Basic Characteristics of In-Wheel Magnetic-Geared Motors

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This paper presents a feasibility study of an in-wheel magnetic-geared motor for walking support machines. The proposed magnetic-geared motor consists of an axial-gap permanent magnet (PM) motor and a magnetic gear. Axial-gap PM motors generally have larger torque than conventional radial-gap motors when their structures are flat like those in in-wheel motors. Moreover, the axial-gap PM motor was combined with magnetic gears since the in-wheel motor requires further large torque at low speed. The characteristics and usefulness of the proposed magnetic-geared motor are demonstrated through experiments and analysis conducted using finite element method (FEM).

Key words: magnetic-geared motor, in-wheel, axial-gap, walking support machines

1. Introduction

In Japan, aging population and lower birthrate are rapidly progressing in comparison with other developed countries. According to "Population Projections for Japan" published by National Institute of Population and Social Security Research ¹⁾, it is expected that total population of our country will decrease, while elderly age population (65 years or older) will increase. The ratio of the elderly age population will be more than 35% after approximately 40 years. This means that one third or more will be over 65 years old in the near future. Therefore, it is one of the important tasks of our country to reduce physical burden in daily life of elderly persons.

The daily life supports include housework support, going out support, *etc.* Among them, the going out support by a walking support machine is expected to have an important role so that the elderly persons independently go out by their own will, which sustains and encourages the elderly persons to connect with a local community. Furthermore, a motor-assisted walking support machine can further expand an active range of the elderly persons since it has high carrying and hill climbing abilities. However, there is a problem of large weight and small luggage space due to the motor.

To resolve the above issue, we have employed an in-wheel motor that a motor mounted inside a wheel. The in-wheel motor requires a flat structure, light weight, and large torque at low speed. Therefore, we propose an axial-gap magnetic-geared motor as the in-wheel motor. The proposed magnetic-geared motor consists of an axial-gap permanent magnet (PM) motor and magnetic gear, which are mechanically combined.

The axial-gap PM motor has larger torque than a conventional radial-gap one, if its structure must be flat ²⁾. The magnetic gear can regulate torque and speed as desired. Various types of magnetic gears have been introduced in previous papers ³⁾⁻⁶⁾. Among them, a flux-modulated magnetic gear has recently attracted interest since its torque density is higher than other magnetic gears ^{3), 4)}. Moreover, its efficiency is

comparable to conventional mechanical gears ⁶⁾⁻⁸⁾. Hence, the desired large torque at low speed can be obtained by combining the axial-gap PM motor with the flux-modulated magnetic gear.

This paper presents feasibility study of the in-wheel magnetic-geared motor for walking support machines. Characteristics and usefulness of the proposed magnetic-geared motor are demonstrated by experiments and finite element method (FEM).

2. Operating principle of the magnetic gear

Fig. 1 illustrates a basic configuration of an axial-gap magnetic gear. It has two permanent magnet rotors, and ferromagnetic pole-pieces placed between the rotors. The upper side rotor is high speed and small torque one, and the lower side rotor is low speed and large torque one, respectively.

Fig. 2 shows a schematic diagram of gap flux distribution produced by the upper side rotor and the pole-pieces. If magnetomotive force (MMF) distribution of the permanent magnet is sinusoidal, it is given by

$$f_h(\theta, t) = F_{ah} \cos\{p_h(\theta - \omega_h t)\}, \quad (1)$$

where the amplitude of the MMF is F_{ah} , the pole-pair number of the upper side rotor is p_h , and the angular velocity of the upper side rotor is ω_h , respectively.

If permeance distribution of the pole-pieces is also sinusoidal, it is expressed by

$$P(\theta) = \lambda_d + \lambda_a \cos(n_s \theta), \quad (2)$$

where the mean value of the permeance is λ_d , the

Fig. 1 Basic configuration of axial-gap magnetic gear.

Fig. 2 Schematic of gap flux distribution produced by upper side rotor and pole-pieces.

variation component is λ_a , and the pole number of the pole-pieces is n_s , respectively.

