Cogging Torque Characteristics of Magnetic-Geared Motor

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Background

◆ Conventional system

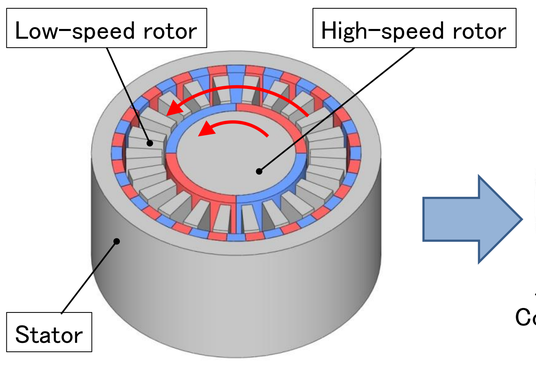
Motor → Mechanical gear → Torque limiter → Output

◆ New system with a magnetic gear

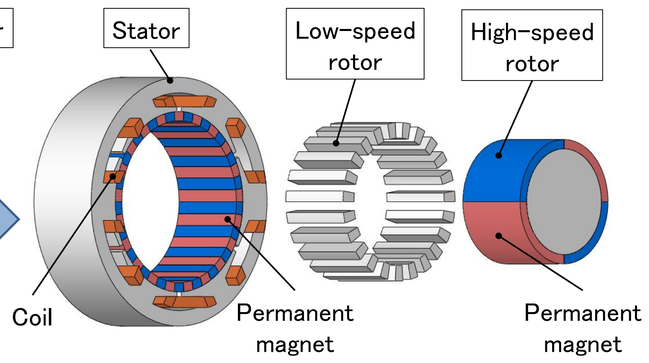
Motor → Magnetic gear → Output

◆ Next-generation system with a magnetic-geared motor

Magnetic-geared motor → Output



Surface-permanent-magnet-type magnetic gear

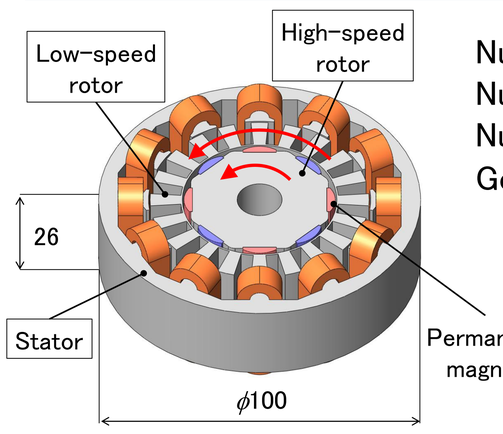


Conventional surface-permanent-magnet-type magnetic-geared motor

Advantage

- Less number of parts
- Downsizing of the driving system

Proposed Magnetic-Geared Motor



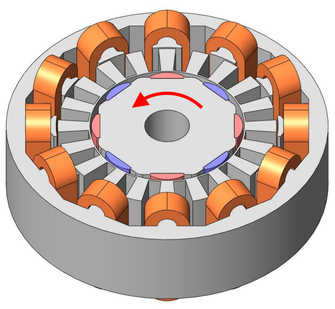
Proposed magnetic-geared motor

Number of pole pairs in the high-speed rotor N_h: 4
Number of poles in the low-speed rotor N_l: 20
Number of slots in the stator N_s: 12
Gear ratio: 2.5

- Permanent magnets are only in the high-speed rotor
- This magnetic-geared motor consists of 8-pole-12-slot brushless motor and 8-pole-20- and 12- pole-piece magnetic gear.

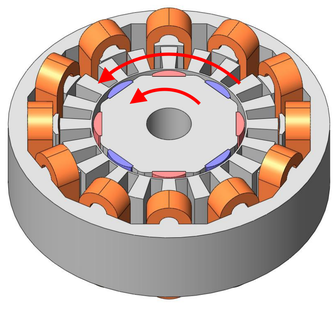
Operational Principle

1. Operational principle as a brushless motor



- 12 coils generate 4-winding-pole-pair magnetomotive force around the high-speed rotor. The low-speed rotor doesn't rotate by this magnetomotive force.
- The high-speed rotor rotates as a 8-pole-12-slot brushless motor.
- N_h and N_s must be selected in the combination that operates as a permanent magnet synchronous motor.

