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Noise source identification of a BLDC motor

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Abstract

This paper proposes an analysis procedure of brushless DC(BLDC) motor noise. A systematic approach for identification of noise sources is suggested considering electromagnetic forces, structural and acoustic modes. It is proved by finite element analysis and experiments that the electromagnetic forces and the structural modes are not the major noise source since the noise characteristics are not closely related to the motor RPM. Acoustic modal analysis and tests reveal that the acoustic mode of the internal airspace of the motor is the major noise source.

Keywords: Acoustic mode; Structural mode; Structural frequency response function; Acoustic frequency response function; BLDC motor; Motor noise

1. Introduction

Acoustic noise characteristics are closely related to machine accuracy, failure, and environmental comfort of the workplace. Acoustic noises generated during motor operation in a mechanical system are from electromagnetic, mechanical, aerodynamic, and electrical sources. Therefore, a system scale approach is needed to identify noise mechanisms in electric motor-driven systems. For identification of mechanical noise sources, misalignment, unbalance, fan shape, resonance, and vibration modes have been extensively considered to describe noise behavior[1-6]. Reduction of noise by considering electromagnetic sources has been also actively studied in many research works[7-12].

Due to the various noise sources in electric motors, the motor noise characteristics differ from type to type. Therefore, an experiment-based approach needs to be adopted for a realistic study into noise and vibration. Noise sources can be classified into two major categories: mechanical and electromagnetic sources.

Mechanical sources such as rotor eccentricity, bearing, unbalance, and fan geometry have been constantly reduced with advanced machining and manufacturing technologies. The other noise sources can be further divided as in Fig. 1.

For the test motor in this paper, experimental results reveal that the noise problem observed with a fan still remains even without the fan. Analysis of motor noise measured at different RPM shows a possibility that the motor noise is from a mechanical rather than electromagnetic source. Experimental results confirm that acoustic resonance is more dominant than structural resonance.

2. Noise test setup and results

A 0.5 HP outer rotor BLDC motor for an air-conditioner fan is chosen and analyzed for noise source identification in this paper; the specifications of the motor and inverter are listed in Table 1. To investigate acoustic noise characteristics, acoustic noise is measured at different motor RPM with the test setup as shown in Fig. 2. The test motor is mounted on a vibration isolation plate and tested with

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fan and without fan. For the measurement of noise, a microphone is placed vertically 1m away from the motor. The motor RPM is obtained from the motor hall sensor signal. Measured noise data are gathered from the test setup as in Fig. 2 and analyzed by Matlab or directly by FFT analyzer. The 1/3 octave band and narrow band are used for signal analysis. For 1/3 octave band analysis, A-weighting, Hanning window, and microphone sensitivity of 1.241 μPa/20mV are used. For narrow band analysis, frequency resolution of 1Hz, frequency motor range from 0 to 6.4 kHz, and a linear average of 500 times are used while weighting and microphone sensitivity are the same as in the 1/3 octave band analysis.

The 1/3 octave band analysis of motor noise without fan is shown in Fig. 3 indicating the fan effect on noise characteristics at 300 RPM. It should be noted that the two peaks occur near 650 Hz and 16 kHz regardless of presence of the fan. It seems that the noise at 16 kHz is from the drive switching frequency.

Table 1. Specifications of BLDC motor and inverter.

Motor	Motor type	3 sensor type outer rotor BLDC
	Input voltage [V_{DC}]	310
	Connection	3-phase WYE
	Number of poles/slots	32/24
	Resistance of phase coil [Ω]	20
	Size of motor[mm^3]	Φ146 X L40
Inverter	Inverter type	6 step system
	Control voltage [V_{DC}]	15
	Control scheme	PWM (180˚Conduction)
	Drive Oscillator [MHz]	4
	Switching frequency [kHz]	16

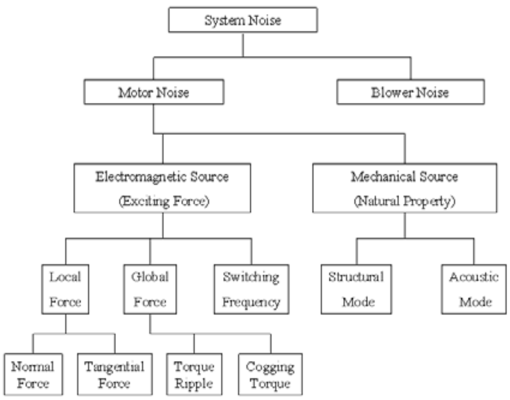

Fig. 1. Noise of system & motor.

