Effect of Drive Modes on the Acoustic Noise of Fluid Dynamic Bearing Spindle Motors

S. Lin, Q. Jiang, A. A. Mamun, *Member, IEEE*, and C. Bi, *Member, IEEE*

***Abstract*—The torque ripple is one of the major sources of acoustic noise in the fluid dynamic bearing (FDB) spindle motors. This paper analyzes the relationship between the acoustic noise frequency, harmonic current and harmonic field, and compares the acoustic noise produced in FDB motors driven by different modes. Results show the effect of drive mode on acoustic noise is significant in the FDB spindle motors.**

***Index Terms*—Acoustic noise, drive mode, fluid dynamic bearing, spindle motor, torque ripple.**

I. Introduction

FLUID dynamic bearing (FDB) motors are being employed widely in hard disk drives (HDDs). One important reason for using FDB spindle motors is that they produce much lower acoustic noise than the ball-bearing (BB) motors. However, the requirement on the acoustic noise in HDDs is becoming more and more strict, which gives new challenges to the design, drive and applications of the FDB spindle motors.

The sources of acoustic noises generated in the motor operation can be classified into four categories: mechanical, aerodynamic, magnetic, and electronic [1]. In the FDB spindle motor, the acoustic noise excited by the bearing is greatly reduced. However, the stiffness of fluid bearing is low and the operation of the rotor is easily affected by the magnetic forces acting on it. Therefore, to study the acoustic noise in FDB motor, the effect of EM force must be considered. Fortunately, without the presence of ball bearing, the acoustic noise in FDB motors caused by EM forces can be easily disclosed.

Three kinds of magnetic forces act on the rotor and the stator: unbalanced magnetic pull (UMP), tangential forces and axial forces [2]–[4]. The UMP and axial forces are caused by the motor structure, and the motor assembly [5], which will not be discussed further in this paper.

When a motor is driven by different modes, it produces different torque ripples with different frequency spectrums, and thus different acoustic noises. In this paper, a comparative study of acoustic noise generated in the FDB spindle motors driven in *BLDC mode* and *PMSM mode* is presented. The research result shows that the acoustic noise produced in FDB operation can be reduced significantly using the PMSM mode.

Manuscript received January 6, 2003.

S. Lin and A. A. Mamun is with the Electrical and Computer Engineering Department, National University of Singapore, Singapore 119260.

Q. Jiang and C. Bi are with the A*Star Data Storage Institute, Singapore 117608.

Digital Object Identifier 10.1109/TMAG.2003.816153

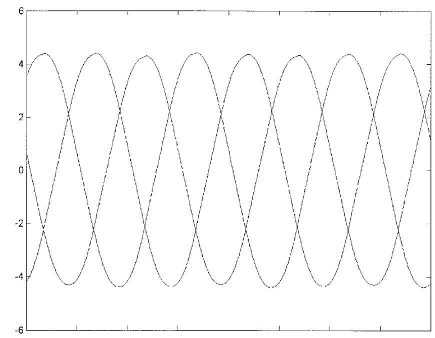


Fig. 1. Measured three phase back EMF.

II. Torque Ripples Produced in the Permanent Magnet FDB Spindle Motor

There are several ways to express the torque developed in the permanent magnet spindle motor [6], [7]. To investigate the influence of drive modes on acoustic noise, the electrical formulation is more appropriate. For the three-phase spindle motor operated in constant speed, neglecting the cogging torque, the electromagnetic torque can be expressed as

$$T(t) = \sum_{j=a,b,c} \frac{i_j(t)e_j(t)}{\Omega}. \tag{1}$$

The currents and back EMFs can be decomposed in Fourier series as

$$i_j(t) = \sum_{k=1}^{\infty} I_k \sin\left[k(\omega t + \alpha_{jk})\right] \tag{2}$$

$$e_j(t) = \sum_{v=1}^{\infty} E_v \sin\left[v(\omega t + \beta_{jv})\right]. \tag{3}$$

