Measure Rotational Inertia and Friction Torque of Spindle Motors with Freewheeling Operations

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Abstract—**A sensorless method is presented for measuring both the rotational inertia and friction torque of spindle motor through freewheeling operations. In the measurement, only the signals of terminal voltages are detected. For improving the accuracy of the speed data obtained by the sensorless method, the optimal spline method is used to process the discrete speed data. The method proposed can process the measurements quickly, and is easy to be applied in rotational system measurement. The principle of the method is introduced in the paper, and experiment results are used to show the effectiveness of the proposed measurement method.**

I. Introduction

Spindle motor is a key component in hard disk drives (HDD). Fig. 1 shows the typical structure of the motor. It is a 3-phase AC motor with surface mounted permanent magnet (PM) ring on the rotor. For saving the space taken by the winding ends, the fractional-slot concentrated winding with 120° winding pitch are used [1]. The stator core is laminated with 0.35 mm, or thinner, silicon steel sheets for reducing the iron loss of the motor. As the optimal technology is used in motor design and magnet magnetization, the back-emf induced in the motor stable operation contains very weak harmonics, see Fig. 2. The three phase windings are Y connected.

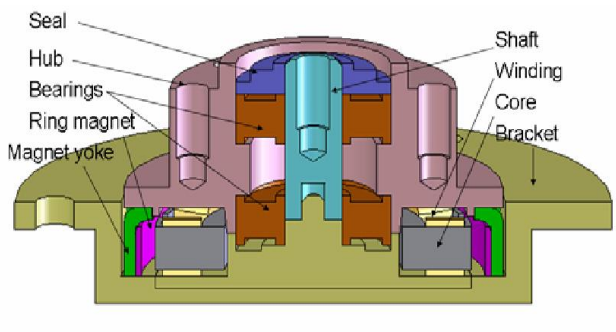

Fig. 1 The structure of spindle motor

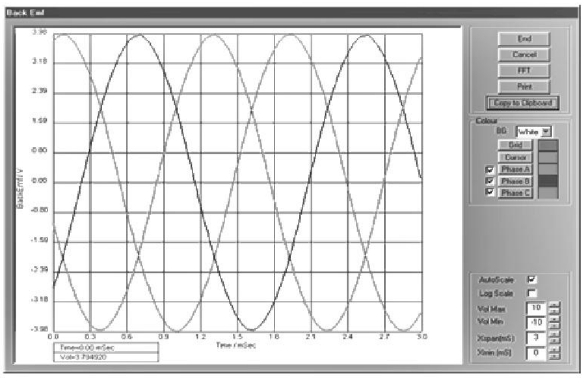

Fig. 2 The typical waveform of the back-emf generated in the armature windings of spindle motor

For realizing high efficiency and accurate speed control, the spindle motor used in HDD are driven by brushless DC (BLDC) mode. In the motor operation, at anytime, there is always one phase winding in silent state, and no current goes through the winding in this state. In the exciting state, the drive current is inputted into the circuit formed by the two phases windings connected serially. The drive current is applied after 30° from the zero-crossing positions (ZCPs) of phase back-EMF and lasts 120°, which is indicated as the exciting state in Fig. 3. By doing so, the effective electromagnetic (EM) torque can be maximum with respect to the same RMS current value. The ZCP signals of the back-emf can be used as a sensorless method to detect the rotor positions and rotor speed, and commutate winding current. Using this sensorless method, six rotor positions can be detected in one electrical cycle, see Fig. 3.

