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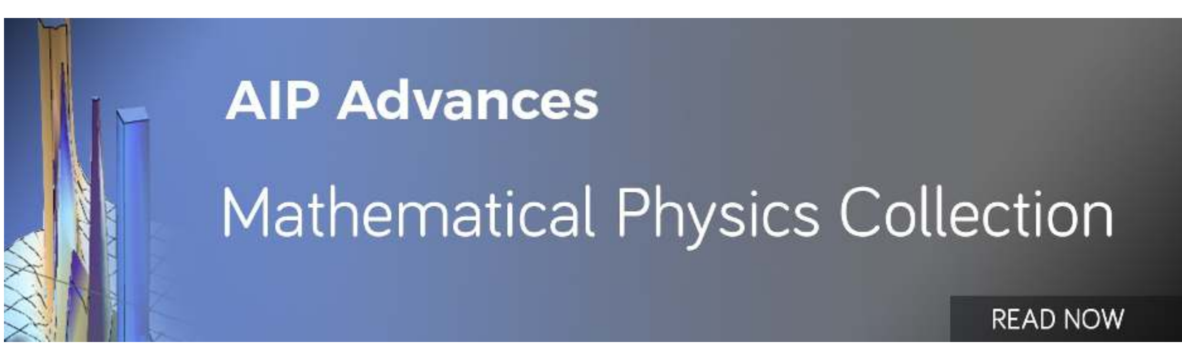

A giant magneto-inductive sensor for measuring high rotational speed of brushed and brushless direct-current motors

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ABSTRACT

There is a paucity of research on measurement of high rotational speed of direct-current motors using giant magneto-inductive sensors. In this work, measurements of high rotation-speed of brushed and brushless direct-current motors were realized by using a magneto-inductive sensing system. Successive square waves and sawtooth waves were observed when the rotation shafts of the motors pass by the giant magneto-inductive sensor. High rotational speed of 51000 r/min was accurately measured with a large distance of 9 cm between the giant magneto-inductive sensor and the rotation shafts, outputting a high voltage response of 5 V. The magneto-inductive sensing system displays a great potential application in ultrasensitive rotational speed measurements.

I. INTRODUCTION

Many kinds of physical sensors such as Hall sensors,[1,2] Magneto-resistance sensors,[3,4] Fiber Bragg Grating sensors,[5,6] Magnetoelectric sensors,[7,8] Laser sensors,[9,10] Capacitive sensors,[11,12] Eddy current sensors[13,14] have been used to measure the rotational speed of motors. Unfortunately, these conventional speed sensors generally have low sensitivity, which limits their applications in high-sensitive rotational speed measurements. However, giant magneto-inductive (GMI) sensors are particularly well suited for rotational speed measurements due to their quick response, good temperature stability, high resolution and high sensitivity.[15–29] So far, there have been few reports on the rotation velocity measurements based on GMI effect. To explore the application of GMI sensors in high-sensitive rotational speed measurements, a magneto-inductive sensing system was established to measure high rotational speed of brushed and brushless direct-current (DC) motors in this article.

II. EXPERIMENTAL DETAILS

Two DC motors were tested in this work, one of which is a brushed DC motor (GRS-550VF-8024) with a rated speed of 20000 r/min, operating voltage of 6-15 V and a no-load current of 1.6 A, as shown in Fig. 1(a). Another brushless motor (LEXY, KCL) is shown in Fig. 1(b), which has a rated velocity of 50000 r/min, a rated voltage of 21.6 V and a rated power of 300 W. The GMI sensor mainly consists of a GMI sensing element (soft ferromagnetic microwire) and input-output electric circuits, as shown in Fig. 1(c). The GMI sensor is based on giant magneto-inductive effect, as shown in Fig. 1(d): The sensor circuit provides high-frequency (several kHz) alternating-current pulses for exciting the soft ferromagnetic microwire. If using an external magnetic field on the microwire, its magneto-inductance will be greatly changed at several kHz. Then, the varied surface magnetic field of the microwire will have a great influence on the pick-up coil, and an electric potential difference can be found in the pick-up coil due to the electromagnetic induction, thus outputting voltage signals after analog-signal processing by the sensor circuit. The GMI sensor possesses high field-resolution of Nano-tesla, linearity range from -40 μT to +40 μT, and high field-sensitivity of 1V/μT. By restricting the cut-off frequency on the low frequency side to 0.1 Hz, the GMI sensor cancels static magnetic field such as the geomagnetic field, and responds to only moving ferrous objects with high sensitivity.

