Development of A Novel In-Wheel Motor System Integrated of Magnetic Gear and Multiple High-Speed Motors

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ABSTRACT: A technical innovation for the downsizing of motor system is necessary to realize the saving energy, and roomy and comfortable car interior space in electric vehicles. In this research, a novel in-wheel motor system of multiple high speed motors and Magnetic Multiple Spur Gear (MMSG) for the electric vehicle is proposed. The MMSG can achieve the high mechanical strength and high transmitted efficiency by the structure separating several input rotors even in the speed region of 50000 min^{-1}. Moreover, the MMSG system realizes the drastic downsizing and the high efficiency by transforming the input of multiple high speed motors. In this presentation, the performances of proposed drive system with MMSG are clarified by the experiment.

KEY WORDS: Magnetic gear, high-speed motors, In-wheel motor system, Electric vehicle (EV).

1. INTRODUCTION

The automotive industry is undergoing a once-in-a-century transformation. The driving power shifts from gasoline engines to electric motors, the development of automated driving technology is transforming the car interior into a free-living space. Therefore, the downsizing and high efficiency of motor drive system are required to achieve the large living space and the energy-saving. Higher motor speed is effective for reducing size and weight. Since the output power of a motor is proportional to the product of torque and rotational speed, the high output power density kW/kg can be obtained by keeping the torque low and satisfying the output by high-speed rotation. Furthermore, the torque and rotational speed are converted by using gears according to the required output characteristic of vehicles. However, mechanical gears have problems that gear teeth are worn by contacting and require the lubrication and the maintenance. Moreover, the gear volume becomes larger and the transmitted efficiency is decreased by increasing the gear ratio as the rotational speed is higher. In order to take advantage of higher motor speeds, the technical innovation of gears is necessary. Therefore, this research focuses on the magnetic gear. Magnetic gears can convert the torque and rotational speed through magnetic force of permanent magnets in non-contact, that can solve problems of mechanical gears and realize the motor system with maintenance-free, low acoustic noise and low vibration characteristics. By taking advantage of the non-contact power transmission, the motor system can be made smaller and lighter by further increasing the motor speed.

Most of magnetic gears are based on the principle of magnetic flux modulation using pole pieces as shown in Fig. 1(a). These magnetic gears transmit the power by the flux modulation technique using stationary pole pieces, that can obtain high torque density of more than 100 kNm/m^3 [(1)-(3)]. Additionally, the magnetic geared motor integrated with a motor and a magnetic gear enable compact system size [(4)(5)]. However, there are no magnetic gears that can be used for applications exceeding 10000 min^{-1} such as automobiles because it decreases the transmitted efficiency because the eddy current loss and core loss due to harmonic flux generate in the flux modulation process. Moreover, the mechanical strength of input rotor is low because large rotor diameter makes it susceptible to centrifugal force at high-speed rotation. Although the rotor can be reinforced by using retaining sleeves [(6)(7)], it is difficult to suppress the mises stress because the magnetic gear needs to ensure the large diameter of input rotor for the high transmitted torque. To realize the high speed drive, a reluctance magnetic gear and a flux switching magnetic gear were reported [(8)(9)]. These magnetic gears can drive up to 30000 min^{-1} because

(a) Conventional magnetic gear (b) Proposed MMSG system

Fig. 1 Magnetic gear structure.

the input rotor has a robust structure constructed by only iron core, and can decrease the eddy current loss in the input rotor. However, the transmitted torque is reduced compared with conventional flux modulation type magnetic gear.

To overcome problems, a novel magnetic gear has been proposed in this research [(10)-(12)]. It called as Magnetic Multiple Spur Gear (MMSG). In Fig. 1(b), MMSG consists of one output rotor, and several input rotors which are input by small-sized high speed motors. It can easily drive in high speed of more than 50000 min^{-1} by separating into multiple input rotors with small diameter. Additionally, the flux transmission method without the pole pieces can decrease the harmonic flux in the air gap and reduce the eddy current loss and core loss, that realizes high transmitted efficiency in the high speed rotation. As multiple motors, commercial blushless motors for drone are used. Blushless motors for drone are small, lightweight, inexpensive, and have very high power density of 5 kW/kg, more than twice that of a typical automotive motor. In the MMSG system, multiple blushless motors are driven by high speed rotation to ensure high power density, and the total output powers are efficiently converted by using MMSG, that can realize the downsizing and high efficiency of the drive system.

