Reduction of Acoustic Noise in FDB Spindle Motors by Using Drive Technology

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***Abstract*—In the operation of fluid-dynamic-bearing (FDB) motors, the acoustic noise caused by the electromagnetic forces takes a big ratio in the noise level. The authors analyze the relationship between the acoustic noise frequency, harmonic current, and harmonic field, and propose a drive mode for reducing the acoustic noise of the FDB motors. The drive mode can also reduce the copper loss in the motor operation.**

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

I. Introduction

FLUID dynamic bearing (FDB) spindle motors are being used widely in hard disk drives (HDDs). One of the reasons for using the FDB spindle motors is that the FDB motors produce lower acoustic noise than the ball-bearing (BB) motors. However, the fast developments of HDD technology demand more and more strict requirements on the level of acoustic noise, particularly in the audible range, and this gives new challenges to the design, control, and applications of the FDB spindle motors.

The acoustic noises generated in the motor operation are from the magnetic, mechanical, aerodynamic, and electronic sources [1]. For BB spindle motors, the metal, or ceramic, balls contact with both rotor and stator. In the motor operation, the acoustic noise and vibration caused by the balls are serious, and the vibration of the rotor can easily be transmitted to the stator, and vice versa. The acoustic noise from this source dominates the acoustic level of the BB spindle motors. Examples will be used to explain this phenomenon. In the FDB spindle motor, the rotor is supported by a liquid thin film. The acoustic noise caused by the balls is eliminated, and the noise caused by the mechanical source is thus much reduced. The effects of other acoustic noise sources, such as the noise caused by the electromagnetic (EM) sources, are thus more obvious. As the stiffness of FDB is low, the operation of the rotor is easily affected by the magnetic forces and torques acting on it. Therefore, to reduce the acoustic noise produced in FDB motor operation, the effects of EM forces in the motor must be considered.

Three kinds of magnetic forces act on the rotor and the stator: unbalanced magnetic pull (UMP), tangential forces, and axial forces [2]–[6]. The variation of these forces causes both irregular and regular movements and deformations of the rotor and stator, and this produces acoustic noise when the motor is operating.

The UMP and axial forces are caused by the motor structure and the motor assembly [7]–[9]. To reduce the acoustic noise caused by these EM sources, the optimization of design and production technologies have to be considered. These issues, however, 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. Developing an effective drive mode to reduce the torque ripples has been studied by researchers [10]–[12]. In this paper, we present the use of the concept of "identity control" [10] to reduce torque ripples. The implementation results are presented and the research shows that the acoustic noise produced in FDB operation can be reduced significantly.

II. Characteristics of Stator Field and Rotor Field in the Spindle Motor

The harmonic fields produce acoustic noise in motor operation. To verify the effects of the harmonic fields and harmonic currents, the relationship between the noise frequencies and the harmonic fields must be analyzed.

In permanent magnet (PM) spindle motors, the magnetic field in the airgap is from two sources, the field due to the PM on the rotor surface and the field produced by the drive current in the armature windings, which are on the stator core.

The airgap field produced by the rotor magnet contains certain harmonics unless it is well shaped. The airgap field produced by the armature windings also contains harmonics. This can be reduced by careful design of winding structure. However, in small PM motors, there are few opportunities for shaping the magnet or using the optimized windings due to the limited motor space and number of stator slots. Hence, the airgap field has a very high proportion of harmonics as shown in Fig. 1.

We use $\mathbf{p}$ to express the pole-pair of the motor and $\mathbf{p_m}$ to express the pole-pair of the mth harmonic field. When the rotor rotates at its synchronous speed $\boldsymbol{n_s}$, all the harmonic fields produced by the PM of rotor rotate at the same speed in space, that is

$$n_m = n_1 = n_s \tag{1}$$

where n_m is the rotational speed of the mth field harmonic produced by the rotor magnet.

For most of the spindle motors used in HDDs, as the motor space is very limited, only the concentrated structure can be used to form the armature winding shown in Fig. 2.

