechanical system enhancement and advanced power drive to meet the requirements of the next-generation hard disk drive with ultrahigh areal density.

***Index Terms*—Commutatorless DC motors, disk drives, disk recording, motor drives.**

I. Introduction

THE hard disk drive (HDD) has been considered as the most important computer component for mass data storage since it was invented by IBM in the early 1950s. In recent years, the market of HDD has been expanding marvelously due to the exponential growth in demand for consumer electronics.

The most remarkable development in HDD technology is that the areal data density (ADD) has been increased rapidly in the recent years. ADD is defined as the product of data bits-per-inch (BPI) and tracks-per-inch (TPI). Therefore, increasing ADD needs the breakthroughs in technologies to boost both BPI and TPI technologies.

The research on high performance spindle motor has been centering around bearing, electromagnetic (EM) design, hard and soft magnetic materials, and motor drive systems. Thanks to the progress in the precision bearing design, especially with the fluid dynamic bearing (FDB), the non-repeatable runout and the acoustic noise of the motor have been reduced greatly. While a low non-repeatable runout is important in realizing high TPI, a low acoustic noise allows HDDs to be used in many consumer electronics.

Traditional spindle motors use radial field structure, where the permanent magnet (PM) ring is surface mounted on the rotor. For realizing compact structure, 120° fractional concentric armature windings are used in the spindle motors, and Fig. 1 shows the typical structure of the motor. For this kind of motor, its equivalent airgap is big, and armature reaction is weak, its winding self inductances are independent to the rotor position, and torque constant value is not influenced by the drive current. As fractional concentric armature windings are used and slot shape is optimized, the back-EMF generated in the windings is quite sinusoidal, i.e., the waveform of back-EMF contains very weak harmonics.

Manuscript received February 11, 2009. Current version published October 23, 2009. Corresponding author: B. Chao (e-mail: Bi_Chao@dsi.a-star.edu.sg).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TMAG.2009.2029637

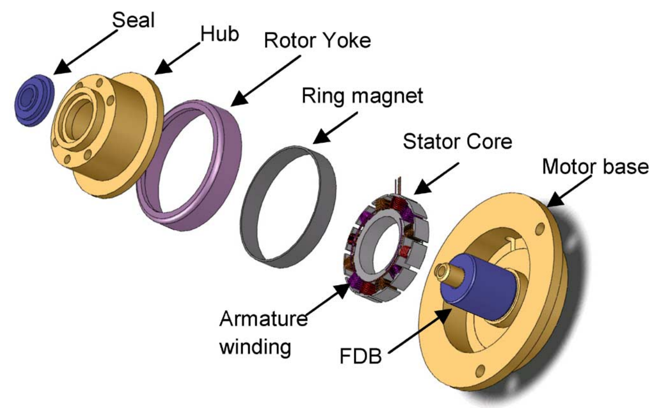

Fig. 1. Key components in the spindle motor with radial field structure.

TABLE I
TPI and NRRO Requested in Ultrahigh Add Recording

BAR	2		4	
ADD	TPI	NRRO	TPI	NRRO
2 Tb/in^2	2,000k	<1.27 nm	2,828k	<0.9 nm
10 Tb/in^2	4,472k	<0.568nm	6,325k	<0.401nm

More and more researchers are exploring the solutions to realize ultrahigh TPI in HDD. Therefore, non-repeatable runout (NRRO) of the motor must be reduced to a very low level. As the TPI is very high, the signal of the magnetic head is quite weak. For assuring the qualified signal to noise ratio (SNR) of magnetic head, the motor speed must be precise.

Table I shows the TPI linked with ultrahigh ADD recording based on the magnetic head with different bit aspect ratio (BAR). The table shows also the requirement on the NRRO of the spindle motor under different ADD. As the NRRO is in the range 0.4–1.27 nm, both the design and application of spindle motor system are facing very stringent challenges.

Also, sensorless drive technology is currently used to drive the spindle motor in HDDs. Using this method, only a few rotor positions can be detected in one revolution. How to utilize these limited rotor position signals to control the speed accurately, is also a challenge to be overcome.