2. Operational principle as a magnetic gear

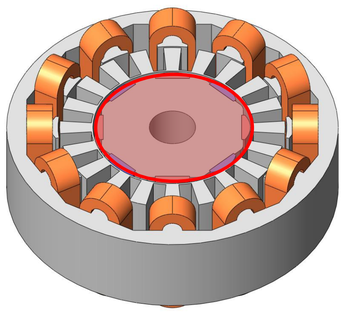


- The low-speed rotor rotates in accordance with the gear ratio G_r when the following relation is satisfied.

$$N_s = N_l \pm 2N_h \qquad G_r = \mp \frac{N_l}{2N_h}$$

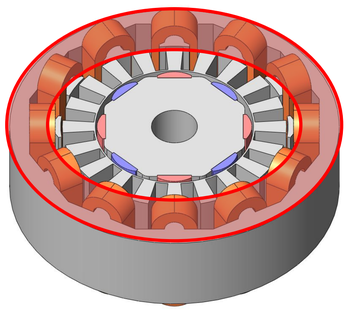
Order of the Cogging Torque

◆ Due to the high-speed rotor



- The high-speed rotor makes 2.5 rotations when the low-speed rotor makes 1 rotation.
- The relative number of poles in the high-speed rotor is $8 \times (2.5-1)=12$.
- The fundamental order of the cogging torque is equal to the least common multiple between 12 and 20.
  ⇨ 60th-fundamental component will be obtained.

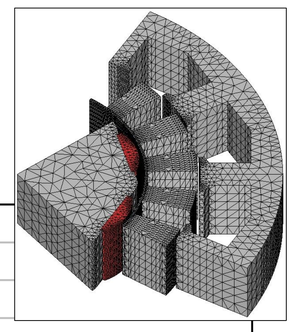
◆ Due to the magnetic flux around the low-speed rotor

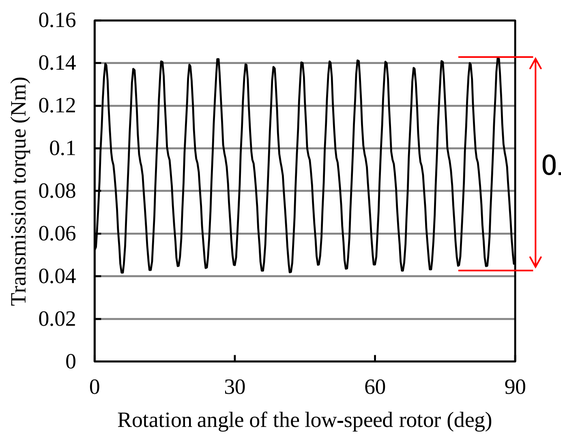


- There are magnetic flux harmonics which contains 4th-fundamental, 16th- and 24th-harmonic components around the low-speed rotor due to the magnetomotive force of the high-speed rotor and permeance of the low-speed rotor.
- The 4th-fundamental magnetic flux makes 2.5 rotations when the low-speed rotor makes 1 rotation.
- The fundamental order of the cogging torque is equal to the least common multiple between $8 \times 2.5=20$ and 12.
  ⇨ 60th-fundamental component will be obtained
- The fundamental order of the cogging torque due to the 16th- and 24th-imaginary magnet is 60, as well.

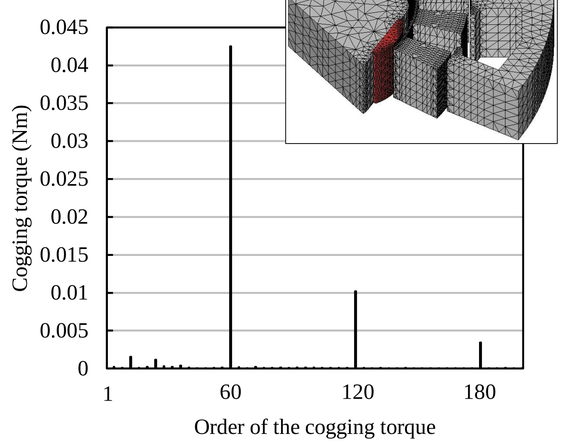
Verification Using 3-D FEM

- Phase difference between rotors is 10 deg.
- Cogging torque is 0.1 Nm.
- The 60th-fundamental component and its multiples are dominant, as theoretically described.