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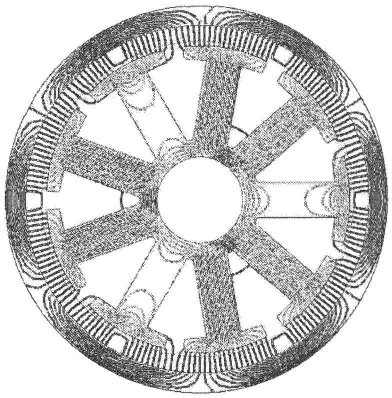

Fig. 1. Magnetic field produced by PM in an eight-pole/nine-slot spindle motor.

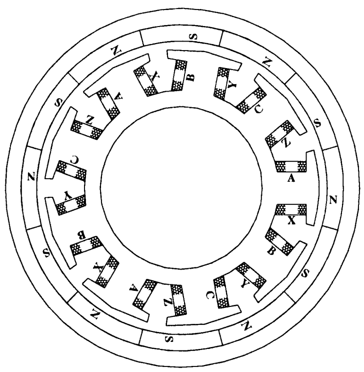

Fig. 2. Armature windings in a 12-pole/nine-slot spindle motor.

It is clear that the EM field produced by the concentrated armature windings described in Fig. 1 is not symmetric in its one pole-pair space. Therefore, both the odd and even order harmonic fields will be produced by such armature windings.

A three-phase drive current set can produce rotational fields in the airgap of a three-phase motor. The rotational speed and direction of the harmonic fields are determined by the motor structure and the frequency of the drive current.

III. Torque Ripple Produced by Harmonic Fields

It is assumed that the airgap of the spindle motor is smooth and narrow and the motor operates in its stable state. The magnetic field in the airgap can thus be expressed as

$$B_g = \sum_m B_{rm}(\theta, t) + \sum_n B_{sn}(\theta, t) \tag{2}$$

where t is the time and θ is the space position. $B_{rm}(\theta, t)$ and $B_{sn}(\theta, t)$ are the mth and nth airgap fields excited by the rotor magnet and stator windings, separately

$$B_{rm} = B_{Rm} \sin[m_r(\theta + \delta_r) + 2\pi f_{mr} t] \tag{3}$$

$$B_{sn} = B_{Sn} \sin[n_s(\theta + \delta_s) \pm 2\pi f_{ns} t]. \tag{4}$$

The rotation speeds of $B_{rm}(\theta, t)$ and $B_{sn}(\theta, t)$ are

$$\Omega_{mr} = \frac{-2\pi f_{mr}}{m_r} \tag{5}$$

$$\Omega_{ns} = \frac{\mp 2\pi f_{ns}}{n_s}. \tag{6}$$

They are related with the pole-pair and frequency of the harmonics.

From (2) the magnetic field energy in the airgap is

$$W_g = \frac{\mu_0 g L R}{2} \int_0^{2\pi} B_g^2 d\theta \tag{7}$$

where μ_0 is the permeability of the air, g is the width of the airgap, L is the length of the motor, and R is the average radius of the airgap.

Using the virtual work method, the EM torque of the motor can be calculated by using the magnetic energy W_g

$$T_M = \frac{-dW_g}{d\delta_r} = -\mu_0 g L R \int_0^{2\pi} B_g \left(\frac{dB_g}{d\delta_r}\right) d\theta = \sum_{m,n} T_{mr-ns}(t) \tag{8}$$

and $T_{mr-ns}(t)$ is the torque harmonic produced by the reaction between fields $B_{rm}(\theta, t)$ and $B_{sn}(\theta, t)$.

From (3), (4), and (8), if $m_r \neq n_s$

$$T_{mr-ns}(t) = 0. \tag{9}$$

If $m_r = n_s = k$

$$\begin{aligned} T_{mr-ns}(t) = & -k\mu_0 g L \pi R B_{Rm} B_{Sn} \sin[2\pi(f_{mr} \mp f_{ns})t \\ & + k(\delta_r - \delta_s)] \\ = & \, k\mu_0 g L \pi R B_{Rk} B_{Sk} \sin[k(\Omega_{kr} \pm \Omega_{ks})t \\ & + k(\delta_s - \delta_r)]. \end{aligned} \tag{10}$$

Equations (5), (6), (9), and (10) show that the reaction between the mth order rotor harmonic field and the nth order stator harmonic field has the following characteristics.

1) If these two fields have the different pole-pairs, no torque is produced by the reaction.
2) If these two fields have the same pole-pairs and the relative speed between the fields is zero, the torque produced by the reaction is constant, and this type of torque cannot induce vibration and acoustic noise in the motor operation.
3) If these two fields have the same pole-pairs and the relative speed between the fields is not zero, the torque produced is a function of time, i.e., the torque varies with time.