TABLE II
TYPICAL SPEED OF SPINDLE MOTOR IN HDD PRODUCTS

Spindle Speed (rpm)	Average Latency Time (ms)	Typical applications
5,400	5.6	IDE, SATA, SCSI, laptops
7,200	4.2	IDE, SATA, SCSI, desktops
10,000	3.0	IDE, SATA, SCSI, desktops
12,000	2.5	SCSI
15,000	2.0	SAS, SCSI
20,000	1.5	SAS

II. SPEED OF THE SPINDLE MOTOR

Besides storage density, the access time, t_{Acc}, is also a concern as it affects the data read/ write rate of the drive. The access time can be expressed as

$$t_{\mathrm{Acc}} = t_{\mathrm{dp}} + t_{\mathrm{seek}} + t_{\mathrm{lat}} \tag{1}$$

where t_{dp} is the data processing time and t_{seek} is time taken by track seeking, and t_{lat} is the rotational latency time related with disk rotational speed.

Following the fast development of electronics technology, t_{dp} has been reduced significantly in the recent years, and it is taking up a small portion in t_{Acc} now. However, t_{seek} is difficult to be reduced obviously as it is related directly to the mechanical inertia of the actuator system. t_{lat} is the time taken by the heads waiting for information of the required angular position. This value can be reduced directly by increasing the rotational speed of the disks. Therefore, for reducing t_{Acc}, there has been an urgency to increase the speed of spindle motor, and the rotational speed of HDD has been increased significantly in recent years.

Table II shows the typical speed used in the existing HDD products, and the related latency time against the motor speed. Increasing the motor speed has been considered as an effective approach to reduce the latency time, but it also induces problems in HDD operation, which include the following.

A. Acoustic Noise

It is well known that the acoustic noise can be increased obviously when the spindle motor speed is raised. Fig. 2 shows the acoustic noise testing result of a 3.5″ HDD, whose rated speed is 15 000 rpm. This HDD will be called as HDD-A for short hereafter in the paper. It can be found that, even when the cover of the HDD is closed, the noise of HDD is increased about 12 dB when the motor speed is increased from 7200 rpm to 15 000 rpm. The serious noise problem limits certainly the application of HDD in many areas.

B. NRRO Induced by Mechanical Vibration

Increasing the spindle motor speed induces the vibration of many HDD components, and complicates airflow structure. These affect finally the flying height of magnetic heads over the magnetic medium. From the point view of NRRO, increasing motor speed is burdensome as it means a worsening NRRO. Table III shows the testing results of HDD-A at different speeds and atmospheric pressures. It can be found that, when the speed is nearly doubled from 7200 rpm to 15 000 rpm, the NRRO is amplified about 4 times. Such deterioration is certainly a serious concern in ultrahigh TPI recording.

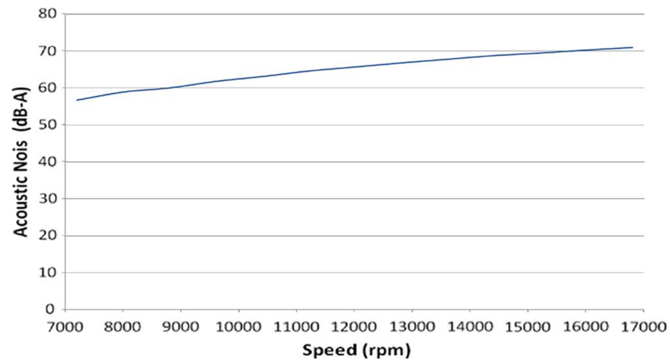

Fig. 2. Acoustic noise results of HDD-A (cover is closed).

TABLE III
NRRO OF HDD-A AT DIFFERENT SPEED AND ATMOSPHERIC PRESSURE

Speed (rpm)	NRRO (Standard deviation, unit: nm)		
	@1 bar	@0.8 bar	@0.6 bar
7200	18.3	20.8	22.2
10000	21.9	23.8	22.1
15000	69.9	70.0	70.1

C. Asymmetry of Winding

The dc-link voltage of the motor drive circuit is fixed, e.g., 12 V for 3.5″ HDD, and 5 V for 2.5″ HDD. Therefore, the voltage constant of the motor must be small for high speed spindle motor. It means also that a few winding turns of the motor must be used for high speed motor. One example is that, for a spindle motor used in 3.5″ HDD, its stator has 12 slots and magnetic pole-pair is 4. When it is used in 7200 rpm operation, its winding turns in one slot is about 24 turns, but the turns must be reduced to 11 or 12 when the motor is used in the 15 000 rpm operation.