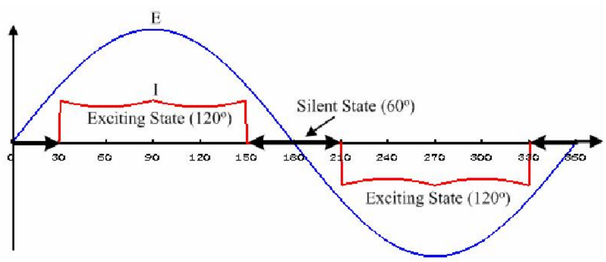

Fig. 3 Optimal status for the spindle motor driven in BLDC mode

Traditionally, the ball bearings (BB) are used in the spindle motors thanks to their low friction and capability in high speed rotation. In these years, for reducing the acoustic noise and non-repeatable-runout of the motor, fluid-dynamic bearing (FDB) has been used widely in the HDD spindle motors. In the FDB, the airgap between the rotational and stationary parts is very small (several microns), and is filled with a thin film of oil. BB and FDB are quite different in their mechanical performances.

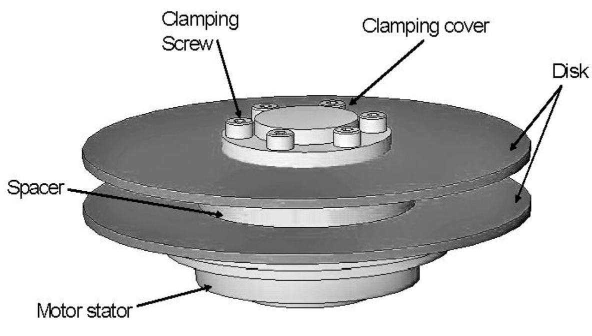

Fig. 4 The spindle motor installed with disks

The rotational system In HDD is quite complex. It is formed by the rotational parts of the motor, e.g., PM ring, rotor core and shell, and the external parts installed on the rotor, e.g. disks, spacers and the clamping parts; see Fig. 4.

In the motor operation, its mechanical loss is just the friction loss against the rotor rotation. The friction loss is formed by the windage loss of the rotational system, and the friction loss of bearing.

Therefore, knowing the rotational inertia and friction characteristic is very important to the cases like HDD production and research. In the hard disk assembly level, the inertia and friction can reflect the quality of HDD rotational system. In the motor component level, they can reflect the quality of the bearing, and also the quality of rotational system assembled.

In this paper, a method will be presented for measuring simultaneously both the rotational inertia and friction torque of the spindle motor. The method utilizes the EM characteristics of the spindle motor, and the performance of the motor in freewheeling operations, to realize accurate and fast measurements.

II. Losses In Freewheeling Operation

For the spindle motors shown in Fig. 1, as the surface mounted PM ring is used, the equivalent airgap of the motor is big. This makes the armature reaction be weak, and armature inductance be small. As the lamination stator core is used, the core loss is normally very small. The cogging torque of the motor is normally also very small as the fractional-slot concentrated armature windings and optimal motor design technology are used. Therefore, in the following analysis, the effects of armature reaction, the core loss and cogging torque of the motor will be neglected, and the back-emf generated is considered as sinusoidal one.

Based on above assumptions, there is no EM torque acting on the rotor in freewheeling rotation as there is no current in the armature windings in this status. In the operation, the kinetic energy of the rotor is consumed only by the friction torque acting on the rotor, and the movement of the motor in the freewheeling status can be described as

$$J\frac{d\omega(t)}{dt} = -T_0(\omega), \quad (1)$$

where, J is the rotational inertia of the rotational system, and it is a constant in the motor operation, i.e., it is independent to the motor operation state. $\omega(t)$ is the angular speed of the rotor and it varies with the time in the freewheeling operation. $T_0(\omega)$ is the torque caused by the friction losses of motor in freewheeling rotation. The negative sign on the right side of (1) means that the direction of $T_0(\omega)$ is opposite to the rotor rotation direction.

