Electromagnetic Vibration Analysis of a Magnetic Gear Employing the 3-D Finite Element Method

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Abstract — This paper describes the electromagnetic vibration of a magnetic gear. The sources of the electromagnetic vibration are shown, and the components contained in the vibration are theoretically described. The components observed in the cogging torque are verified by employing 3-D finite element method and carrying out measurements on a prototype, and those which are not observed in the cogging torque are verified by employing coupled analysis between electromagnetic and structural analysis. Lastly, these results are also verified through measurements of the sound pressure.

I. INTRODUCTION

Magnetic gears have some advantages such as low mechanical loss and maintenance-free operation that are not observed in mechanical gears. In addition, magnetic gears have an inherent overload protection. Therefore, a variety of magnetic gears have been proposed, but few studies are focused on the electromagnetic vibration of the magnetic gear [1]-[3].

During practical use, quiet operation is required from the magnetic gear. This paper describes the electromagnetic vibration of the magnetic gear. The sources of the electromagnetic vibration are shown, and the components contained in the vibration are theoretically described [4]-[6]. The vibration is mainly due to the electromagnetic forces whose components are observed or not observed in the cogging torque. The components observed in the cogging torque are verified by employing 3-D finite element method (FEM) and carrying out measurements on a prototype. Those which are not observed in the cogging torque are verified by employing coupled analysis between electromagnetic and structural analysis. Lastly, these results are also verified through measurements of the sound pressure.

II. MAGNETIC GEAR

The magnetic gear used in this study is shown in Fig. 1. This gear has to satisfy (1) to operate as a reduction gear.

$$(2l-1)N_s = N_l \pm (2m-1)N_h \tag{1}$$

where N_h and N_l is the number of pole pairs in the high-speed and low-speed rotors, respectively, N_s is the number of the stationary pole pieces, l and m are positive integers. In this study, N_h = 4, N_l = 10, and N_s = 14 is employed. The gear ratio G_r = –2.5 is obtained from (2).

$$G_r = \mp \frac{(2m-1)N_h}{N_l} \tag{2}$$

where the minus sign shows that the low-speed rotor rotates in the opposite direction of the high-speed rotor.

III. ANALYSIS METHOD AND CONDITION

The noise is mainly generated from the electromagnetic vibration of the low-speed rotor if sound echo is ignored.

The cogging torque of the low-speed rotor is calculated by employing 3-D FEM. The A method is employed:

$$\mathrm{rot}(\nu\,\mathrm{rot}\,\boldsymbol{A}) = \nu_0 \mathrm{rot}\,\boldsymbol{M} \tag{3}$$

where ν and ν_0 are the reluctivity of magnetic material and vacuum, respectively, $\boldsymbol{M}$ is the magnetization.

The components of the vibration which are not observed in the cogging torque are calculated according to the flow chart shown in Fig. 2. The resonant frequency is calculated by employing modal analysis:

$$[M]\{\ddot{u}\} + [K]\{u\} = 0 \tag{4}$$

where $[M]$ is the mass matrix, $[K]$ is the stiffness matrix, $\{u\}$ is the displacement.

The deformation mode of the low-speed rotor is calculated by employing modal frequency response analysis:

$$\left(-\omega^2[M] + [K]\right)\{u\} = \{F\} \tag{5}$$

where ω is the frequency, F is the electromagnetic force.

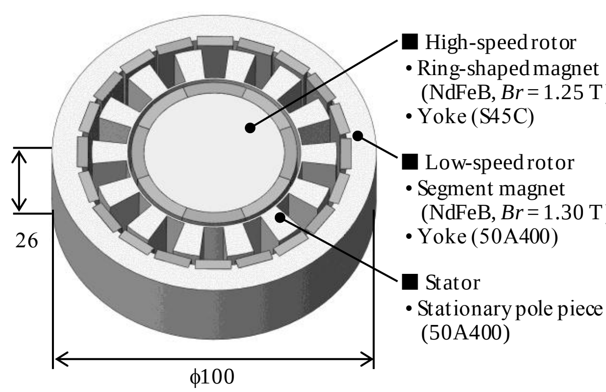

Fig. 1. Magnetic harmonic gear in this study.

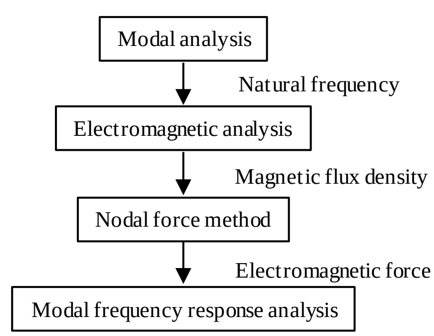

Fig. 2. Procedure of the coupled analysis.