Letting the winding terminals of the spindle motor be concentrated in a limited area is necessary as it allows the wires to be connected reliably to external circuit. However, the leading wires of each phase winding have thus to go through several slots to get to the required stator location, and this makes the global winding structure of the motor asymmetric. For low speed motors, such an asymmetry is not a serious issue as the winding turns are numerous. The asymmetry may contribute noteworthy unbalanced magnetic pull (UMP) in the high speed spindle motor due to the noticeable asymmetry of the windings. Fig. 3 shows the winding structure of a spindle motor, in which we can see asymmetry of the winding is obvious as the winding turns in one slot is fewer. This problem will be explained further in Sections III and IV.

D. Electrostatic Charge and Discharge

When the spindle system rotates with high speed, electrostatic charges are easily induced in the rotational parts, e.g., rotor and disks. For reducing acoustic noise and NRRO, now all HDD products are using FDB in the spindle motor. This kind of bearing is poor in allowing discharge between the rotor and stator of the motor. Following the increment of ADD, magnetic

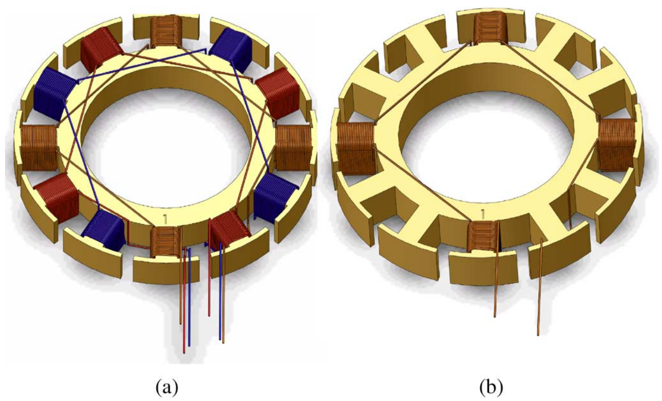

Fig. 3. Winding structure of a spindle motor with 12-slots and 4 magnetic pole-pairs. (a) 3-phase winding. (b) 1-phase winding.

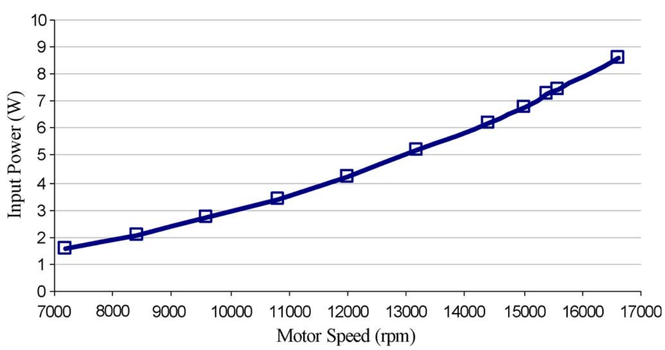

Fig. 4. Input power of HDD-A at different speed.

head sensors have been upgraded in recent years, and many of them are very sensitive to the electrostatic charges accumulated on the disks. On the other hand, the sudden discharge in the FDB may change the characteristics of FDB lubrication oil and the surface conditions of the sleeve and shaft. Finally, the performance of FDB is worsened. All these are the concerns in realizing ultrahigh TPI recording.

E. Power Consumption

It is well known that the windage loss can increase rapidly with motor speed. Reference [1] presented that the windage loss can be described as

$$P_w = \xi N_d D^{4.6} \Omega^{2.8} \tag{2}$$

where ξ is related with the HDD structure, D is the disk diameter, and Ω is the speed of the spindle motor.

From (2), big power loss is concomitant with high speed operation. Fig. 4 shows the power variation of HDD-A at different speeds, and we can see that motor power consumed at 15 000 rpm is 5.6 times that at 7200 rpm. High power consumption leads to heat generation, and then temperature rising. The latter is one of the major reasons worsening the performance of many HDD components. All of these are concerns to be addressed in the next generation HDD products.