The friction torque $T_0(\omega)$ is non-linear to the motor speed. This torque can be considered as the sum of $T_f(\omega)$, the friction torque of the bearings, and $T_w(\omega)$, the torque caused by the windage loss , that is,

$$T_0(\omega) = T_f(\omega) + T_w(\omega). \quad (2)$$

It is clear, $T_f(\omega)$ and $T_w(\omega)$ are not related with the motor current. For the spindle motors used in HDDs, as their magnet are surface mounted on the rotor, and NdFeB permanent magnet is used, the airgap field is almost independent to the motor drive current. Therefore, the friction torque of the spindle motor can be considered as the one only related with motor speed and environment conditions, but being independent to the motor current.

All the items on the right site of (2) vary with speed changing. Their relationships with the rotor speed are quite complicated [1][3]. However, it can be assumed that they are all the monotone functions of the speed. That means, at a specific speed and with the same circumstance, $T_0(\omega)$ is identical. This assumption will be used in the following analysis.

In HDD production, all the components of the spindle motors must be made precisely, and the surface of the rotor must be processed smoothly. Therefore, in the motor component level, the major parts of $T_0(\omega)$ is taken by the friction torque of the bearing, especially to the motors with FDB and the motors used in small-form-factor HDDs.

If we know the value of J, and the acceleration of the rotor at time point t_1, the friction torque value at the time t_1 can be known by using (1). However, in many cases, as the problems in the motor assembly and component quality, J is a value to be determined accurately even if the geometric structure of the rotor is known. How to get the acceleration accurately is another issue, especially to the sensorless BLDC motors as only few rotor position can be detected in one rotor revolution (refer to the section-I). Therefore, for a requested time t_1 in the freewheeling operation, the values of J, $T_0(t_1)$ and $\omega'(t_1)$ are unknowns in (1). It is clear, using only the results obtained in freewheeling operation is not enough in calculating J and $T_o(t_1)$ even if the acceleration of the motor is known.

III. Measuring The rotational Inertia With Freewheeling Operations

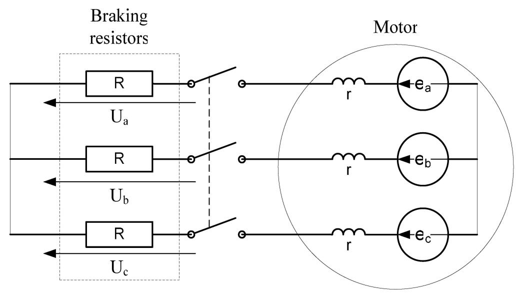

Fig. 5 The spindle motor with external electrical braking circuit

If the acceleration of the rotor in the required speed range has been known, from (1), the accuracy of the rotational inertia is critical to the accuracy of the friction calculated. As there are two unknowns, J and T_0, in the equation, besides (1), another equation must be built up for forming a set of nonsingular simultaneous equations. An additional operation which is in different operation state must be considered. In our research, this additional operation is realized by using an external electrical braking circuit. In this additional operation, the motor still operate in freewheeling state, but the armature winding terminals are connected with the external braking circuit which is formed by 3 resistors; see Fig. 5. In this operation, the back-emf of the windings generates currents in the close-loop circuits formed by the armature windings and external resistors. Therefore, besides the friction torques mentioned above, an additional braking torque, $T_b(\omega)$, is also generated, and the torque acts also on the rotor. The performance of $T_b(\omega)$ is similar to the friction torque $T_0(\omega)$, i.e., its direction is always opposite to the rotor rotational direction. The existence of $T_b(\omega)$ makes the motor performance be different from the original freewheeling operation, the motor operation can be described by the following equation,

$$J\frac{d\omega(t)}{dt}=-T_b(\omega)-T_0(\omega). \quad (3)$$

For simplifying the descriptions, in the following analysis, the freewheeling operation without the braking resistors will be called as freewheeling operation, and the one with the braking resistors will be called as braking operation.

It will be explained later that $T_b(\omega)$ is not difficult to be measured accurately in the braking operation. For a given speed Ω, rewrite and rearrange (1) and (3), the following simultaneous equations can be obtained,

$$\begin{cases} J\cdot\omega_f'(\Omega)+T_0(\Omega)=0 \\ J\cdot\omega_b'(\Omega)+T_0(\Omega)=-T_b(\Omega) \end{cases}, \quad (4)$$

where, ω_f' and ω_b' are the accelerations of the rotor in the freewheeling and braking operations, separately.