Substituting (2) and (3) into (1), the torque expression is

$$T(t) = \sum_{j=a,b,c} T_j(t) \tag{4}$$

where

$$T_j(t) = \sum_{k=1}^{\infty}\sum_{v=1}^{\infty} \frac{I_k E_v}{2\Omega}\left\{\cos\left[(k-v)\omega t + (k\alpha_{jk} - v\beta_{jv})\right] + \cos\left[(k+v)\omega t + (k\alpha_{jk} + v\beta_{jv})\right]\right\}. \tag{5}$$

In the symmetric three-phase system, (5) can be written as

$$T(t) = \sum_{j=a,b,c} T_j = \sum_{k=1}^{\infty}\sum_{v=1}^{\infty} T_{kv}(t) \tag{6}$$

where if $k - v = 3m$, $m = \pm 1, \pm 2, \pm 3, \ldots$

$$T_{kv}(t) = \frac{3 I_k E_v}{2\Omega} \cos\left[(k-v)\omega t + (k\alpha_{ak} - v\beta_{av})\right] \tag{7}$$

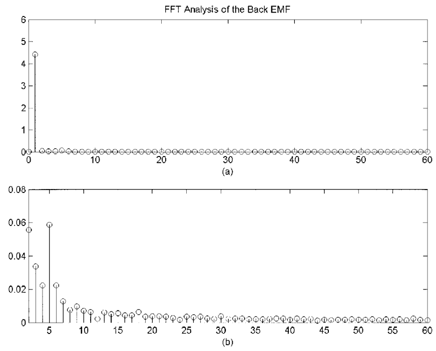


Fig. 2. FFT result of the back EMF developed in the motor.

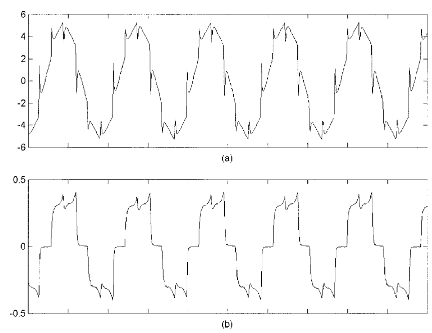


Fig. 3. (a) Phase voltage and (b) phase current in BLDC mode.

if $k+v=3m$, $m=1, 2, 3, \ldots$

$$T_{kv}(t) = -\frac{3I_k E_v}{2\Omega}\cos\left[(k+v)\omega t + (k\alpha_{ak} + v\beta_{av})\right] \quad (8)$$

otherwise

$$T_{kv}(t) = 0. \quad (9)$$

However, if asymmetry exists in the three-phase spindle motor, (4) will be the final expression of instant electromagnetic torque, where all possible harmonic orders $(k+v)$ and $(k-v)$ exist. Equation (5), (7), (8), and (9) show that the reaction between the kth order phase current and vth order back EMF has the following characteristics.

1) The developed torque component is constant which does not produce acoustic noise, if and only if the order of a current harmonic is the same as the order of a back EMF harmonic.
2) If the order of a current harmonic is different from that of a back EMF harmonic, the torque component will be either zero or time-varying, and such a time-varying torque will be one of the sources of acoustic noise.

III. Current and Back EMF Harmonic in the PM Spindle Motor Under Test in Two Modes

The back EMF in the PM spindle motor is close to sinusoidal wave, as shown in Fig. 1. The FFT analysis shows that some harmonics exist in the back EMF, shown in Fig. 2.

To get rotor position without sensors, the most commonly used method in HDD industry is to energize two phases only and measure the third phase back EMF to get position information. This mode is named *BLDC mode* in this paper. The phase voltage and current in this mode is depicted in Fig. 3. FFT analysis of the current is shown in Fig. 4.

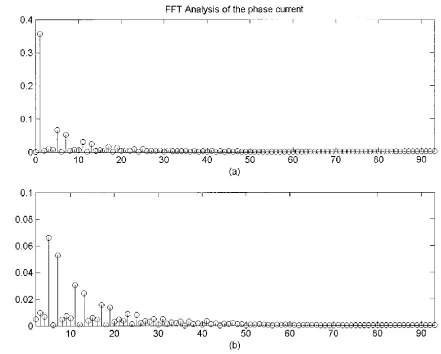


Fig. 4. FFT result of drive current in BLDC mode.