Modern HDD products are using FDB in the spindle motor as it can make the NRRO and acoustic much lower than the tra-

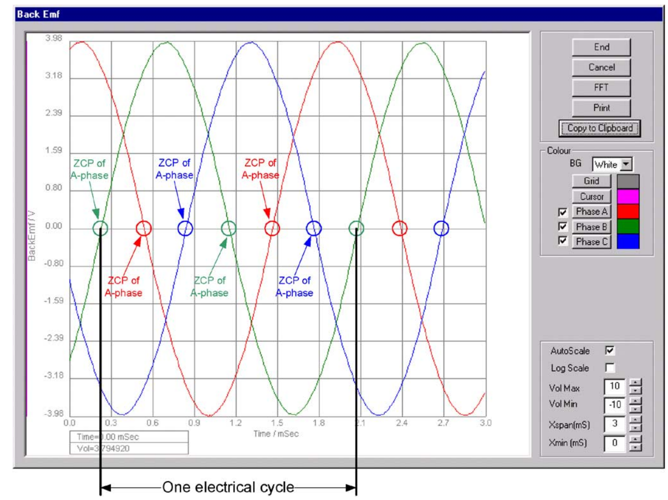

Fig. 5. Back-EMF and its ZCPs in the motor operation.

ditional ball-bearing. However, if the speed is high, NRRO and acoustic noise of the motor cannot be reduced further significantly. Therefore, high speed spindle system should not be used in the HDD with ultrahigh TPI data recording. Reducing the latency time should be achieved through other solutions, e.g., multiple-actuator used before [14].

III. EM Structure of the Spindle Motor

Increasing the pole-pair is significant to realize accurate speed control. Due to the strict requirements on motor size and concerns in cost and reliability, the position sensor, e.g., Hall sensor, has been abandoned in the spindle motor for many years. The spindle motors have to be driven by sensorless drive technology for all the existing HDD products [1], [3], [4]. Using this kind of drive technology, the rotor position is detected by zero-crossing-positions (ZCPs) of the back-EMF. In every electrical cycle, 6 rotor positions can be detected (see Fig. 5). Therefore, $\boldsymbol{N_z}$, the total number of the rotor position detected is given by

$$N_Z = 6p. \tag{3}$$

From (3), increasing the pole-pair of the motor can increase the number of detectable rotor position. This is significant to realize accurate speed control. For the HDD with ultrahigh areal density, if the sensorless drive technology is still to be used, increasing the magnetic pole-pairs of the motor is necessary.

For the spindle motor used in HDD, one basic requirement is that the leakage field of the motor must be small, otherwise the storage cells could loss their data information, and signal from the magnetic head could contains a lot of noise. The ultrahigh density recording will be more sensitive to the leakage field. Increasing $\boldsymbol{p}$ can shorten the passage of the magnetic field produced by the magnet in both the rotor and stator yokes, and thus reduce the leakage field of the motor.

From the above description, multimagnetic pole-pair is necessary to HDD spindle motors in future. But, multimagnetic pole-pair structure also induces problems in the motor operation. In high speed operation, multipole-pair structure makes the frequency of drive current high. This increases the difficulty in realizing high performance motor drive system. The issue will be discussed further in Section IV.

The required drive torque of the spindle motor is generated by the reaction between the EM fields which is generated by PM ring on rotor, and stator current. As surface mount magnet and fractional concentrated windings are used, the cogging torque of the spindle motor is not as serious as many other PM AC motors. However, cogging torque is still a concern for the spindle motor used in HDD with ultrahigh TPI as it induces vibration, acoustic noise, and speed error. The fundamental frequency of the cogging torque is quite high. The vibration induced by the cogging torque could contribute a lot to the NRRO. Therefore, designing the spindle motor for next generation HDD, the cogging torque should be reduced to the minimum level. But this reduction should not worsen motor efficiency.

In motor operation, besides the EM torque, the airgap EM field can also induce local radial forces which act on the rotor and stator. When the EM field is balanced, the resultant force caused by these radial local forces is zero. However, if the field is not balanced, the resultant force is not zero, and unbalanced magnetic pull is thus induced. UMP varies with the changing of rotor position and drive current. The unbalanced field could be caused by component quality, e.g., the magnet ring is not symmetrically magnetized, and the stator core dimensions are not correct. The unbalance can also be induced by the eccentricity of the rotor, which could be formed in the motor assembling procedure. The UMP caused by these quality issues are defined as ***Extrinsic UMP*** [7]. This kind of UMP should be reduced to very low level through quality control in the components and motor production.

On the other hand, the UMP may also be induced by EM structure itself. Even the components and production are perfect, this kind of UMP still exist in the motor. Therefore, this kind of UMP is defined as ***Intrinsic UMP*** [6], and Fig. 6 shows the intrinsic UMP generated in a spindle motor with 9 stator slots and 4 magnetic pole-pairs. The intrinsic UMP can be avoided by using EM structure with even pole-pair and even slot number [6].