Considering the case where the spindle motor operates in its synchronous speed and its three-phase drive currents are symmetric and sinusoidal, from Section II, the fundamental harmonic of the stator field and rotor field rotate with the same speed and same direction. Therefore, the torque produced by the reaction of the fundamental stator and rotor fields is constant.

If the drive current contains kth harmonic field, the magnetic fields in the motor will be more complicated. In this case, besides the fundamental current I_1 whose frequency is f_1, the motor is also driven by another current I_k whose frequency is k times of f_1. When the current I_k goes through windings, it also produces its own fundamental field and harmonic fields. From (1), as the frequency of I_k is different from the I_1, the speed of the harmonic fields is also different from those produced by I_1. Rotational speeds of various harmonic fields are shown in Table I.

TABLE I
ROTATIONAL SPEED OF THE HARMONIC FIELDS

	Speed of the 1st harmonic	Speed of the 2nd harmonic	Speed of the 4rth harmonic	Speed of the 5th harmonic	Speed of the 7th harmonic	Speed of the 8rth harmonic
The 1st order current	n_s	$-n_s/2$	$n_s/4$	$-n_s/5$	$n_s/7$	$-n_s/8$
The 2nd order current	$-2n_s$	n_s	$-n_s/2$	$2n_s/5$	$-2n_s/7$	$n_s/4$
The 4th order current	$4n_s$	$-2n_s$	n_s	$-4n_s/5$	$4n_s/7$	$-n_s/2$
The 5th order current	$-5n_s$	$5n_s/2$	$-5n_s/4$	n_s	$-5n_s/7$	$5n_s/8$
The 7th order current	$7n_s$	$-7n_s/2$	$7n_s/4$	$-7n_s/5$	n_s	$-7n_s/8$

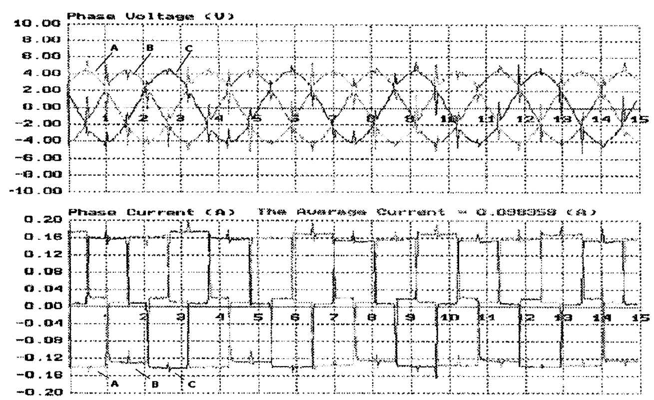

Fig. 3. Three-phase drive voltages and currents (constant-current BLDC drive mode).

IV. RELATIONSHIP BETWEEN THE FREQUENCY OF THE ACOUSTIC NOISE AND HARMONIC FIELDS

Constant current and constant voltage sensorless brushless dc (BLDC) drive modes are two major drive modes used in HDDs and other small PM synchronous (PMSM) drive systems. Using the constant current drive mode, the current in one phase winding is kept constant in its 120° exciting period. Using the constant voltage drive mode, the line voltage between two terminals is kept constant in the 120° exciting period. Figs. 3 and 4 show the waveforms of the three-phase voltages and three-phase currents generated by these two drive modes. These drive modes use the signals of back-emf in the three-phase windings to detect the rotor position and thus realize the accurate phase communication. These sensorless drive modes are important for the spindle motors used in HDDs as their space is too limited to install position sensors.

For the fields F_{s5-1} and F_{s7-1}, which are the fundamental harmonics produced by fifth- and seventh-order stator currents, their pole-pairs are same as F_{r1}, the fundamental field produced by permanent magnet of the rotor. Therefore, the reactions between these stator fields and rotor fields can produce torque. But, as their speeds in the space are different, from Section II, the torques produced by these fields are not constant, and therefore the torque ripples and acoustic noises are induced.