In this paper, the performances of torque density, efficiency and loss of the proposed drive system are clarified in the input speed up 42000 min^{-1} and maximum output power 25.5 kW by the experiment.

2. A NOVEL IN-WHEEL MOTOR SYSTEM INTEGRATED OF MMSG AND MULTIPLE MOTORS

As described in Section I, the motivation of this research is to take advantage of the non-contact power transmission of magnetic gear, the motor system can be made smaller and lighter by further increasing the motor speed. In this section, the proposed a novel in-wheel motor system is described. Its motor system combines the MMSG with multiole commercial brushless motors for drones to achieve a compact, lightweight, and highly efficient system.

2.1. Magnetic Multiple Spur Gear (MMSG)

Fig. 1 (a) shows the conventional flux modulation type magnetic gear. It consists of three concentric components such as stationary steel pole pieces, input rotor, and output rotor which have surface permanent magnets. The magnetomotive force of input rotor is modulated by the stationary pole-pieces. The output rotor can output the high torque and low speed by utilizing the modulated magnetic flux. The transmission process by the flux modulation technique has improve the torque density of magnetic gear. However, as described in section I, the conventional flux modulation type magnetic gears have following problems for high speed drive. (i) The mechanical strength of the input rotor is weak due to the surface magnets on the input rotor. The large mises stress is generated in the input rotor because the magnetic gear needs the large diameter of input rotor to obtain the high transmitted torque. (ii) The eddy current loss in the magnet and core loss much increase in high speed region because a lot of harmonic flux are generated by pole pieces in the flux modulation.

Fig. 1(b) shows the structure of the proposed MMSG. It consists of one output rotor and several input rotors which are rotated by the multiple high speed motors. The magnetomotive force of each input rotor is directly transformed to the output rotor because of no stationary pole pieces. Then, the gear ratio G between the input rotor and the output rotor is given by:

$$G = Z_l / Z_h \qquad (1)$$

where Z_h and Z_l, and G are the pole pairs of the input rotor and the output rotor, and the gear ratio, respectively. The output torque T_l is defined as follow:

$$T_l = G T_{nh} \times N \qquad (2)$$

where T_{nh}, N are the torque of the n_{th} input rotor, number of input rotors, respectively. That is, the output torque is obtained by the product of the torque of one motor, gear ratio, and number of motors. From the operation principle, there are some advantages in MMSG as follows. (i) The mechanical strength of input rotor is high because the mises stress generating at the input rotor can be reduced in high speed rotation by separating into multiple small-sized input rotors. (ii) High efficiency is realized in the high speed region because the eddy current loss in the magnet and core loss can be much reduced by decreasing the harmonic flux due to pole piece less construction. Moreover, (iii) it can achieve high torque density because the fundamental component of flux density contributes generating the torque.

2.2. Multiple high speed motors

The MMSG is driven by using the commercial blushless motors for drones. The market for drone motors has been expanding recently, it has characteristics such as small and light weight, and low expensive. The commercial motor for drone is easy to obtain and easy to configure for anyone, and it offers high customization performance. Additionally, the motors for drones can easily drive at high speed region of more than 10000 min^{-1}, obtain high power density. The total powers of multiple motors are converted by using MMSG, that realize the high power density, high efficiency, and downsizing of the drive system.

3. PERFORMANCES EVALUATION OF MMSG BY FEA

3.1. Simulation models

The characteristics of transmitted torque, efficiency and loss of MMSG were compared with the conventional flux modulation type magnetic gear by the Finite Element Analysis (FEA)[12]. Table 1 shows the simulation models. As shown in Table 1, the specifications and dimensions of MMSG are based on those parameters of the prototype gear, it is designed to satisfy the gear ratio 1:10, the maximum output power 25.5 kW, the maximum torque 195 Nm, the maximum input speed 50000 min^{-1}. It has the 15 input rotors for the motor input. The outer diameter of output rotor is 220 mm and the stack length is 26.5 mm. The conventional magnetic gear is designed to satisfy same specifications of MMSG. It has same pole pairs of rotors and same as dimension of output rotor for MMSG. The stack length of the conventional magnetic gear is designed to 41.7 mm in order to achieve the same maximum torque. The magnet volumes of conventional magnetic gear and MMSG are 2.1 kg and 1.3 kg.