In [8], the author analyzed in detail the winding structure of the spindle motor, and pointed out several ways to avoid the UMP induced by the winding structure. However, as it was mentioned in Section II, the winding asymmetry induced by the leading wires is still a concern, especial for high speed motor. Fig. 7 shows the UMP of a spindle motor generated by its asymmetric winding due to the leading wires. This motor is used in HDD-A, its stator slot is 9, and pole-pair is 3. For this kind of motor, no intrinsic UMP can be induced [6]. However, due to the existence of the leading wires, the drive current can still induce UMP in motor operation. From Fig. 7, the UMP induced by the asymmetry of the winding should not be overlooked in ultrahigh TPI recording.

UMP of the spindle motor must be reduced to minimum as it worsens the runout and acoustic noise of the motor. For UMP induced by the current, as the frequency spectrum of the BLDC drive current is very wide, it can certainly induce NRRO in the motor rotation. From the analysis before, such NRRO will be more serious in the high speed motor. Therefore, the EM structure of the motor must be optimized to reduce the asymmetry caused by the leading wires.

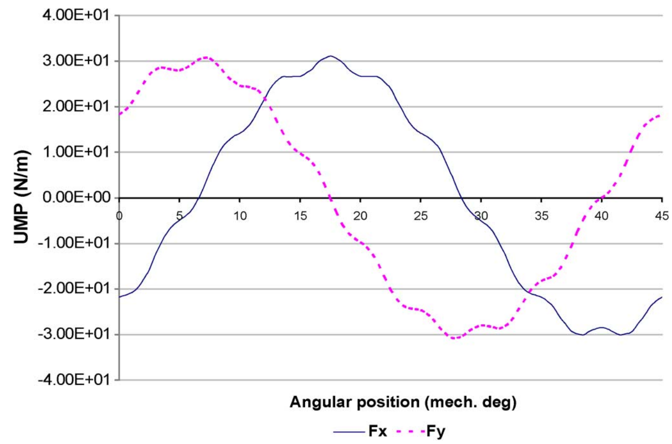

Fig. 6. Intrinsic UMP generated in the spindle motor with 9 stator slots and 4 magnetic pole-pair.

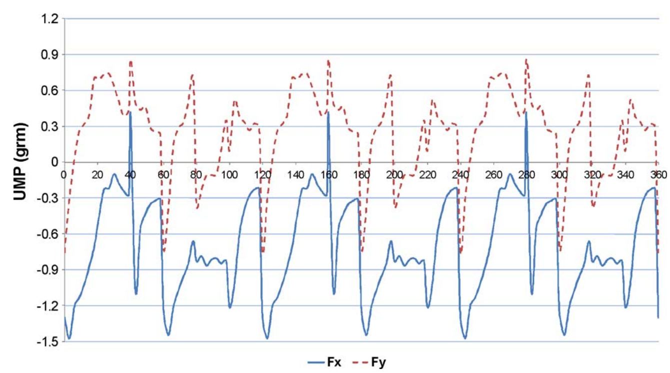

Fig. 7. UMP of HDD-A spindle motor generated by leading wires in one revolution.

From the above analysis it can be known that for handling the challenges from ultrahigh TPI recording, the cogging torque of the motor must be very low, intrinsic UMP must be eliminated, winding symmetry must be good, and the magnetic pole-pair of the motor should be increased.

IV. Drive Mode of Spindle Motor

NRRO is linked with acoustic noise. Their relationship can be found through the spectrum analysis of the acoustic noise and runout. When the FDB is used, the NRRO and acoustic noise induced by the bearing are much reduced, and this make the influence of the drive current to acoustic noise and NRRO clear. It has been mentioned in Section III that the spindle motors used in HDD are driven by sensorless BLDC drive mode. Using this mode to drive the 3-phase spindle motor, the current is commutated with six steps in one electric cycle. In the current commutating, there are current jumps in the windings.

The typical current waveform of one phase winding is shown in Fig. 8, where, the influence of the winding inductance is ignored. For such a current waveform, the torque ripple is unavoidable as shown in Fig. 9, and this kind of ripple is defined as ***Intrinsic Torque Ripple***, which is linked directly with the

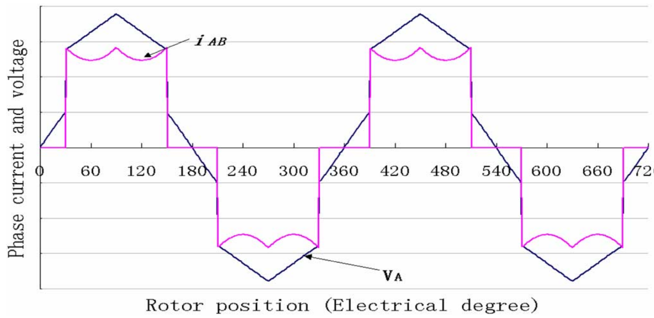

Fig. 8. Typical waveforms of i_{AB} and V_{AB} in the CV-BLDC operation without winding inductance.