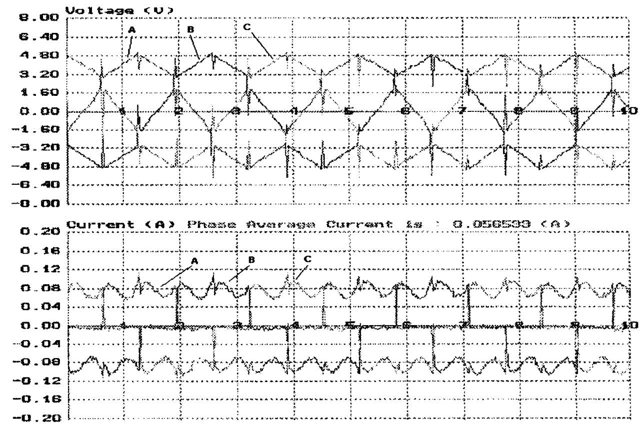

Fig. 4. Three-phase drive voltages and currents (constant-voltage BLDC drive mode).

F_{s5-1}, from Table I, rotates at five times the rotor speed and its direction is in opposition to that of the rotor. Therefore, $n_{r1/s5-1}$, the relative speed between F_{s5-1} and F_{r1}, is

$$n_{r1/s5-1} = n_s - (-5n_s) = 6n_s. \tag{11}$$

We can see that the frequency of the noise due to these two fields is six times the fundamental frequency, that is,

$$f_{r1s51} = 6f_s \tag{12}$$

where f_s is the frequency of the fundamental drive current.

The field F_{s7-1}, from Table I, rotates at seven times the rotor speed in the same direction. Therefore, $n_{r1/s7-1}$, the relative speed between F_{s7-1} and F_{r1}, is

$$n_{r1/s7-1} = |n_s - (7n_s)| = 6n_s. \tag{13}$$

In this case, the frequency of the noise due to these two fields is again six times of the fundamental frequency, that is,

$$f_{r1/s7-1} = 6f_s. \tag{14}$$

Using the same method of analysis, we can show that

$$f_{r2/s5-2} = 3f_s \tag{15}$$
$$f_{r2/s7-2} = 9f_s \tag{16}$$
$$f_{r4/s5-4} = 9f_s \tag{17}$$
$$f_{r5/s5-5} = 0 \tag{18}$$
$$f_{r5/s7-5} = 12f_s \cdots. \tag{19}$$

From the above analysis, we can conclude that a reduction in the current harmonics can reduce the acoustic noise at the frequency orders of 3, 6, 9, 12, 15, 18, and so on.

V. OPTIMAL CURRENT ANGLE AND IDENTITY SINUSOIDAL CURRENT

The EM torque in a PMSM can be described as

$$T_{em} = \frac{1}{2}[I_t]\frac{dL}{d\theta}[I_t]^T \tag{20}$$

where $[I_t]$ is the phase current matrix and L is the inductance matrix of the motor [10].

From (20), the EM torque performance is closely related with the current waveform, that is, change in the drive current waveform will change the average EM torque value and torque ripple. Another effect that must be considered is that change in the current will also change the copper loss in the armature windings.

It is well known that for a three-phase PMSM, if the back-emfs of its armature windings are sinusoidal and symmetric in the time domain, the use of symmetric sinusoidal drive current can reduce the torque ripple in the motor operation. However, for producing a required EM torque, many kinds of three-phase sinusoidal currents could be used which have different phase angle with the back-emf of the armature windings. It is clear that we can use only the currents that can reduce also, besides the torque ripple, the copper loss in the motor operation. The concept of "identity current" was developed from this consideration [10] which can determine the "optimal angle" of the current.

The spindle motor used in HDD is a surface-mounted PMSM. Its back-emf is sinusoidal. If we consider only the effects of the first-order component of the motor inductances, it can be proven that the "identity current" of this motor is sinusoidal, and the phase angle of the current is

$$\delta = \sin^{-1}\left(\frac{-T_{af1} + \sqrt{T_{af1}^2 + 8I_m^2(T_{aa1} + 2T_{ab1})^2}}{4I(T_{aa1} + 2T_{ab1})}\right) \tag{21}$$

where T_{af1}, T_{aa1}, and T_{ab1} are determined by the motor self-inductances and mutual-inductances [10]. I_m is the amplitude of the current. Using the current with the phase angle shown in (21), both the torque ripple and copper loss can be reduced.