Solving (4) generates,

$$\begin{cases} J=\dfrac{T_b(\Omega)}{\omega_f'(\Omega)-\omega_b'(\Omega)} \\ T_0(\omega)=\dfrac{-\omega_f'(\Omega)\cdot T_b(\Omega)}{\omega_f'(\Omega)-\omega_b'(\Omega)} \end{cases}. \quad (5)$$

Therefore, in the whole measurement speed range, both J and T_0 can be calculated by using (5). However, as the solution at a speed point relies on the derivatives of speeds in the freewheeling and braking operations, the accuracies of these derivatives are critical in using (5). The local errors in ω_f'(Ω) and ω_b' (Ω) may affect seriously the accuracies of the J and T_0 obtained. We must find effective ways to attenuate the influence of the local errors in the accelerations.

Integrate both sides of J in (5) from Ω_0 to Ω and then rearrange the equation, it yields

$$J=\frac{1}{\Omega-\Omega_0}\int_{\Omega_0}^{\Omega}\frac{p_b(\omega)}{\omega[\omega_f'(\omega)-\omega_b'(\omega)]}d\omega. \quad (6)$$

Using (6) to calculate the inertia J, the major advantage is that, all the derivative values of the speed in a wide range can be used in the calculation. Therefore, the sensitivity to the local errors of the derivatives can be much reduced.

From (1) and (3), when J has been known, the following results can be derived,

$$\begin{cases} T_{01}(\omega)=-J\omega_f'(\omega) \\ T_{02}(\omega)=-J\omega_b'(\omega)-T_b(\omega) \end{cases}. \quad (7)$$

And the average value of $T_{01}(\omega)$ and $T_{02}(\omega)$ is used as the friction torque $T_0(\omega)$, that is

$$T_0(\omega)=\frac{T_{01}(\omega)+T_{01}(\omega)}{2}=-\frac{J[\omega_f'(\omega)+\omega_b'(\omega)]+T_b(\omega)}{2}. \quad (8)$$

Equations (6) to (8) supply an effective tool in calculating the values of the rotational inertia and the friction torque of motor in the required speed point. Using this method, only the voltages on the motor terminals are measured. The measurement procedure is thus simple and fast, and signals utilized can be obtained accurately.

IV. Speed Signal Measurement And Processing

It is clear, knowing the motor speed accurately is the precondition in utilizing (6) and (8) to calculate the inertia and friction torque. It was mentioned in the section-I, all the spindle motors used in HDDs are the 3-phase AC PM motor, and they are driven by sensorless BLDC mode. As no sensor is installed in the motor, only the back-emf generated in the armature windings can be used to detect the rotor position and speed.

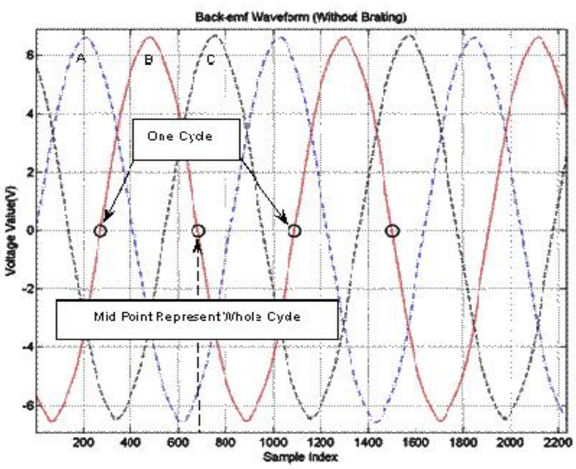

Fig. 6 The back-emf generated in the motor operation

Fig. 6 shows the back-emf generated in the spindle motor. For one phase winding, the ZCP number of the back-emf is equal to the pole number (p) of the PM ring. As the relative relationship between the rotor positions and ZCPs are fixed for a given spindle motor, the ZCPs can be used effectively in judging the rotor position. Therefore, for the 3-phase motor, the total positions detectable in one revolution (N) is