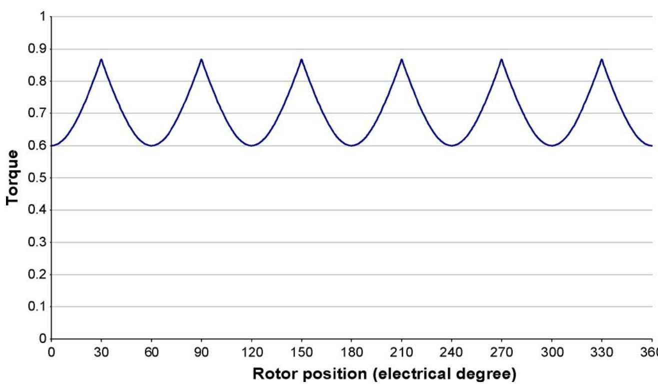

Fig. 9. Typical EM torque generated in the CV-BLDC operation.

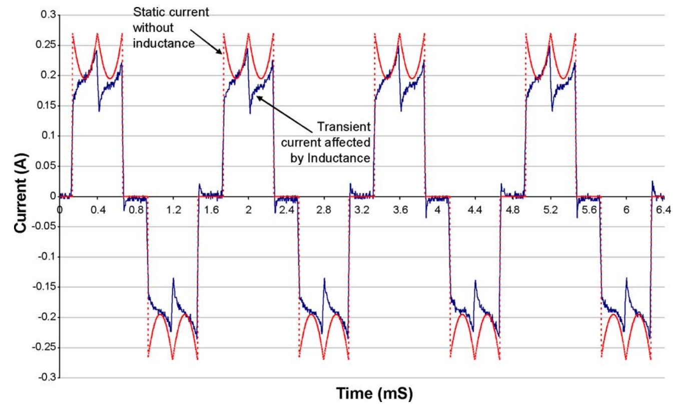

Fig. 10. Drive current of the PM AC motor in using the constant voltage BLDC drive mode.

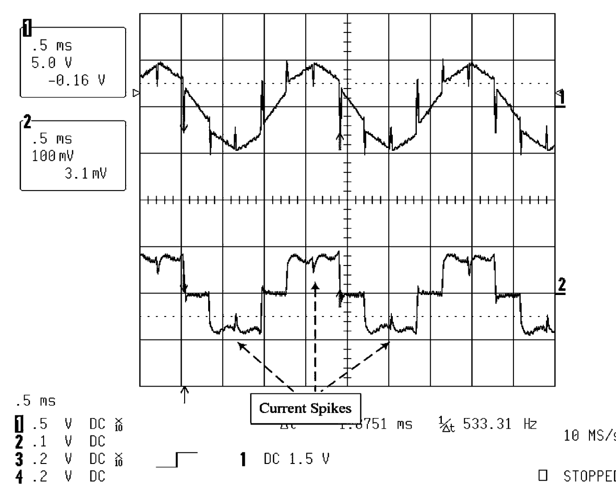

Fig. 11. Experimental result: phase voltage and current of a FDB motor in normal CV-BLDC operation.

BLDC drive mode. The intrinsic torque ripple can certainly produce acoustic noise, like the influence of cogging torque mentioned in Section III.

However, as the multipole EM structure is used and motor speed is high, the frequency of drive current is high. Therefore, the influence of the inductances of spindle motor cannot be neglected. Fig. 10 shows the current waveforms of a spindle motor driven by the BLDC mode. Two current results are provided, one of which is a simulated waveform (dotted) for the motor with inductance set to zero, and the other is the experimental current containing the transient component. It can be found that in such a case, the current is obviously affected by the winding inductance, which can certainly induce additional torque ripple which is not expected. [15] proves that when the inductance is considered, the optimal commutation angle is smaller than the 30°, the one been normally used as the optimal angle in many applications.