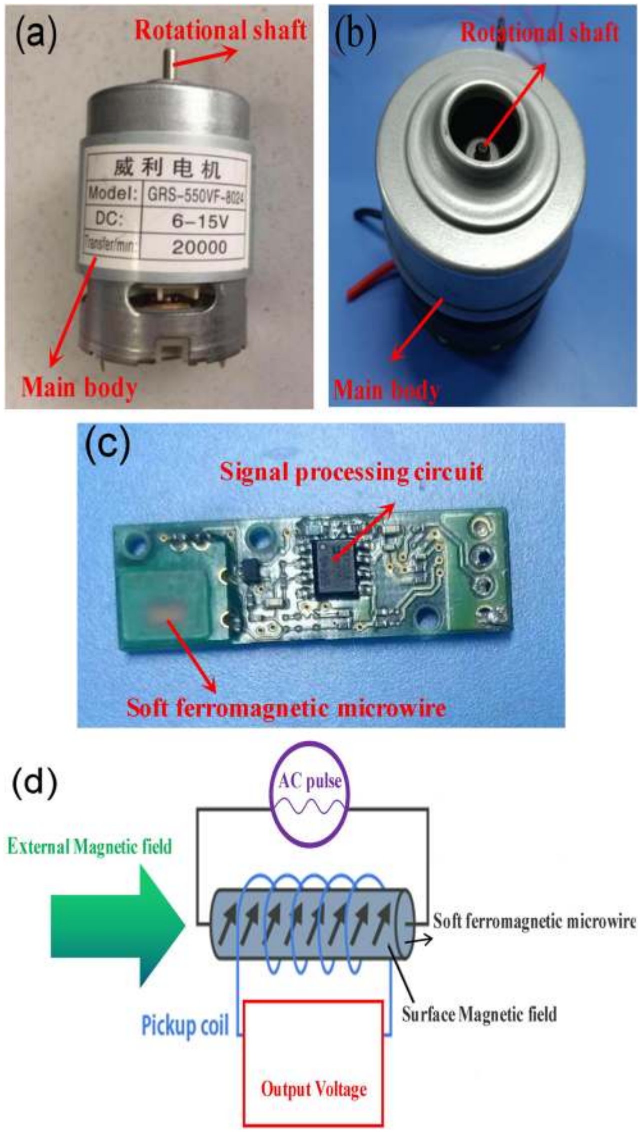

FIG. 1. Apparatuses and principle for measuring the rotational speed of DC motors (a) brushed DC motor (b) brushless DC motor (c) GMI sensor (d) operational principle of GMI sensor.

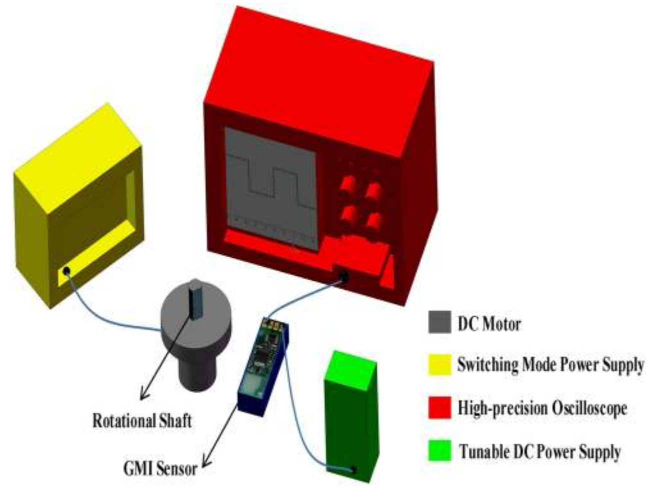

FIG. 2. The rotation-speed sensing system based on GMI effect.

The rotation-speed sensing system is mainly composed of a GMI sensor, a DC motor, a switching mode power supply (~27 V, ~17 A), a tunable DC power supply (~25 V) and a high-precision oscilloscope (MSO 5204), as shown in Fig. 2. The tunable DC power supply is connected with the GMI sensor. The switching mode power supply is connected with the DC motor. The DC motor is placed near the GMI sensor, the rotation shaft of which is about several centimeters away from the GMI sensor. The outlet port of the GMI sensor is connected with the oscilloscope.