$$N = 3p. \qquad (9)$$

Using these rotor position signals, the motor speed can be calculated by

$$\omega(t_{i-}) = 4\pi/(t_{i+1} - t_i) \times p, \qquad (10)$$

where, t_i and t_{i+1} are the time of the ith and (i+1)th ZCPs, and t_{i-} is

$$t_{i-} = 0.5(t_{i-1} + t_i). \qquad (11)$$

Using equations (6) , (7) and (8) to calculate the inertia and friction torque, the accuracy of the acceleration is important. However, in the application of (10) to calculate the speed, as the ZCPs are discrete, the speed results obtained are also discrete. It is clear, this kind of speed results cannot be used directly in calculating the acceleration, i.e., the speed derivatives.

The ZCPs contain also errors and these errors could worse seriously the accuracy of the speed, say nothing of the acceleration. Theoretically, when all the ZCPs of the 3-phase back-emf are used, in the space domain, the interval between one pair of ZCPs is 60 electrical degrees, i.e., the signal is discrete. Moreover, as the quality issues in the PM ring, stator core and armature windings, and the EMI in the signal transferring, the accuracy of the ZCPs obtained may contain serious errors. Fig. 7 shows a typical speed curve obtained by using (10), (11) and ZCPs. The curve is quite rough.

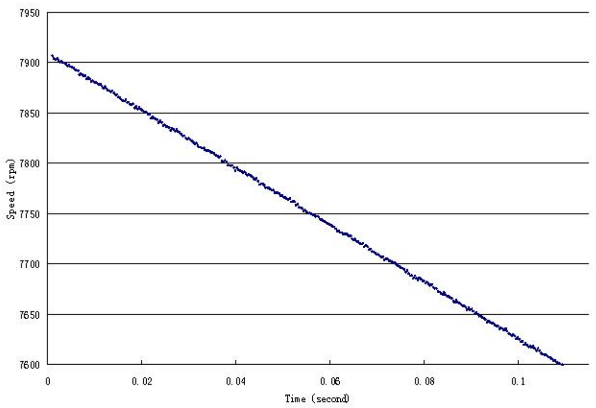

Fig. 7 The speed results obtained through ZCPs

The discrete values of the speed and the errors in the ZCPs make the accurate calculation for the accelerations be difficult. For solving these problems, [4] presented an effective method which is based on the optimal spline concept. Using this method, the discrete speed can be converted to a continuous one, and the effects of the errors in the speed detection can be much attenuated. The accuracy of the acceleration calculated can thus be much improved. This method is easy to be used in processing the transient signals like the dynamic speed signals of the spindle motors.

Using the optimal-spline method, in the data range $[x_{k-1}, x_k]$, the result of the processing can be expressed as

$$S_k = \sum_{i=0}^{N} A_{ki}(x, x_k, x_{k-1})v_i + B_k(x, x_k, x_{k-1})m_0 + C_k(x, x_k, x_{k-1})m_N, \qquad (12)$$

where, the functions of A_{ki}, B_{ki} and C_{ki} are cubic polynomial functions. The coefficients in these functions, and the coefficients v_i, m_0 and m_N are determined by solving a set of simultaneous equations, which is derived through a least-square processing related with whole test data range [4]. Using this method, the signal processed is C^2 smooth in whole data range, i.e., both the function and its 1st derivative are smooth in the whole data range [5]-[8].

The back-emf of motors is weak at the low speed. If the back-emf is too weak to be detected, the ZCP signals cannot be detected. Therefore, the sensorless speed sensing method based on the back-emf ZCP signal detecting is difficult to be used in the low speed range.