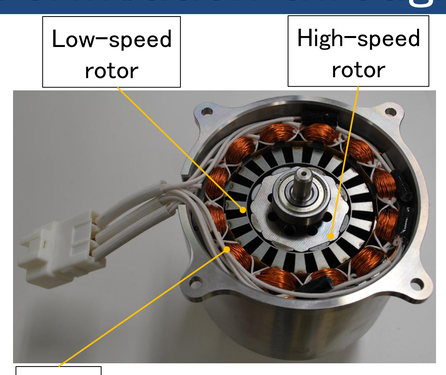


Cogging torque waveform.

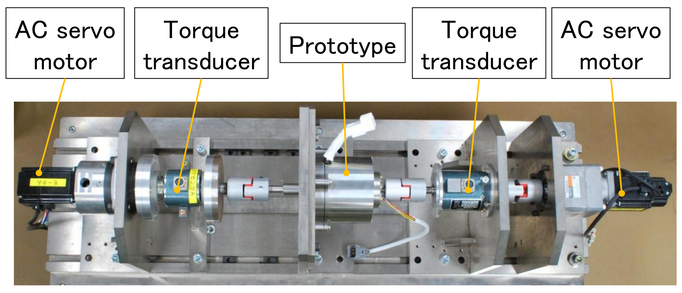


Order of the cogging torque

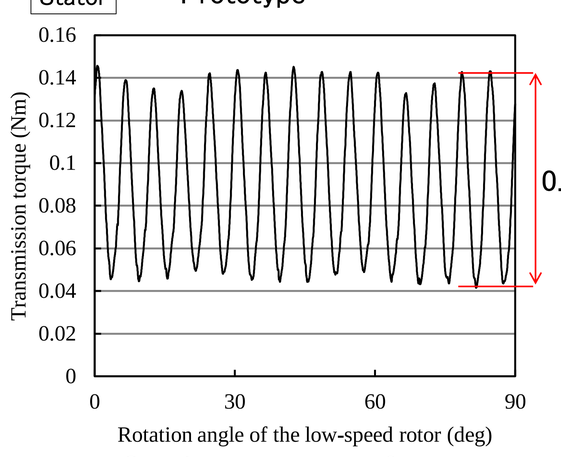
Verification through the Experiment



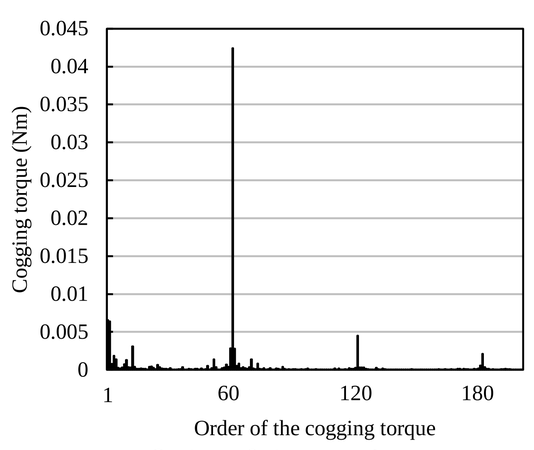
Prototype



Transmission torque measuring system



Cogging torque waveform.



Order of the cogging torque

- Cogging torque is 0.1 Nm, and it show a good agreement with the computed value.
- The 60th-fundamental component and its multiples are also dominant.

Conclusion

◆ A magnetic-geared motor with permanent magnets only in the high-speed rotor was proposed, and its operational principle was described.
The high-speed rotor rotates by the magnetomotive force of the stator as a brushless motor.

◆ The order of the cogging torque was mathematically described, and verified by conducting 3-D FEM. Furthermore, it was verified through the experiment.
In this study, the fundamental order of the cogging torque is 60.