In the following analysis, the sinusoidal current with the phase angle determined by (21) will be called the identity sinusoidal (IS) current.

VI. Test Results

A drive system, to verify the analysis given above, was built to drive the spindle motor in the IS mode and constant voltage BLDC mode. Fig. 5 shows an example of the IS current and the related voltage produced by the system. A PWM circuit is used in the system to adjust the current waveform, and the switching frequency of the PWM circuit is 20 kHz.

We used constant voltage BLDC drive mode and the IS drive mode to drive two FDB spindle motors, respectively, and measured the related acoustic noises generated in the motor operation. Figs. 6 and 7 show the acoustic noise test results for these two FDB motors. The corresponding frequencies at the dominated peaks are listed in Tables II–V.

For comparing the effects of FDB motors and the influences of the drive modes, BB spindle motors were also tested, and Fig. 8 shows the acoustic noise of a BB spindle motor driven by constant voltage BLDC dive mode and IS drive mode, separately. From the test results, it is difficult to recognize the influence of the different drive modes as the dominated noise of the BB motor is produced by the ball bearings.

Comparing Fig. 8 with Figs. 6 and 7, it is clear that FDB can reduce the acoustic noise significantly. From Figs. 6 and 7, changing the drive mode can change the acoustic noise of FDB spindle motor obviously. The influence of the drive modes can thus be recognized.

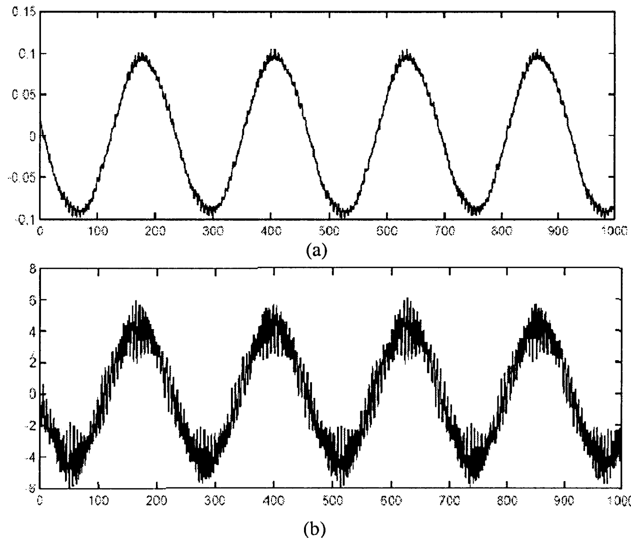

Fig. 5. Waveform of the IS drive current and voltage: (a) current (A) and (b) voltage (V).

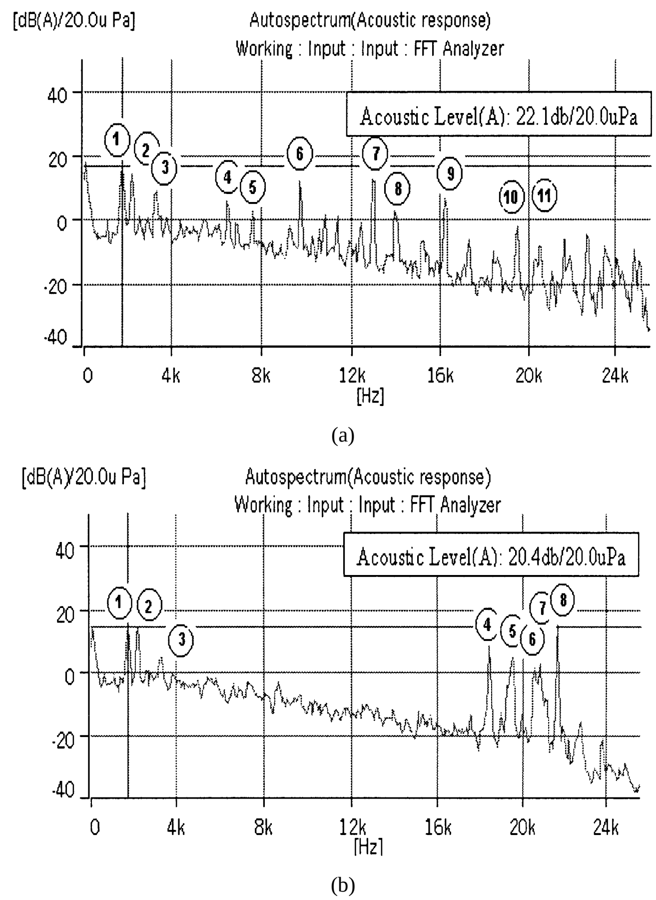

Fig. 6. Acoustic noises produced by Motor-A (12-poles/nine-slots) at speed 5400 rpm. (a) Constant voltage BLDC drive mode. (b) IS drive mode.