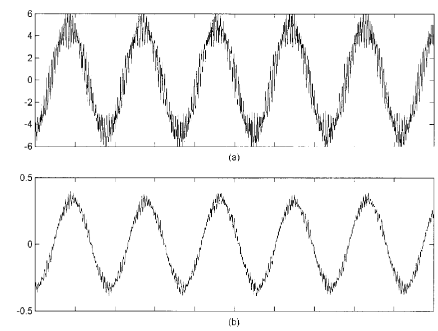


Fig. 5. (a) Phase voltage and (b) phase current in PMSM mode.

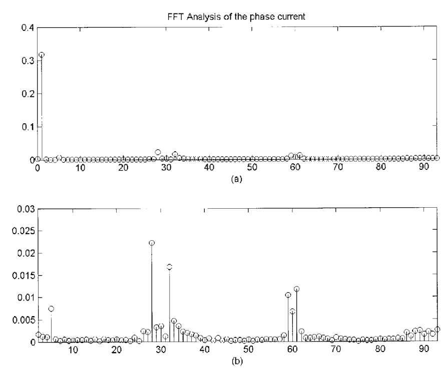


Fig. 6. FFT result of drive current in PMSM mode.

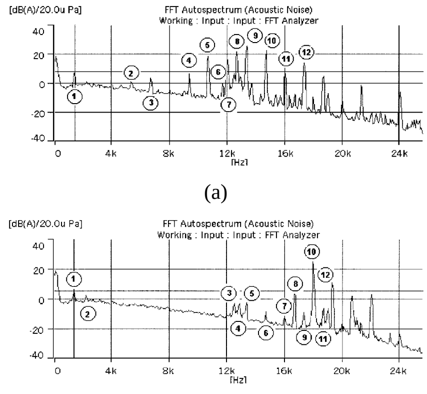
Another drive mode is studied in this paper, in which all three phases are conducting, and it is named *PMSM mode*. SPWM inverter is employed in this mode with the PWM frequency of 20 KHz. The measured phase voltage and current is illustrated in Fig. 5. FFT result of the corresponding current in this mode is shown in Fig. 6.

IV. Acoustic Noise Test Results

A drive system was built to drive the spindle motor in the BLDC mode and PMSM mode respectively, and measured the acoustic noises generated in the motor operation. Fig. 7(a) and (b) show the acoustic noise test results for these two modes.

Comparing Fig. 7(a) with 7(b), it is clear that changing the drive mode can change the acoustic noise of FDB spindle motor obviously. The acoustic noise level is much lower in PMSM mode than in BLDC mode with 3.4 dB less.

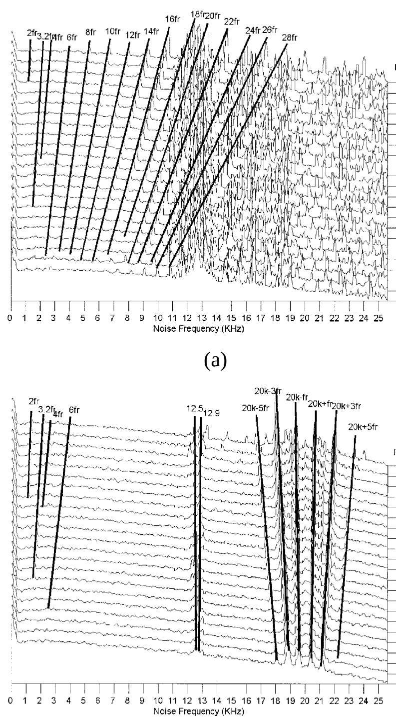
To show the effect of drive modes on the acoustic noise clearer, waterfall test of the acoustic noise was performed at different rotating speeds in the two modes. The results



(a)

(b)

Fig. 7. Acoustic noises produced in a 8-pole/12-slot PM spindle motor at the speed 10 000 rpm. (a) in BLDC mode and acoustic level (A): $29.8\ \mathrm{db}/20.0\ \mu\mathrm{Pa}$. (b) in PMSM mode and acoustic level (A): $26.4\ \mathrm{db}/20.0\ \mu\mathrm{Pa}$.