Accordingly, as the product of the MMF $f_h(\theta, t)$ and the permeance $P(\theta)$, the gap flux distribution is obtained as follows:

$$\begin{aligned} \phi_h(\theta, t) = & F_{ah} \lambda_d \cos \left\{ p_h (\theta - \omega_h t) \right\} \\ & + \frac{1}{2} F_{ah} \lambda_a \cos \left\{ (n_s + p_h) \left(\theta - \frac{p_h}{n_s + p_h} \omega_h t \right) \right\} \\ & + \frac{1}{2} F_{ah} \lambda_a \cos \left\{ (n_s - p_h) \left(\theta - \frac{-p_h}{n_s - p_h} \omega_h t \right) \right\} \quad . \quad (3) \end{aligned}$$

From (3), it is understood that the gap flux has two modulated-components $(n_s + p_h)$ and $(n_s - p_h)$ in addition to the normal component p_h caused by the upper side rotor. The rotational speeds of these modulated components are $p_h \omega_h / (n_s + p_h)$ and $-p_h \omega_h / (n_s - p_h)$, respectively. Therefore, if the pole-pair number of the lower side rotor p_l is set to $(n_s + p_h)$ or $(n_s - p_h)$, the lower side rotor rotates with the speed as follows:

$$\omega_l = \pm \frac{p_h \omega_h}{(n_s \pm p_h)} = \pm \frac{p_h}{p_l} \omega_h \quad (4)$$

It is clear from (4) that the gear ratio of the magnetic gear is simply determined by the ratio of the pole-pair numbers of the upper and lower side rotors.

In (3), the amplitudes of the $(n_s + p_h)$ and $(n_s - p_h)$ components are the same, but actually the $(n_s - p_h)$ component is larger than the $(n_s + p_h)$ one, since the actual distributions of the MMF and the permeance are approximately square wave not sinusoidal. Hence, the pole-pair number of the lower side rotor is set as $p_l = n_s - p_h$, and the speed ratio is given by

$$\frac{\omega_l}{\omega_h} = - \frac{p_h}{p_l} \quad (5)$$

On the other hand, when the lower side rotor is fixed, the pole-pieces work as an output rotor instead of the lower side rotor. In this case, the speed ratio of the upper side rotor and the pole-pieces rotor is given by

$$\frac{\omega_s}{\omega_h} = \frac{p_h}{n_s} \quad (6)$$

3. Calculation of basic characteristics of the magnetic-geared motor

3.1 Basic configuration of the magnetic-geared motor

Fig. 3 indicates a basic configuration of an axial-gap magnetic-geared motor used in the consideration. As shown in the figure, the PM rotor works as both a motor output rotor and a gear input rotor.

The motor part is composed of the 12-slots stator with three-phase concentrated windings and the 4-pole-pairs PM rotor. The core material is non-oriented Si steel with a thickness of 0.35 mm. The rotor magnet is sintered Nd-Fe-B.

The gear part consists of the 4-pole-pairs PM rotor, the 19-pole-pairs PM stator, and the 23-poles pole-pieces (PP) rotor. The material of the PP rotor is soft magnetic composite and the magnet materials are sintered Nd-Fe-B.

When three-phase sinusoidal current flows into the stator windings, the PM rotor synchronously rotates with the rotating magnetic field. Then, mechanical output can be obtained from the PP rotor of which the speed is reduced by the gear ratio of 5.75 ($= 23/4$).

Fig. 3 Basic configuration of axial-gap magnetic-geared motor.

3.2 Calculated characteristics of the magnetic-gear motor

Table 1 indicates required specifications for the in-wheel motor of a certain walking support machine which is currently under joint development with a company. The torques shown in the table are the required values per one motor, and the required torque at 25% incline is to ride over a step on the road.

Table 2 shows specifications of the designed axial-gap magnetic-gear motor. The motor diameter is 100 mm, and the axial length is 20 mm. The lengths of three air-gaps are 0.5 mm each.

Table 1 Required specifications for the in-wheel motor of a walking support machine.

Diameter (include housing)	110 mm
Axial length (include housing)	27 mm
Rated speed	125.3 rpm
Supply voltage	DC 12 V
Required torque	
Flat ground	0.47 N·m
5% incline	0.93 N·m (under 5 A/mm ²)
25% incline	2.73 N·m (under 10 A/mm ²)

Table 2 Specifications for the designed axial-gap magnetic-gear motor.