Though the FDB spindle motors used in the test are different in the slot number, pole number, and rated speed, by comparing the results shown in Fig. 6(a) with Figs. 6(b),7(a) with Fig. 7(b), Table II with Table III, and Table IV with Table V, we can form the following summaries.

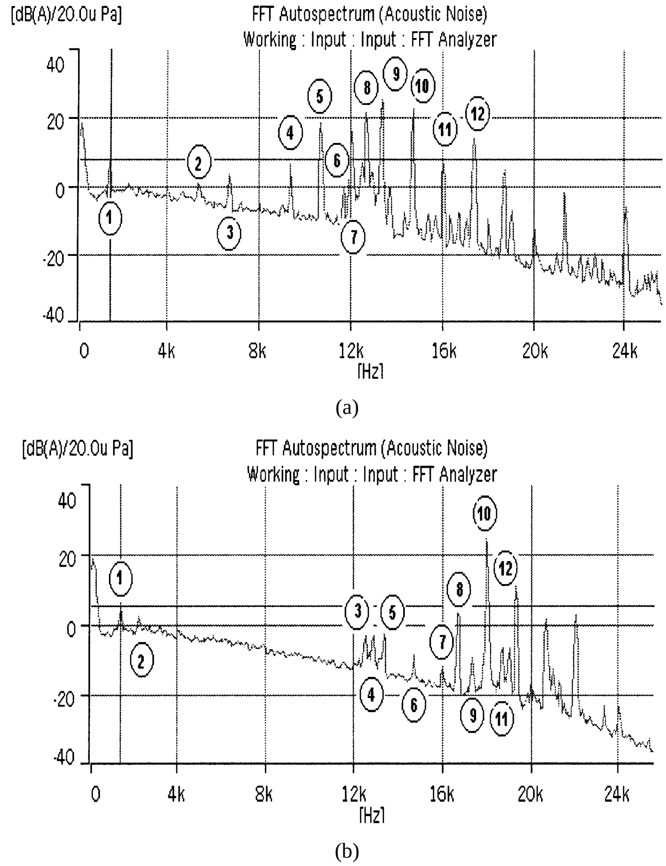

Fig. 7. Acoustic noises produced Motor-B (eight-poles/12-slots) at the speed 10 000 rpm. (a) Constant voltage BLDC drive mode and acoustic level (A): 29.8 db/20.0 μPa. (b) IS drive mode and acoustic level (A): 26.4 db/20.0 μPa.

TABLE II
FREQUENCY OF THE DOMINANT PEAKS IN FIG. 6(a)

Point	1	2	3	4	5
Frequency (kHz)	1.728	2.160	3.240	6.480	7.560
Frequency/f_s	3.2	4	6	12	14
Point	6	7	8	9	10
Frequency (kHz)	12.96	14.04	16.20	19.44	20.52
Frequency/f_s	24	26	30	36	38

TABLE III
FREQUENCY OF THE DOMINANT PEAKS IN FIG. 6(b)

Point	1	2	3	4
Frequency (kHz)	1.728	2.160	3.240	18.36
Frequency/f_s	3.2	4	6	34
Point	5	6	7	8
Frequency (kHz)	19.44	20.54	20.79	21.60
Frequency/f_s	36	38	38.5	40

1) Using the IS current, the acoustic noise harmonics at the orders 6, 9, 12, 15, 18 … can be reduced. This confirms the analysis in Section IV.
2) For some frequency points, e.g., $4f_s$ for motor-A and $2f_s$ for motor-B, the IS drive mode cannot reduce the related noise significantly. These acoustic noises are caused by

TABLE IV
FREQUENCY OF THE DOMINANT PEAKS IN FIG. 7(a)