To confirm the noise component at 16 kHz, the switching frequency effects on noise are analyzed by experiments. Noise at 16 kHz turns out to be from the switching since a noise decrease at 16 kHz is observed when the motor is driven at 300 RPM with switching frequency of 20 kHz as shown in Fig. 4. Increasing switching frequency can also effectively reduce the overall noise level. However, this inevitably causes cost rise.

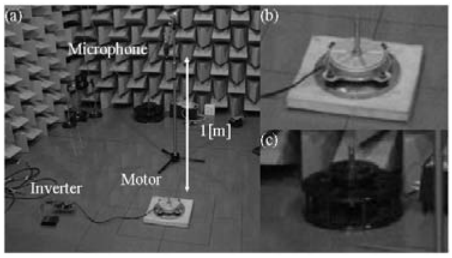

Fig. 2. Photograph of acoustic noise test setup ; (a) Anechoic chamber, (b) Test motor, (c) Fan.

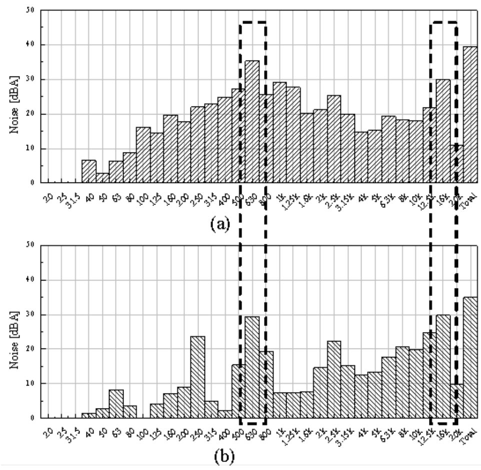

Fig. 3. 1/3 octave band noise spectra at 300 RPM ; (a) With fan, (b) Without fan.

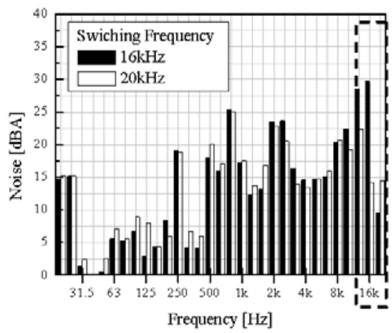

Fig. 4. Switching frequency effects on motor noise.

3. Electromagnetic sources

Due to the variation of airgap length, electromagnetic forces acting between the stator and rotor vary with respect to the rotor angular position. This unbalanced force, affected by the electromagnetic sources, is transmitted to the motor frame causing propagation of vibration. Harmonic components of electromagnetic forces must be analyzed since the electromagnetic forces are often found to be the major noise and vibration source in many cases.

Electromagnetic sources are divided into local and global forces. The local force is affected by the magneto-motive force and the airgap permeance. For a 3-phase BLDC motor, frequency components of local forces such as normal and tangential forces, and global forces such as torque ripple and cogging torque, can be expressed as in (1-3)[13].

$$f_{lf} = n \bullet p \bullet \frac{N}{60} \tag{1}$$

$$f_{tr} = 6n \bullet \frac{p}{2} \bullet \frac{N}{60} \tag{2}$$

$$f_{ct} = n \bullet lcm \bullet \frac{N}{60} \tag{3}$$

Frequency decomposition of the global and local forces, calculated by 2D FEM and the Maxwell method, is performed to analyze the force harmonics. Fig. 5 shows the electromagnetic analysis results which display flux lines and flux density distribution of the test motor at different rotor position. The local forces at A and B are analyzed with respect to the rotor angular position as shown in Fig. 7. It can be seen in Fig. 6 and 7 that the 32nd and the 96th harmonic orders are local force and global forces, respectively. However, the noise characteristics shown in Fig. 8 indicate that the noise emission near 650 Hz is not much affected by the electromagnetic forces since the frequency components of electromagnetic forces are proportional to the motor RPM. These results imply that the noise source is from mechanical or acoustic resonance.