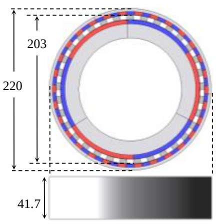
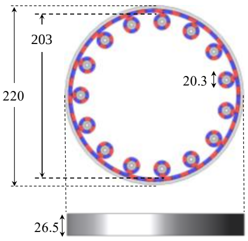
3.2. Torque waveforms

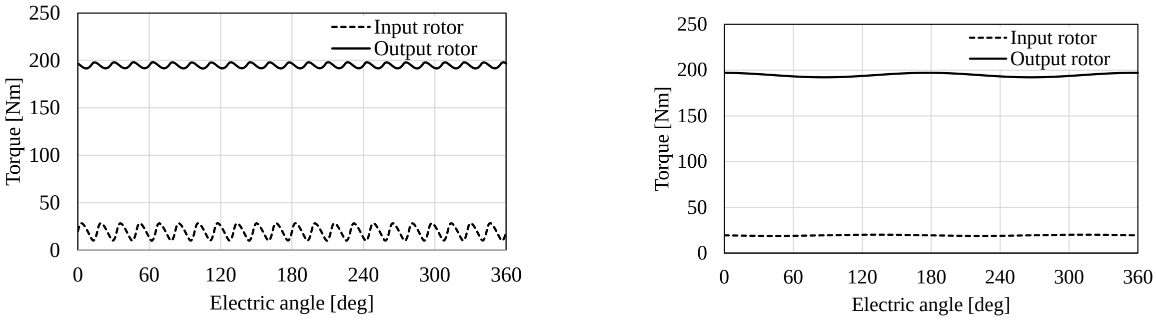
The transmitted torque under the maximum load condition is shown in Fig. 2. The torque of the input rotor represents the total torque of 15 pieces in MMSG. As shown in Fig. 2, MMSG can smoothly transform the output torque because the harmonic flux component is lower in the air-gap due to no pole-pieces. The torque density of MMSG and conventional magnetic gear are 193 kNm/m^3 and 123 kNm/m^3, respectively. In magnetic gears with flux modulation, the modulated flux of the input rotor contributes to the torque, whereas in MMSGs, the fundamental flux of the input rotor contributes to the torque, resulting in a high torque density [11].

3.3. Loss and efficiency

Fig. 3 and Fig. 4 show the gear efficiency and the gear loss. As shown in Fig. 3, the efficiency of the conventional magnetic gear declines due to the eddy current loss in the magnet and the

Table 1 Specifications of simulation models.

	Conventional magnetic gear	MMSG
Model		
Air gap length [mm]	0.5	0.5
Pole pairs of input rotor	3	3
Pole pairs of output rotor	30	30
Number of pole pieces	33	-
Number of input rotor	1	15
Gear ratio	1:10	1:10
Output power [kW]	25.5	25.5
Maximum gear torque [N m]	195	195
Maximum motor speed [min^{-1}]	50000	50000
Core material of low speed rotor	Magnetic steel sheet (35H300)	Magnetic steel sheet (35H300)
Permanent magnet material	Sintered Nd-Fe-B	Sintered Nd-Fe-B
Magnet volume [kg]	2.1	1.3
Gear weight [kg]	6.6	2.2



(a) Conventional magnetic gear (b) MMSG

Fig. 2 Torque waveforms under the maximum load condition.

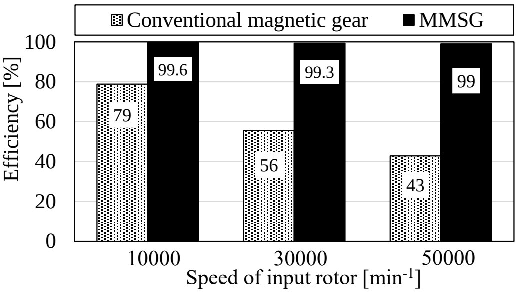


Fig. 3 Gear efficiency (Maximum torque:194.5Nm).