Point	1	2	3	4	5
Frequency (kHz)	1.333	5.333	6.667	9.333	10.00
Frequency/f_s	2	8	10	14	15
Point	6	7	8	9	10
Frequency (kHz)	11.33	12.00	12.67	13.33	14.67
Frequency/f_s	17	18	19	20	22

TABLE V
FREQUENCY OF THE DOMINANT PEAKS IN FIG. 7(b)

Point	1	2	3	4
Frequency (kHz)	1.333	2.153	12.50	12.90
Frequency/f_s	2	3.23	18.75	19.35
Point	5	6	7	8
Frequency (kHz)	13.33	14.67	16.00	16.67
Frequency/f_s	20	22	24	25

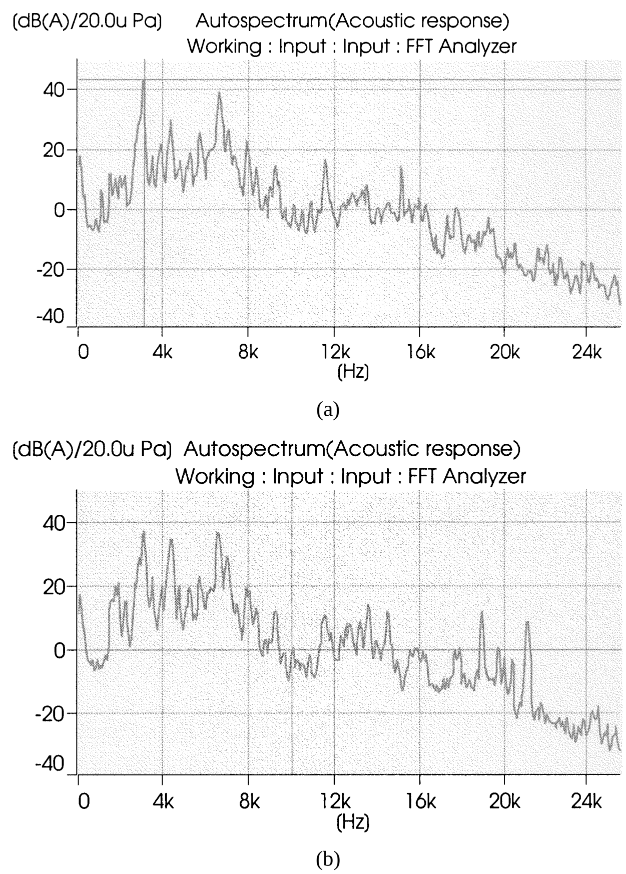

Fig. 8. Acoustic noises produced by the BB spindle motor (eight-poles/12-slots) at the speed 5400 rpm. (a) Constant voltage BLDC drive mode and acoustic level (A): 46.5 db/20.0 μPa. (b) IS drive mode and acoustic level (A): 44.9 db/20.0 μPa.

TABLE VI
COPPER LOSS OF THE MOTORS

Drive mode	BLDC (w)	IS (w)
Motor-A	0.048	0.041
Motor-B	0.22	0.151

the UMP, which is determined by the motor structure and the fundamental frequency of the drive current.

3) As PWM technology is used to produce the IS current, the acoustic noise is introduced at some frequency points around 20 kHz. The cause of this noise has been analyzed by many researchers [13]–[15]. We can move this noise to inaudible frequency range by setting a suitable switching frequency. Some other methods could also be effective in reducing the acoustic noise caused by the PWM circuit [13]–[16].
4) IS drive mode is also effective in reducing the average acoustic level.

Besides reducing the acoustic noise, using the IS current to drive the FDB motor can also reduce the copper loss of the motor. Table VI shows the copper loss of the Motor-A and Motor-B when they are driven by the BLDC mode and IS mode at the speeds shown in Figs. 6 and 7, separately.

VII. Conclusion

In this paper, the relationship between the harmonics of acoustic noise and harmonic fields is analyzed. As the acoustic noise of FDB spindle motors is sensitive to the EM forces, the use of the identity sinusoidal drive mode is an effective way to reduce it and the copper loss as well. The test results show the effectiveness of such a drive mode. As this is an electronic method which does not rely on the mechanical processing, the method is easily applied to the motors used in hard disk drives and other electronic products. The speed of spindle motors in HDDs is expected to increase further, 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.

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