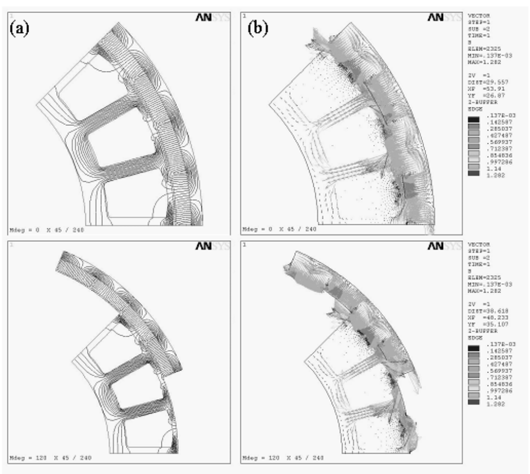

Fig. 5. Electromagnetic analysis using 2D FEM ; (a) Flux line, (b) Flux density.

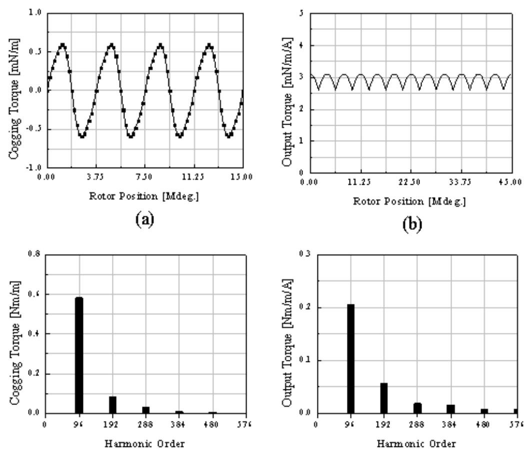

Fig. 6. Global force & harmonics ; (a) Cogging torque, (b) Output torque.

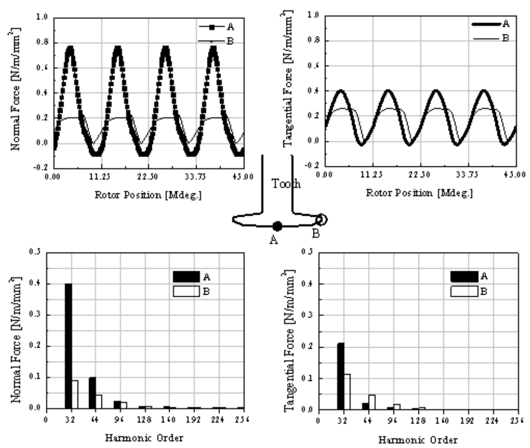

Fig. 7. Local force & harmonics ; (a) Normal force (b) Tangential force.

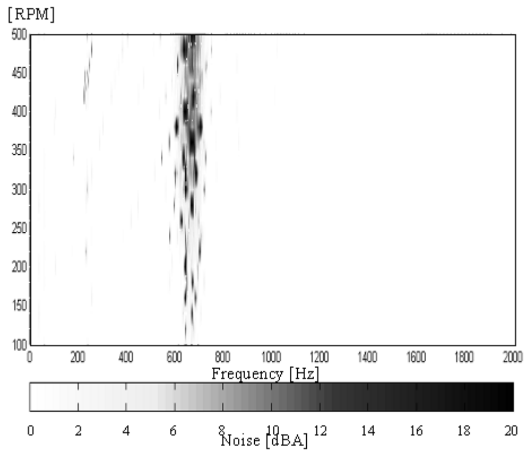

Fig. 8. Noise spectra vs. RPM without fan.