Firstly, the brushed DC motor (GRS-550VF-8024) is tested with a separation of 2 cm away from the GMI sensor. During the test, the switching mode power supply provides a large current of 0-6 A for the DC motor, and the rotational speeds of which are controlled by regulating the current intensity of the DC power supply. The tunable DC power supply provides 5 V of excitation voltage for driving the GMI sensor in a field-sensitive range. The shaft of the brushed DC motor possesses a semi-circle structure, thus, each side of the shaft can produce two negative and positive magnetic poles. Therefore, it can be theoretically predicted that there may be two high voltage signals and two low voltage signals spinning around once due to the semi-circle structure of the shaft. Hence, calculation of the rotational speed of motors can be represented by equation (1), where N is the number of rotation-turns in one minute, Q is the number of the high voltages or high voltages in a time-span (T). When the ferromagnetic shaft passes by the GMI sensor, the impedance of which can be dynamically altered since the interference magnetic fields of the shaft modify the magnetic permittivity of the microwire. The impedance variation of the microwire would transform into the voltage signals through the analog-signal processing performed by the circuit on the sensor, and then outputting a time-dependent repeated waves on the oscilloscope after digital signal processing.

$$N = \frac{30Q}{T} \tag{1}$$

Secondly, the brushless DC motor (LEXY, KCL) is tested. The shaft of the brushless DC motor possesses a cylindrical structure, thus, there should be a pair of opposite magnetic poles induced by the magnetic field of the electrified coil in the motor. Therefore, it can be theoretically predicted that there may be one high voltage and one low voltage in a circle due to the two magnetic poles of the shaft. Hence, calculation of the rotational speed of brushless motor can be represented by equation (2), where N is the number of rotation-turns in one minute, Q is the number of high voltage or low voltage in a time-span (T).

$$N = \frac{60Q}{T} \tag{2}$$

Since the largest rated velocity of the DC motors is 50000 r/min, there should be 833.33 high voltages or low voltages captured by the

GMI sensor per second. Based on the sampling theorem,[30] original signal can be completely covered if the sampling frequency (f_s) is at least 2 times more than the maximal frequency (f_{max}) of the original signal [equation (3)]. Here, we set f_s = 10 kHz, which is about 10 times larger than f_{max} (833.33 signals/s), and enough to cover all