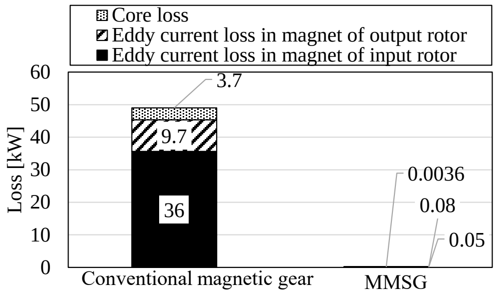
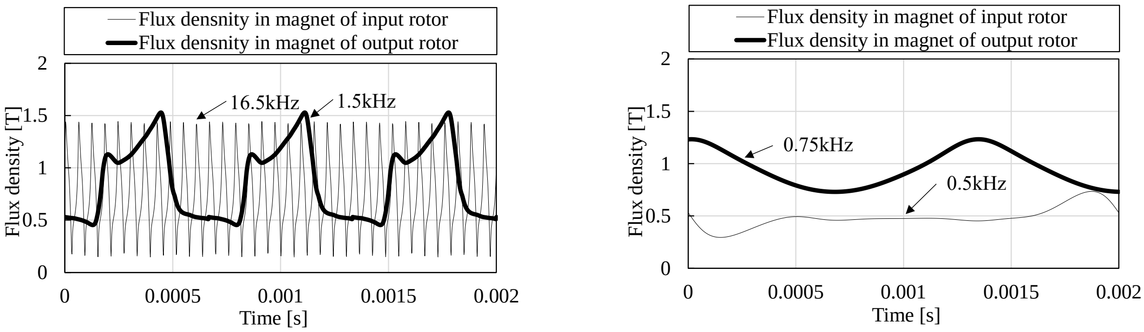


Fig. 4 Gear loss (Input rotor speed:30000min-1).



(a) Conventional magnetic gear (b) MMSG

Fig. 5 Flux density time distribution in surface magnet.

core loss as the speed of input rotor increases. As shown in Fig. 4, especially, the eddy current loss in the magnet of input rotor much increases in the high-speed region in the conventional magnetic gear. On the other hand, the MMSG achieves high efficiency even if the speed of input rotor increases because the eddy current loss in the magnet and the core loss are much lower than that of the conventional magnetic gear. As a reason for the results, the time distribution of flux density in the surface magnet is analyzed. Fig. 5 shows the time distribution of flux density in the surface magnet of each rotor. As shown in Fig. 5, the harmonic flux of MMSG is low and the fundamental frequency of flux density in each rotor of MMSG is lower than that of the conventional magnetic gear. The fundamental frequency of flux density in the conventional magnetic gear is expressed as follow:

$$f_{sh} = \frac{S_h}{60} \times Z_s \tag{3}$$

$$f_{sl} = \frac{S_l}{60} \times Z_s \tag{4}$$

where f_{sh}, f_{sl}, S_h, and S_l are the fundamental frequencies of flux density in the input rotor and the output rotor in the conventional magnetic gear, the speed of input rotor, and the speed of output rotor, respectively. In the conventional magnetic gear, the fundamental frequency of flux density becomes higher because it is proportional to the number of pole pieces Z_s. On the other hand, the fundamental frequency of flux density in the MMSG is expressed as follow:

$$f_{mh} = \frac{S_h}{60} \tag{5}$$

$$f_{ml} = \frac{S_l}{60} \times N \tag{6}$$

where f_{mh}, f_{ml} are the fundamental frequencies of flux density in the input rotor and the output rotor in the MMSG, respectively. The fundamental frequency of flux density in the input rotor is proportional to only the rotational speed of input rotor, it of output rotor is proportional to the rotational speed of output rotor and number of input rotors. Therefore, the losses of MMSG are kept to low value in the high-speed region.

4. PERFORMANCES EVALUATION OF DRIVE SYSTEM

4.1. Prototype drive system of MMSG and motors

In this section, the torque density, the efficiency and loss of the prototype MMSG are verified in the experiment. Fig. 6 shows the prototype drive system. The specifications of prototype gear are shown in Table 2. The prototype magnetic gear is designed to satisfy 25.5 kW and the gear ratio 1:10, the dimension of the gear is φ220 mm×L26.5 mm. As changes from the simulation model, the outer diameter of input rotor is decreased from 20.3mm to 19.3 mm, and the air gap length between the input rotor and the output rotor is increased from 0.5 mm to 1 mmm. Additionally, the magnets are reinforced with a 0.3 mm thick stainless steel (SUS) retaining sleeve as shown in Fig. 7 (12).