The torque tipple can also be induced by another reason. The winding inductance generates current sparks in the commutating (see Fig. 11). The spectrums of these sparks are quite wide. Therefore, for a practical spindle motor driven by BLDC mode, besides the intrinsic torque ripple, the commutation current sparks can also act with the rotor field and generate the torque ripples, which will be called ***Commutating Torque Ripple***. Both the intrinsic and commutating torque ripples exist in the BLDC motor operation [9]–[13]. As the frequency bandwidth of the commutation current sparks is very wide, its influence on the torque ripple and UMP generated by the sparks must not be overlooked. It was mentioned before that, both the UMP and torque ripple are linked closely with the acoustic noise and runout of the motor. It is expected to develop a drive mode whose commutating current jumping is weak, and intrinsic torque ripple is low. Some drive modes have been analyzed and tested by the author to reduce the acoustic noise and NRRO. Fig. 12 shows the results of normal BLDC and QBLDC drive modes [12] and the effects of QBLDC in the noise reduction is clear. Fig. 13 compares the acoustic noise generated by the normal BLDC and PSIN drive modes [11], and it can be seen that the latter is quite effective in reducing the acoustic noise of both FDB and aerodynamic bearing motors. These drive modes are part of efforts from author's laboratory in reducing the acoustic noise and NRRO through drive solution. The results show that, advanced drive mode is quite effective in reducing the acoustic noise of the spindle motor.

The drive technology is also linked directly with the accuracy of spindle motor speed, which was mentioned that it is critical to ultrahigh TPI recording. How to use sensorless drive technology to realize accurate speed is a concern as only few rotor positions can be detected. We must develop effective algorithm to estimate the motor speed accurately in the sensorless drive, and attenuate the effect of torque ripple to the motor speed.

As motor drive is linked closely with electronics, which has been developing very fast in recent years, the drive solution will

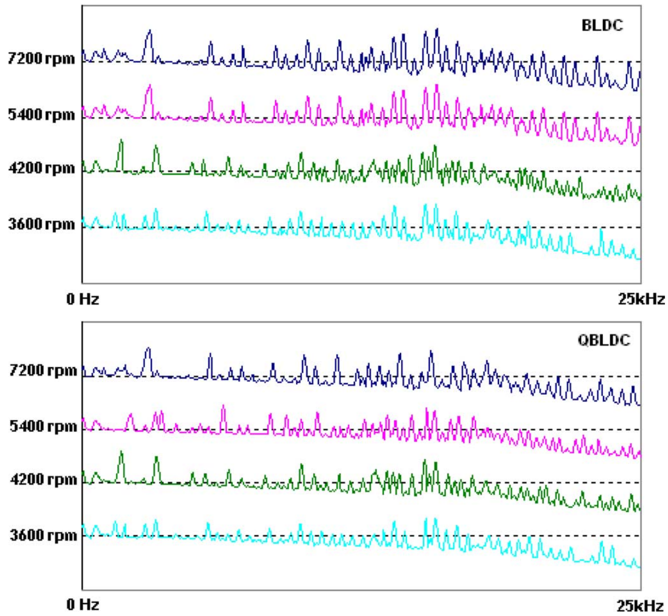

Fig. 12. Acoustic noise spectrum waterfall of a FDB spindle motor generated by normal BLDC and QBLDC drive modes.

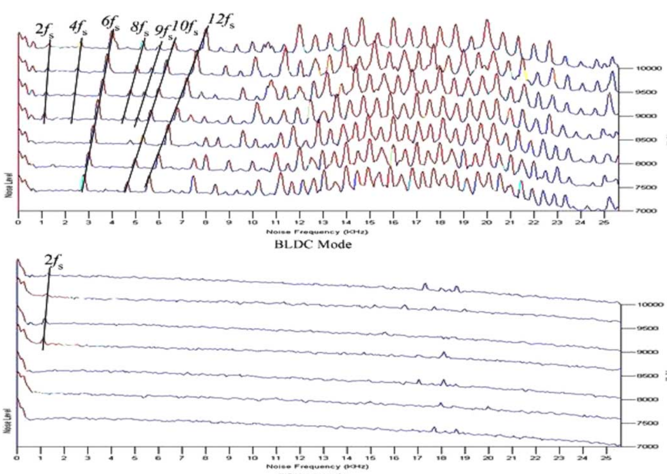

Fig. 13. Acoustic noise spectrum waterfall of an ADB spindle motor generated by normal BLDC and PSIN drive modes.

certainly plays an important role in realizing advanced spindle system for ultrahigh TPI recording.