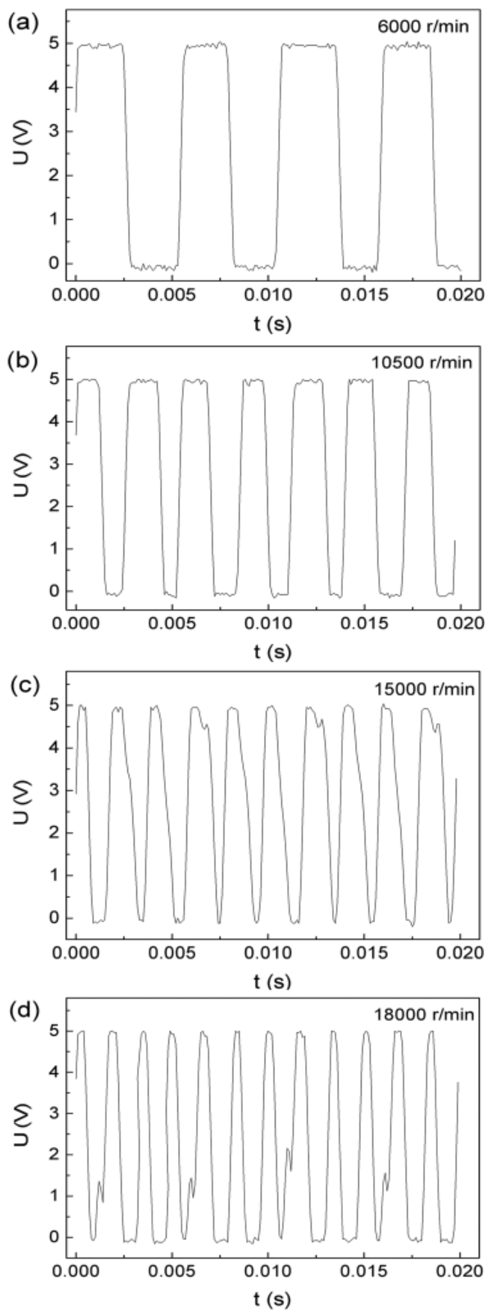

FIG. 3. The rotation-speed measurement results of DC motor (GRS-550VF-8024) below rated speed (20 000 r/min) with 2 cm space (a) 6000 r/min (b) 10 500 r/min (c) 15 000 r/min (d) 18 000 r/min.

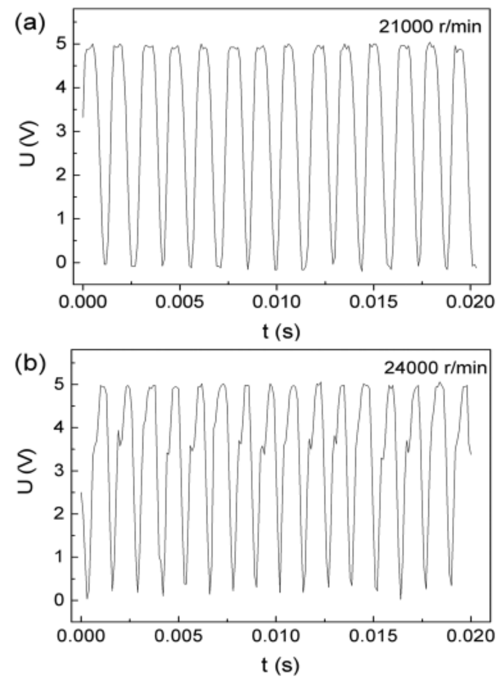

FIG. 4. The rotation-speed measurement results of DC motor (GRS-550VF-8024) over rated speed (20000 r/min) with 2 cm space (a) 21000 r/min (b) 24000 r/min.

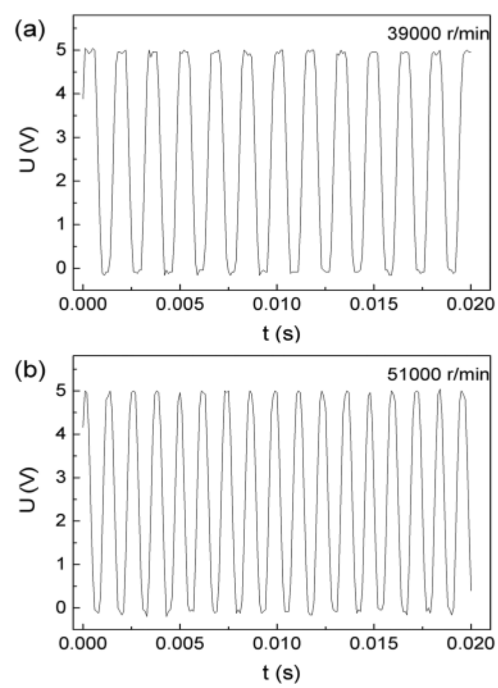

FIG. 5. High rotation-speed measurement results of the DC motor (LEXY, KCL) with 2 cm space (a) 39 000 r/min (b) 51 000 r/min.

the high voltage signals and low voltage signals.

$$f_s > 2f_{\max} \tag{3}$$

III. RESULTS AND DISCUSSION

The voltage responses caused by the rotation of the DC motor (GRS-550VF-8024) are shown in Fig. 3. There are successive square waves and sawtooth waves in Fig. 3, the more the wave crests and troughs, the quicker the motor rotates. We observed two high voltages when the two corners of shaft passed by the GMI sensor. On the other hand, two low voltages were found when the semi-circular center and plane center of the shaft passed by the GMI sensor. Since two high voltages or two low voltages represent one rotation circle, using equation (1), there are 12 high voltages from 0 s to 0.02 s in Fig. 3(d). So there are 300 circles in one second and 18 000 circles in one minute. It is noteworthy that the square waves gradually change into sawtooth waves with increasing the rotation speed.