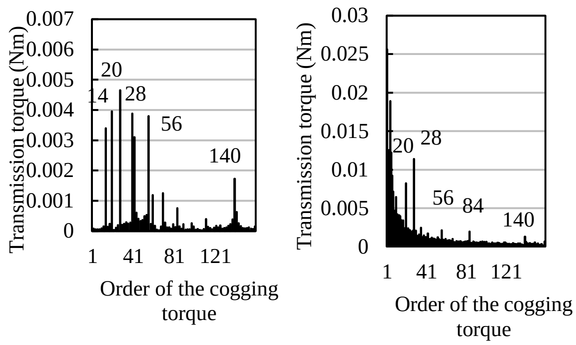

Fig. 3. (a) Computed cogging torque, and (b) measured cogging torque.

TABLE I
FUNDAMENTAL DEFORMATION MODE AND FREQUENCY

	Stator	4th component of the magnetic flux	18th component of the magnetic flux
Fundamental deformation mode	2nd	2nd	4th
Rotation speed (Hz)	1.6×20	5.6×6	5.6×9×4/18
Fundamental frequency (Hz)	64	67.2	44.8

IV. ELECTROMAGNETIC VIBRATION SOURCES

A. Cogging torque

The cogging torque of the low-speed rotor is generated by the stator, 4th and 18th magnetic flux around the stator.

The components in the computed and measured cogging torque of the low-speed rotor are shown in Fig. 3.

B. Electromagnetic Vibration Mode

According to the results of the modal analysis, this magnetic gear has the 1st deformation mode at 1972 Hz. Therefore, a rotation speed of 5.6 Hz is given to the high-speed rotor, and 1.6 Hz is given to the stator because the low-speed rotor has to be fixed.

1 period of the nodal force is mapped on the new node, and the modal frequency response analysis is conducted. The fundamental deformation mode of the low-speed rotor due to the stator, 4th and 18th components of the magnetic flux around the stator, its rotation speed, and its fundamental frequency are shown in Table I. Therefore, in order to compute the deformation due to the stator, the modal frequency response analysis has to be conducted at a frequency of a multiple of 64 Hz. The deformations due to the 4th and 18th components of the magnetic flux are computed at a frequency of a multiple of 67.2 Hz and 44.8 Hz, as well, respectively. In this study, the modal frequency response analysis is conducted at a frequency of less than 250 Hz.

The deformation mode at 64 Hz is shown in Fig. 4, the 2nd deformation mode is clearly observed. Furthermore, the frequencies due to the components that are observed in the cogging torque were also observed.

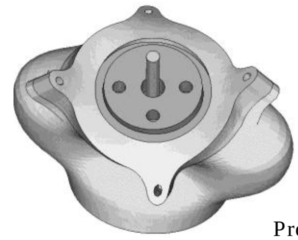

Fig. 4. Deformation mode.

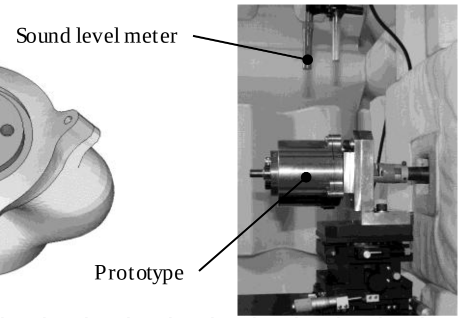

Fig. 5. Sound measuring system.

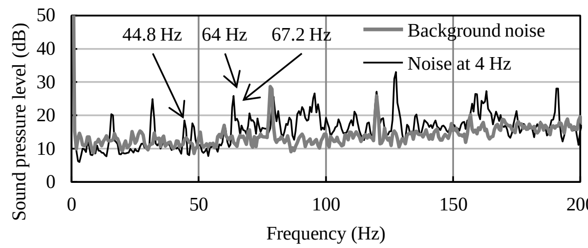

Fig. 6. Measured sound pressure level.

V. VERIFICATION BY THE SOUND MEASUREMENTS

In order to verify the electromagnetic vibration, the noise was measured when the high-speed rotor was rotating at 4 Hz, and the low-speed rotor rotates at 1.6 Hz. Figs. 5 and 6 show the measuring system and measured sound pressure level, respectively.

As shown in Fig. 6, the fundamental frequencies shown in Table I were observed.

VI. CONCLUSION

The sources of the electromagnetic vibration were clarified by 3-D electromagnetic analysis and the usefulness of electromagnetic vibration mode analysis, in which the electromagnetic field analysis was coupled with the modal frequency response analysis, was verified through the measurements on a prototype.

VII. REFERENCES

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