(a)

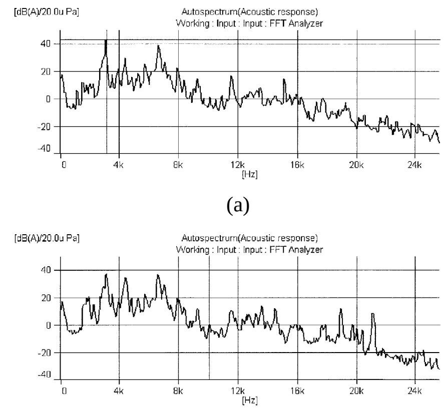
(b)

Fig. 8. Acoustic noise waterfall test result (a) in BLDC mode (b) in PMSM mode.

are shown in Fig. 8(a) and (b). The relationship between the acoustic noise dominant frequencies and the spindle motor rotating speeds in both modes are clearly depicted.

It can be seen from these two figures that acoustic noise is introduced at some frequency points around 20 kHz in the PMSM mode because of the use of PWM. We can move these noises to inaudible frequency range by setting a suitable switching frequency. For the frequencies 12.5 kHz and 12.9 kHz, they are obviously caused by the mechanical resonance of the motor parts. These noise parts can be reduced by modifying the motor structure.

Although the effect is obvious for FDB motors, it is not the same case for ball bearing (BB) spindle motors. Fig. 9 shows



(a)

(b)

Fig. 9. Acoustic noises produced by the BB spindle motor at the speed 5,400 rpm. (a) BLDC mode and acoustic level (A): $46.5\ \mathrm{db}/20.0\ \mu\mathrm{Pa}$. (b) PMSM mode and acoustic level (A): $44.9\ \mathrm{db}/20.0\ \mu\mathrm{Pa}$.

the acoustic noise of a BB spindle motor driven by BLDC mode and PMSM mode separately. The test results show again that acoustic noise of the BB motor is not sensitive to the drive modes, i.e., is not sensitive to the torque ripples.

V. Conclusion

In this paper, the relationship between the harmonics of acoustic noise and harmonic torques is analyzed. The acoustic noise of FDB spindle motors is sensitive to the EM forces as the noise caused by the bearing is much smaller than the normal motors. The use of the PMSM drive mode is an effective way to reduce it. Both the theoretical analysis and the test results show the effectiveness of such drive mode. As this is an electronic method that does not rely on the mechanical processing, the method is easily applied to the motors used in hard disk drives, and other electronic products. As the spin speed in HDDs increases, and some new bearing technologies, such as aerodynamic bearings and active magnetic bearings, may also be used in future. In these cases, the effectiveness of the method proposed to reduce the acoustic noise will be more significant as the noise ratio caused by the mechanical sources will be further reduced.

References

[1] P. Vijayraghavan and R. Krishnan, "Noise in electric machines: a review," in *Proc. 1998 IEEE Ind. Applicat. Conf.*, vol. 1, St. Louis, MO, Oct. 12–15, 1998, pp. 251–258.
[2] C. Bi, Z. J. Liu, and T. S. Low, "EM force calculation for electric machines using a combined numerical and analytical technique," in *Proc. 25th Annu. Symp. Incremental Motion Contr. Syst. Devices, IMCSD'96*, San Jose, CA, June 1996, pp. 17–22.
[3] S. Huang, M. Aydin, and T. A. Lipo, "Electromagnetic vibration and noise assessment for surface mounted PM machines," in *Proc. Power Eng. Soc. Summer Meeting*, vol. 3, 2001, pp. 1417–1426.
[4] S. J. Yang, *Low Noise Electrical Motors*. Oxford, U.K.: Clarendon Press, 1985.
[5] Z. J. Liu, C. Bi, H. Lin, J. P. Yang, and M. A. Jabbar, "Electromagnetic design of permanent magnet motors for high speed applications," in *Proc. 9th Int. Conf. Elect. Mach. Drives*, 1999, pp. 45–48.
[6] A. E. Fitzgerald, C.Charles Kingsley, and S. D.Stephen D. Umans, *Electric Machinery*. New York: McGraw-Hill, 1983.
[7] H. Le-Huy, R. Perret, and R. Feuillet, "Minimization of the torque ripple in brushless dc motor drives," *IEEE Trans. Ind. Applicat.*, vol. IA-22, pp. 748–755, July/Aug. 1986.