V. Electrical loss Measurement And Processing In The Braking Operation

From (6), the accuracy of the power loss p_b is important in calculating the rotational inertia. Neglecting the armature inductance and variation of the armature resistance, and refer the circuit shown in Fig. 5, $p_b(t)$ can be calculated with the following equation in the freewheel-braking operation,

$$p_b(t) = \frac{1}{r+R}\sum_{j=a,b,c} e_j^2(t) = \frac{r+R}{R^2}\sum_{j=a,b,c} U_j^2(t), \qquad (13)$$

where, R is the resistance of the braking resistor, and r is the sum of the resistance in the circuit loop, which includes the resistances of the armature winding and connecting cable. U_j is the voltage crossing the jth phase braking resistor. As it was mentioned in the section IV, the curve of $\omega_b(t)$ can be obtained in the breaking operation, $p_b(t)$ is not difficult to be converted to $p_b(\omega_b)$, and then can be used in (6).

In the breaking operation, as the speed of the motor varies from high speed to low speed, the frequency of the armature current also varies with time in the breaking operation, and this makes the resistance of armature windings vary with time in the breaking operation. The curve r(f) can be obtained before the freewheeling tests with LCR meter, and then be utilized to improve the accuracy of the $p_b(\omega_b)$ calculated. As the relationship between the motor speed and voltage frequency is fixed, r(f) is easy to be converted to $r(\omega_b)$.

As the voltage values $U_j(t)$ and resistor values can be obtained accurately, the major error of $p_b(\omega_b)$ is actually induced in the procedure converting p_b from time domain to speed domain. Therefore, the accuracy of the curve $\omega_b(t)$ is critical in the $p_b(\omega_b)$ calculation. This shows again that using the optimal spline to process the speed signal is important.

VI. Analysis Of experimental Results

The test results of two spindle motors are used for verifying the effectiveness of the method proposed. They are called Motor-B and Motor-F, respectively. Motor-B uses ball-bearings, and Motor-F uses FDB. In the measurement, the motors were driven to 6,600 rpm, and then switch off the drive circuit to let the motor operate at freewheeling and braking states, respectively. The speeds were detected by using the sensorless method based on ZCP signals, and processed by the optimal-spline method. Fig. 8 and Fig. 9 show the speeds of these two motors in the freewheeling and braking operations, respectively.

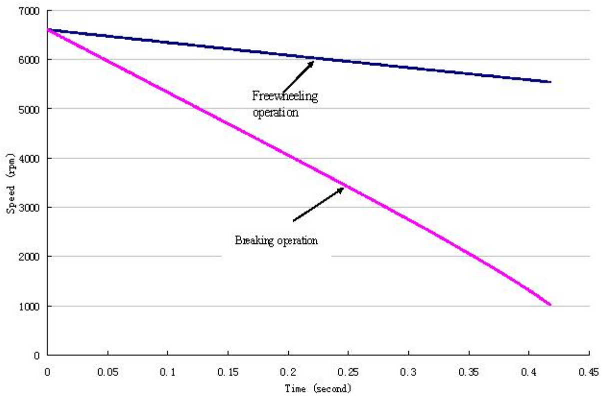

Fig. 8 The speeds of Motor-B detected by sensorless method (freewheeling and braking operations)

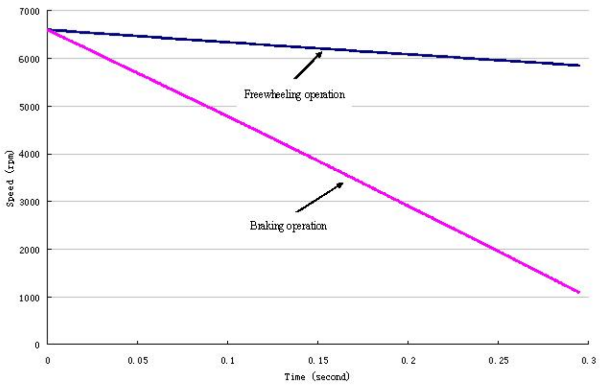

Fig. 9 The speeds of Motor-F detected by sensorless method (freewheeling and braking operations)

Based on the speed curves processed by the optimal spline method, the related accelerations were calculated; see Fig. 10 and Fig. 11. These results can also be converted to speed domain; see Fig. 12 and Fig. 13.