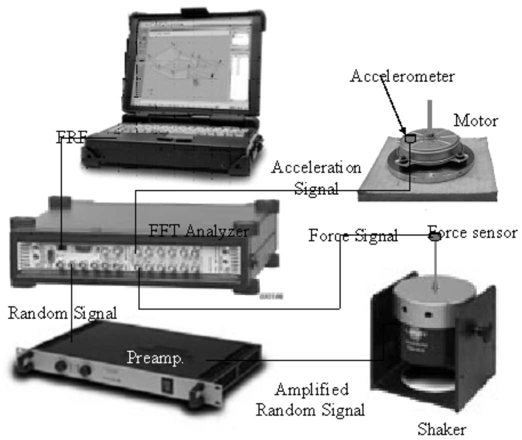

Fig. 9. Photograph of structural modal test setup.

4. Structural modal test

Vibration generated in an electric motor is often from its structure. The motor structure has many resonant frequencies. When one of the frequencies of the excitation forces coincides with the structural or acoustic resonant frequency, resonance occurs resulting in excessive acoustic noise. When the frequency components of the noise are proportional to the motor RPM, noise emission is related to electromagnetic excitation forces. However, when the frequency components of the noise are not related to the motor RPM, noise phenomena are related to structural or acoustic mode.

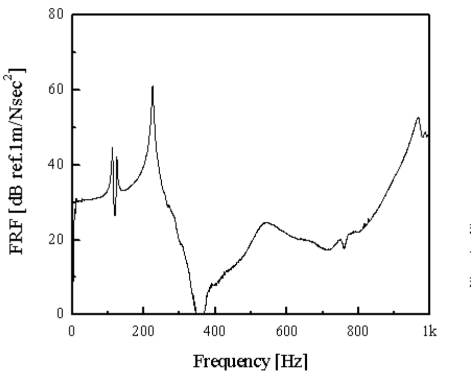

Fig. 10. Structural frequency response function.

A structural modal test was performed by random excitation with a shaker to examine the structural frequency response of the motor and its test setup is shown in Fig. 9. The frequency response function of the motor is shown in Fig. 10, where no resonance is observed near 650 Hz. Therefore, the noise component of 650 Hz seems not to be related to the mechanical resonance.

5. Acoustic modal test and simulation

To examine the acoustic characteristics of the motor internal airspace, white noise excitation by a horn driver is applied to the motor at standstill through a 25 mm diameter hole introduced on the rotor frame, and the noise is measured by a microphone as shown in Fig. 11.

The acoustic frequency response function is shown in Fig. 12 where acoustic resonance is observed near 650Hz. In many cases, noise independent of the motor RPM can be regarded as structural resonance. However, for the test motor, acoustic resonance seems to be more dominant than structural resonance. To confirm the existence of acoustic resonance near 650Hz, acoustic mode analysis is performed with commercial FEM software Sysnoise to consider complexity of the motor internal geometry.[14,15] The internal airspace of the motor is modeled by using 39,288 elements and 29,088 nodes as shown Fig. 13. For better recognition of geometry, 1/2 and 1/4 symmetry models are additionally shown and the analysis results are listed in Table 2; the first acoustic resonance occurs at 658.4Hz, confirming that the motor noise near 650Hz originates from the acoustic resonance. The first acoustic mode shape is shown in

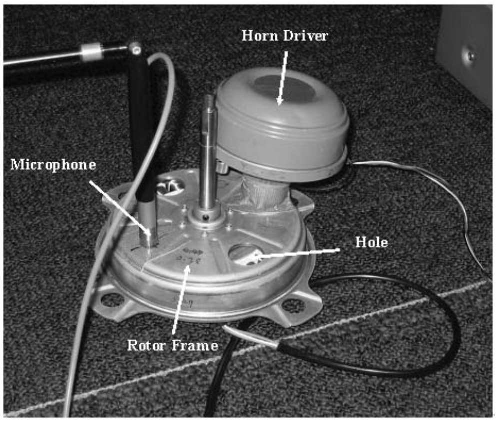

Fig. 11. Photograph of acoustic modal test setup.