The MMSG is driven by the 15 motors and 15 inverters, the commercial brushless motors and inverters for drones are used. Each blushless motor is equipped with a commercial inverter as shown in Fig. 6 and is controlled by a gate signal comparing duty ratio and carrier under the open-loop and position sensorless 120-degree conducting drive. Fig. 8 and Table 3 show the dimension and specifications of the blushless motor and inverter. As shown in Table 3, the maximum output power of a motor is 1.7 kW and the maximum speed is 50000 min^{-1}. The weight of a motor and an inverter are 340 g and 155 g, respectively. The drive system realizes the compact and lightweight by the high-speed drive, and achieves the system torque density 3.5 kW/kg and 22 Nm/kg including the motors and the gear.

3.2. Torque density of magnetic gear

The maximum torque is measured by applying a load to one input rotor until its step out under the condition which the output rotor is locked by the hysteresis brake. And the maximum torque of the gear is obtained by multiplying the measured torque by the number of rotors. Fig. 9 shows the comparison of the maximum transmitted torque between 2D FEA and experiment value. As shown in Fig. 9, the maximum torque is 158Nm, and the maximum torque of the prototype gear almost corresponds to that of simulation result. It is verified that MMSG can obtain high torque density 158 kNm/m^3.

3.3. Gear efficiency and system efficiency

The efficiency and loss are measured for output torque up to 120 Nm, load rate 75% and input speed up to 21000 min^{-1}. The

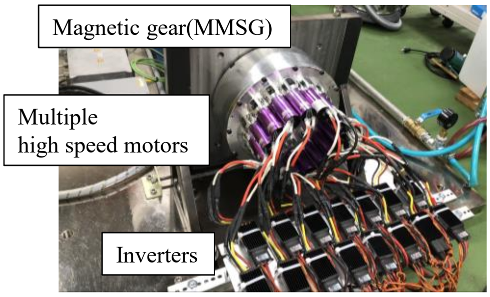


Fig. 6 Prototype motor system.

Fig. 7 Input rotor of MMSG.

Table. 2 Specifications of MMSG.

Maximum output power [kW]	25.5
Maximum torque [Nm]	160
Maximum input motor speed [min^{-1}]	50000
Pole pairs of high speed rotor	3
Pole pairs of low speed rotor	30
Number of high speed rotor	15
Gear ratio	1:10
Gear dimension [mm]	φ220×L26.5

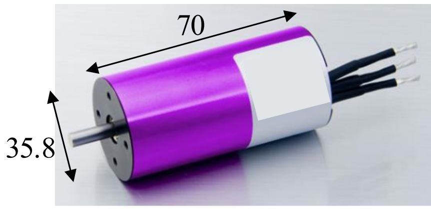


Fig. 8 Commercial brushless motor.

Table. 3 Specifications of motor and inverter.

Maximum output power [kW]	1.7
KV [rpm/V]	986
Maximum speed [rpm]	60000
Maximum inverter current[A]	130
Maximum inverter voltage [V]	51
Inverter size [mm]	35×23×105
Inverter weight [g]	155

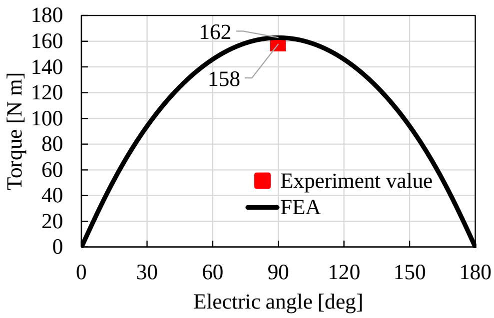


Fig. 9 Maximum output torque of gear.