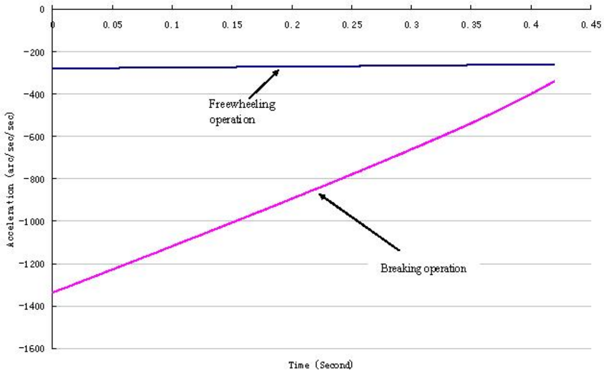

Fig. 10 The speeds and acceleration of Motor-B processed by the optimal spline method (freewheeling and braking operations)

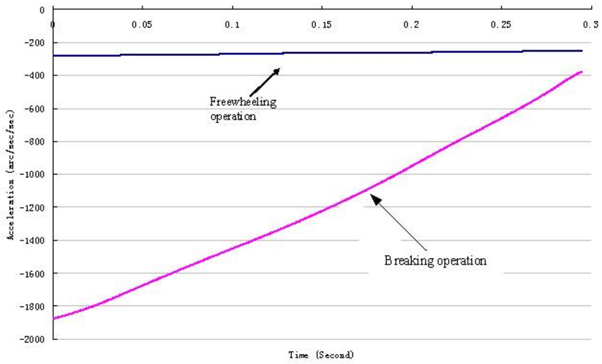

Fig. 11 The speeds and acceleration of Motor-F processed by the optimal spline method (freewheeling and braking operations)

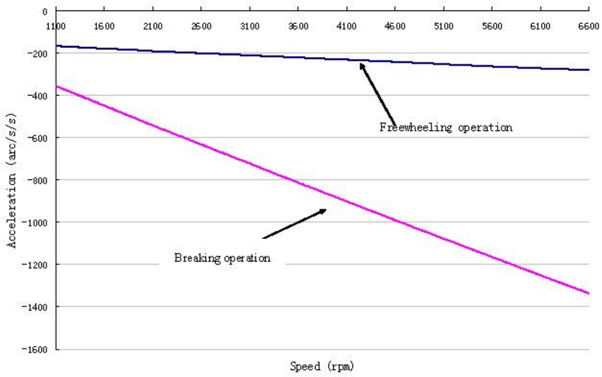

Fig. 12 The acceleration of Motor-B expressed in the speed domain (freewheeling and braking operations)

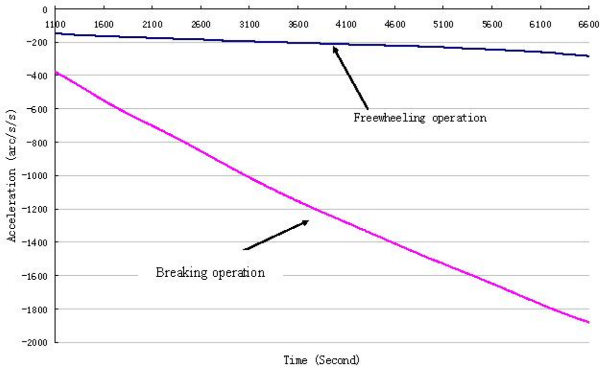

Fig. 13 The acceleration of Motor-F expressed in the speed domain (freewheeling and braking operations)

Using the method presented, the rotor rotational inertias and frictions of the motors were calculated, and the results are shown in Table-I and Fig. 14, respectively.