V. Conclusion

The performance of spindle motor is critical to the achievable storage density of HDDs. The current research shows that limiting the motor speed is significant to achieving ultrahigh TPI recording as it can reduce NRRO, acoustic noise and power consumption of the spindle system. Using reasonable EM structure of the motor is also important in improving the performance of the motor. The motor should be designed to be ultralow in cogging torque and unbalanced magnetic pull and the symmetry of armature winding must be good. Reducing the torque ripple induced by the drive system, especially by reducing the commutation spark of the drive current, is notable to reduce the NRRO and acoustic noise of the motor. Using advanced drive technology to improve the motor speed accuracy is also important in the next generation HDD. Therefore, the effective solution of the spindle motor system should be developed through the integration of EM design and the drive system. Meantime, improving the performance of mechanical components, especially the bearing, is also critical to achieving ultrahigh TPI recording.

Acknowledgment

The author gratefully acknowledges his colleagues Dr. Lin Song, Dr. Hla Nu Phyu, and Mr. Soh Cheng Su, Mr. Yu Yin Quan, and Dr. He Zhiming for their support in this work.

References

[1] E. Grochowski and R. D. Halem, “Technological impact of magnetic hard disk drives on storage systems,” *IBM Syst. J.*, vol. 42, no. 2, 2003.

[2] A. A. Mamun, G. Guo, and C. Bi, *Hard Disc Drive—Mechatronics and Control*. Boca Raton, FL: CRC Press, 2006.

[3] C. S. Soh, C. Bi, and K. K. Teo, “The FPGA implementation of quasi-BLDC drive,” in *7th Int. Conf. Power Electronics & Drive Systems*, Bangkok, Thailand, Nov. 27–30, 2007.

[4] C. Bi and S. Lin, “Analysis of acoustic noise sources of FDB and ADB spindle motors operating at BLDC mode,” in *The 4th Int. Conf. Power Electronics, Machines and Drives 2008*, York, UK, Apr. 2–4, 2008.

[5] W. C. Blount, Fluid Dynamic Bearing Spindle Motors: Their Future in Hard Disk Drives [Online]. Available: http://www.hitachigst.com/tech/techlib.nsf/techdocs

[6] C. Bi, Q. Jinang, and S. Lin, “Unbalanced-magnetic-pull induced by the EM structure of PM spindle motor,” in *ICEMS05*, Nanjing, China, Sep. 26–29, .

[7] C. Bi, N. L. H. Aung, Q. Jiang, and S. Lin, “Influence of rotor eccentricity to unbalanced-magnetic-pull in PM synchronous motor,” in *ICEMS06*, Nagasaki, Japan, Nov. 20–23, 2006.

[8] C. Bi, N. L. H. Aung, H. N. Phyu, Q. Jiang, and S. Lin, “Unbalanced magnetic pull induced by drive current in PM-BLDC motor operation,” in *ICEMS-2007*, Seoul, Korea, Oct. 8–11, 2007.

[9] Q. Jiang, C. Bi, and R. Y. Huang, “A new phase-delay free method to detect back emf zero-crossing points,” in *APMRC’04*, Seoul, Korea, Aug. 16–19, 2004.

[10] 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. Ind. Electron.*, vol. 47, no. 1, pp. 109–114, Feb. 2000.

[11] S. Lin, Q. Jiang, A. A. Mamun, and C. Bi, “Effect of drive modes on the acoustic noise of fluid dynamic bearing spindle motors,” *IEEE Trans. Magn.*, vol. 39, no. 5, pp. 3277–3279, Sep. 2003.

[12] C. S. Soh, C. Bi, and K. K. Teo, “The FPGA implementation of quasi-BLDC drive,” in *Seventh Int. Conf. Power Electronics and Drive Systems*, Bangkok, Thailand, Nov. 27–30, 2007.

[13] B. H. Kang, C. J. Kim, H. S. Mok, and G. H. Choe, “Analysis of torque ripple in BLDC motor with commutation time,” in *IEEE Int. Symp. Ind. Electronics*, Jun. 2001, vol. 2, pp. 1044–1048.

[14] [Online]. Available: http://www.storagereview.com/guide/actMultiple.html

[15] C. Bi and C. S. Soh, “Influence of transient current to PM-AC motor driven by BLDC mode,” in *ICEMS08*, Wuhan, China, Oct. 17–20, .