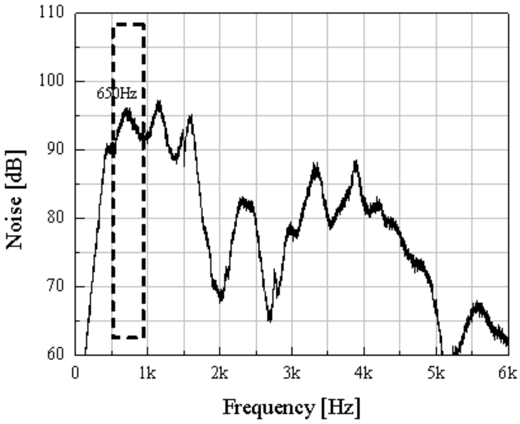

Fig. 12. Acoustic frequency response function.

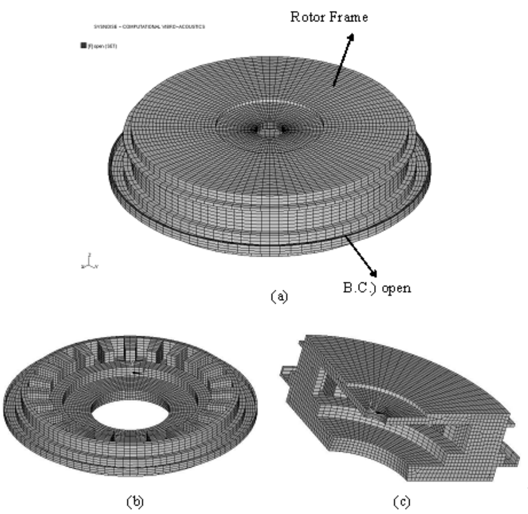

Fig. 13. 3-D modeling for FEA; (a) Full model, (b) 1/2 model, (3) 1/4 model.

Table 2. Analysis results of acoustic resonant frequency.

Acoustic mode	1	2	3	4	5
Resonant frequency [Hz]	658.4	1243.3	1243.3	2033.9	2033.9

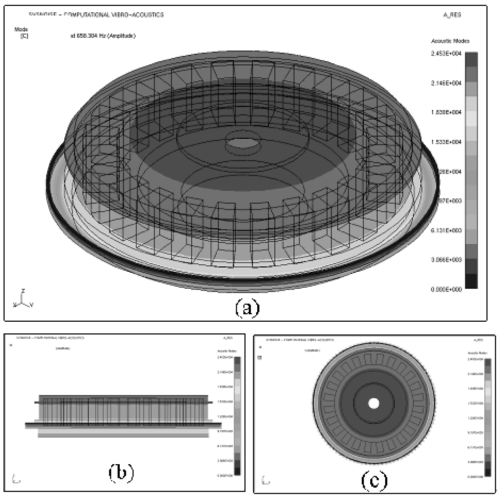

Fig. 14. 1st acoustic mode shape; (a) Iso. view, (b) Top view, (c) Front view.

Fig. 14.

6. Conclusion

For identification of BLDC motor noise, this paper proposes a systematic procedure that considers the electromagnetic forces, the structural and the acoustic modes both by analysis and experiments.

The analysis and experiments reveal the noise source is not from the electromagnetic forces and the structural modes but from the acoustic modes of the motor internal airspace. The acoustic modes as a noise source of electric motors can be regarded as quite rare. However, the proposed procedure considering the acoustic mode can be available for noise source identification, which is hard to do with the conventional mechanical and electromagnetic approaches.

Nomenclature

f_{ct} : Frequency of cogging torque (Hz)
f_{lf} : Frequency of local forces such as normal and tangential forces (Hz)
f_{tr} : Frequency of torque ripple (Hz)
n : Arbitrary integer

p : Number of poles
N : Motor RPM (rev/min)
lcm : Least Common Multiple of corresponding elements of poles and slots

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