TABLE I
THE ROTATIONAL INERTIAS OF MOTOR-B AND MOTOR-F

Motor	Rotational Inertia*	Remarks
Motor-B	29.84	The clamping parts are installed on the motor
Motor-F	33.14	The clamping parts are installed on the motor

* The inertia includes the clamping components, see Fig. 4

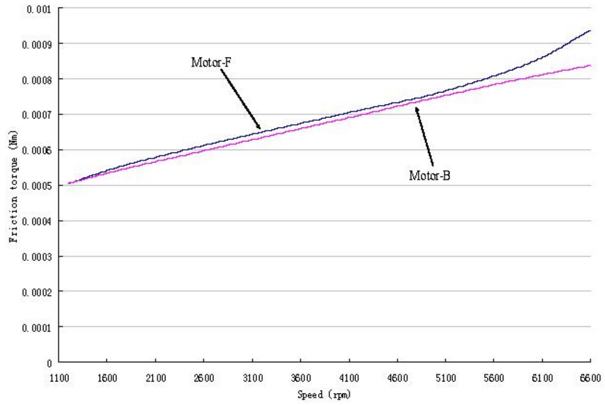

Fig. 14 The friction torque of Motor-B and Motor-F

For verifying the accuracy of the presented method, the spindle motors assembled with disks were also tested. Motor-F is assembled with one disk and Motor-B is assembled with two disks. These two kinds of disks have different thickness. However, as the shapes of the disks are regular, their inertias can be calculated accurately with the following equation,

$$J = \frac{W(D^2 + d^2)}{8}, \tag{14}$$

where, W is the weight of the disk, which can be measured accurately with precision balance. D is the outer diameter of the disk and d is the diameter of the inner hole of the disk, and both of them can be measured accurately.

TABLE II
THE RESULTS OF ROTATIONAL INERTIAS OF MOTOR-B AND MOTOR-F
(UNIT OF THE INERTIA: GCM^2)

Motor	Test result without disk*	Test result with disk*	Test result of disk	Inertia of the disk calculated	Δ(%)**
Motor-B	29.84	583.52	553.68	552.70	0.177
Motor-F	33.14	252.58	219.44	220.02	0.236

* The inertia includes the clamping components, see Fig. 4
** Difference in the disk inertias

Table II shows the measurement results of the rotational inertia of the disks obtained by the presented method, and the calculation results obtained by using (14). From the table, it can be found that the accuracy of the proposed method is good in measuring the rotational inertia of the rotational systems. These results prove the effectiveness of the proposed method from the point of rotational inertia measurement.

VII. CONCLUSION

In the paper, a method is presented for measuring the rotational inertia and friction torque of the spindle motor, which are very concerned in the spindle motor application. The measurement procedure is formed by two kinds of motor operations: freewheeling operation and braking operation. In the measurement, only the ZCP signals of the back-emf are used to detect the speed of motor, and the voltages on the external braking resistors are used to detect the additional electrical loss. For improving the accuracy of the speed data obtained and calculate the acceleration of the motor, the optimal spline method is used to process the discrete speed data. These make the measurement be accurate and quick, which is import in many applications, like the quality analysis of hard disk drive products. In the paper, the inertia measurement results of one spindle motor with ball bearing and one spindle motor with fluid dynamic bearing are used to show the effectiveness of the proposed method. In the motor component level test, the proposed method can measure quickly the rotational inertia of the rotor and friction torque of the bearing. In hard disk assembly level, the method can measure the inertia of whole rotational system, and the load of the motor. The proposed method is also easy to be extended to measure the rotational inertia and friction torque of other kinds of permanent-magnet AC motors, and analyze the performance of the bearings used in the motors.

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