Diameter	100 mm
Axial length	20 mm
Rotational speed (PM rotor)	690 rpm
Rotational speed (PP rotor)	120 rpm
Number of turns/pole	67 turns
Pole-pairs of the PM rotor	4
Pole-pairs of the PM stator	19
Pole number of the PP rotor	23
Gear ratio	5.75
Gap length	0.5 mm × 3
Magnet material	Sintered Nd-Fe-B
Material of the PP rotor	Soft magnetic composite
Material of the stator core	Non-oriented Si steel

Fig. 4 Calculated torque characteristics of the axial-gap magnetic-gear motor.

Characteristics of the axial-gap magnetic-gear motor are calculated by three-dimensional FEM, since the motor has a three-dimensional structure. In the calculation, only copper loss is considered.

Fig. 4 shows calculated torque characteristics of the axial-gap magnetic-gear motor. It is clear that the obtained torque is sufficiently larger than the required torque of the in-wheel motor for the walking support machine shown in Table 1.

4. Experimental results of the magnetic-gear motor

Fig. 5 shows an external view of a trial axial-gap magnetic-gear motor. Fig. 6 indicates actual gap lengths of the trial magnetic-gear motor. Although the gap lengths shown in Fig. 4 were 0.5 mm each, the gap lengths of the trial machine were regulated due to assemble and allowance reasons.

Fig. 7 shows measured and calculated torque characteristics of the trial axial-gap magnetic-gear motor. The calculated values shown in the figure are obtained from the FEM simulation when the

Fig. 5 Photograph of trial axial-gap magnetic-gear motor.

Fig. 6 Gap lengths of the trial magnetic-gear motor.

Fig. 7 Torque characteristics of the trial axial-gap magnetic-gear motor.

magnetic-gear motor has the same gap lengths shown in Fig. 6. In addition, the measured three-phase current waveform is used as the input current of the simulation. The iron loss of the core, and eddy current in the magnets are taken into consideration in addition to the copper loss.

It is seen from the figure that the measured torque satisfies the required torque of 5% incline under 5 A/mm², and also exceeds the required torque of 25% incline under 10 A/mm², respectively.

Fig. 8 shows load characteristics of the trial axial-gap magnetic-gear motor. In the figure, the solid lines denote the measured values, and the broken lines indicate the calculated ones. The electrical input is P_{in} . The mechanical output is P_{out} , which is obtained from the following equation:

$$P_{out} = \omega_s \tau_s, \quad (7)$$

where the angular velocity of the PP rotor is ω_s , and the torque of the PP rotor is τ_s , respectively.

The calculated efficiency is obtained from

$$\eta = \frac{P_{out}}{P_{out} + W_c + W_i + W_e} \times 100(\%), \quad (8)$$

where the mechanical output is P_{out} , the copper loss is W_c , the iron loss of the stator, yoke, and pole-pieces is W_i , and the eddy current loss in the magnets is W_e , respectively. Hence, the calculated electrical input is given by $P_{in} = P_{out} + W_c + W_i + W_e$. The losses W_c , W_i , W_e are individually calculated by the FEM simulation.

It is understood from the figure that the calculated and measured values are approximately in good agreement. The measured maximum efficiency is about 60%. Further improvement of the efficiency is required in the future studies.

Fig. 9 indicates loss characteristics of the trial axial-gap magnetic-gear motor. In the figure, the solid lines show the measured values, and the broken lines denote the calculated ones. It is clear that the calculated copper loss almost agrees well with the measured one. On the other hand, the sum of the calculated iron loss and eddy current loss in the magnets ($W_i + W_e$) are remarkably different from the measured values ($P_{in} - P_{out} - W_c$). The reason is that the mechanical loss of the trial machine W_m cannot be separated from the

Fig. 8 Load characteristics of the trial axial-gap magnetic-gear motor.

Fig. 9 Loss characteristics of the trial axial-gap magnetic-gear motor.

measured values. It is understood that the reduction of the copper loss and the mechanical loss is the most important to improve the efficiency of the trial magnetic-gear motor.

5. Conclusion

This paper presented the feasibility study of the in-wheel magnetic-gear motor for walking support machines. The proposed axial-gap magnetic-gear motor demonstrated that it has the sufficient torque as the in-wheel motor for walking support machines by experiments and FEM.

However, since the efficiency of the trial machine is not enough high, it is necessary to conduct further detailed investigation of the losses in the future studies.

Acknowledgements A part of this work was supported by JSPS KAKENHI Grant-in-Aid for Scientific Research (b), Grant Number 24360102.

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Received Oct. 22, 2014; Accepted Nov. 26, 2014