We have tested the rotational speed of the DC motor (GRS-550VF-8024) over the rated velocity (>20 000 r/min), the results are shown in Fig. 4. For instance, there are 16 high voltages in 0.02 second in Fig. 4(b), using equation (1), the rotation shaft goes 24 000 rounds in one minute. As we tested the rotational speed without using any loadings on the motor, the unloaded rotational speed can be measured over the rated speed. When the rotational speed passes over 24 000 r/min, the rotational speed becomes unstable. Thus, the GMI sensor can accurately measure the unloaded rotational speed of reaching 24 000 r/min.

The results of testing high rotational speed of the brushless DC motor (LEXY, KCL) with a 2 cm space are shown in Fig. 5. There are 13 high voltages in 0.02 second in Fig. 5(a), using equation (2), so it's about 650 circles in one second and 39 000 circles in one minute. Likewise, there are 17 high voltages in 0.02 second in Fig. 5(b), so it's about 850 circles in one second and 51 000 circles in one minute, which is higher than the rated rotational speed of 50 000 r/min. Hence, the GMI sensor is able to measure the unloaded rotational speed of 51 000 r/min. As can be seen from Fig. 5(b), there are about 4.5 high voltages (sawtooth waves) from 0.000 to 0.005 s. Since one high voltage represents one rotation circle, the motor only spends 0.0012 s to go through one round, demonstrating the quick response of the GMI sensor. The sawtooth waves become more and more obvious with increasing rotational speed, which is similar to the results in Fig. 3.

9 cm space between the GMI sensor and the shaft was set for testing different rotation speeds, the results of which are shown in Fig. 6. Significantly, the number of sawtooth waves in Fig. 6 is accord with the previous results (Fig. 5). Furthermore, the voltage response amplitude of the GMI sensor is almost kept to 5 V even a large space of 9 cm is set, indicating the high sensitivity of the GMI sensor. Therefore, there is a great potential of GMI sensor in high-sensitive rotation-speed measurements.

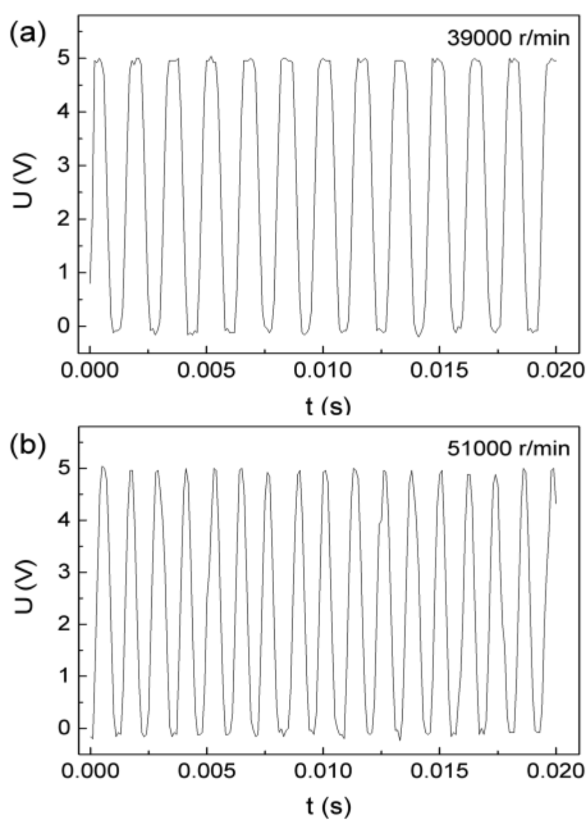

FIG. 6. High rotation-speed measurement results of the DC motor (LEXY, KCL) with 9 cm space (a) 39 000 r/min (b) 51 000 r/min.

IV. CONCLUSIONS

Accurate measurements of high rotational speed of brushed and brushless DC motors were achieved by using a magneto-inductive sensor. We observed successive square waves and sawtooth waves by rotating the rotational shafts, the quicker the shaft rotates, the narrower the time-dependent wave. There were 17 high voltages and 17 low voltages in 0.02 second when testing the high rotational speed of 51 000 r/min. A high voltage response of 5 V was found even setting a large distance of 9 cm between the GMI sensor and the rotational shaft, demonstrating the high sensitivity of the GMI sensor. The obtained results can provide guidance and direction for development of quick rotation-speed sensor based on GMI effect.

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