gear efficiency is calculated by the ratio of output power of gear and the input motors. The output torque of gear is directly measured by the toque transducer, the input torques of motors are estimated by sensing the phase current using the current-torque characteristic of motor obtained in advance. The phase current and the input power of motors are measured by the precision power analyzer WT5000 (Yokogawa Test & Measurement Corporation). Fig. 10 and Fig. 11 show the measured efficiency and loss. As shown in Fig. 10, the prototype gear achieves the high efficiency of more than 95 % even if the rotational speed increases up to 21000 min^{-1}, the efficiency becomes higher under the high load condition because the output power increases and the loss decreases. As shown in Fig. 11, the loss in the high load condition is lower than that in low load condition because it is thought that the flux density distribution in each rotor is changed by the load condition. Fig. 12 and Fig. 13 show the motor efficiency and the system efficiency, respectively. As shown in Fig. 12 and Fig. 13, the system efficiency of about 80 % to is achieved in the high-speed and low load area. However, the system efficiency is low in the low speed and the high load area, that depends strongly on the efficiency distribution of the brushless motor. It is possible to more enhance the system efficiency if the motor efficiency can be improved. Fig. 14 shows the gear efficiency and system efficiency at maximum power 25.5 kW and in the input speed up to 42000 min^{-1}. The gear efficiency of more than 95%, the system efficiency of more than 85% can be obtained because the motor efficiency increases in the range of high speed and high output power.

4. CONCLUSION

In this paper, a novel in-wheel motor system of multiple high-speed motors and Magnetic Multiple Spur Gear (MMSG) for the electric vehicle was proposed. In the experiment, it was shown that the prototype MMSG can obtain the high torque density 158kNm/m^3, the prototype MMSG realizes the gear efficiency of more than 95 % and the system efficiency of about 80 % for speed up to 21000 min^{-1}. Moreover, the gear efficiency of more than 95%, the system efficiency of more than 85% can be obtained at the maximum output power 25.5 kW and maximum input speed 42000 min^{-1}. From the experiment results, the proposed drive system is effective for the downsizing of system, the fact that gear efficiency of more than 95% was obtained in the high-speed range is an important achievement.

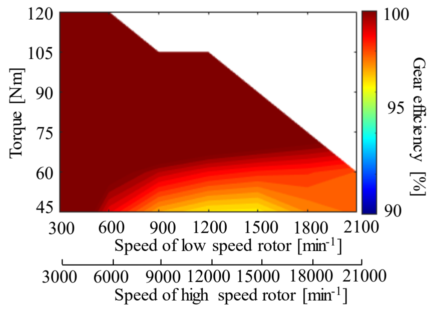


Fig. 10 Measured gear efficiency.

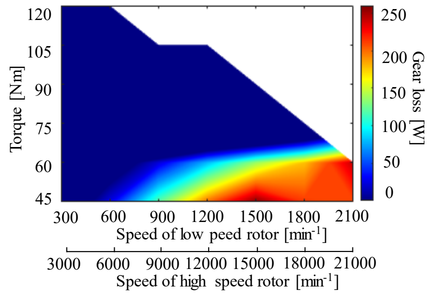


Fig. 11 Measured gear loss.

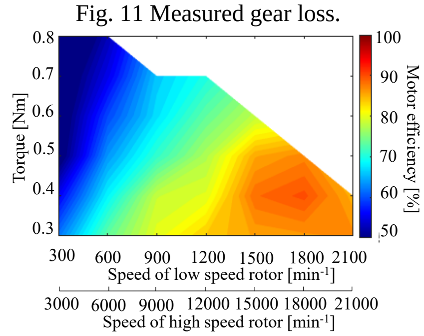


Fig. 12 Measured motor efficiency.

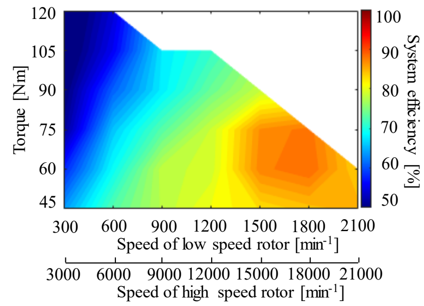


Fig. 13 Measured system efficiency including motor and gear.

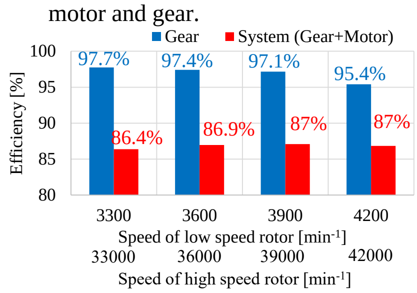


Fig. 14 Measured system efficiency and gear efficiency at maximum output power 25.5 kW.

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