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Increasing the efficiency of a drone motor by arranging magnetic sheets to windings

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Abstract

In recent years, there has been an increase in motorization; therefore, the demand for high-efficiency motors in automobiles and aircrafts will further increase. A drone is an aircraft that flies without a human pilot onboard; it has a short flight time because the size of the mounted battery is limited. The magnetic sheet consists of a composite material with magnetic powder and silicone rubber. The eddy current loss and copper loss of the drone motor reduces when the sheet is attached to the coil. This paper reports on the effect of improving the drone motor efficiency by lowering the leakage magnetic flux of the rotor and increasing the heat dissipation in the simulation and the experiment.

Keywords

Copper loss; Magnetic composite material; Magnetic sheets; Motor; Stray load loss; Thermal conductivity

1. Introduction

Motors have become an essential power source that support modern life ([2]). The ratio of motors to the total industrial power consumption in the world is approximately 35% to 40% ([1]). Improving the efficiency of motors is also important from the perspective of preventing global warming ([7], [10]). In recent years, motorization has increased substantially, and the demand for motors in the automobile and aeronautics industry is expected to increase further. A drone is an aircraft that is remotely controlled using a motor. Drones have a wide variety of applications such as scientific research, aerial photography at disaster sites, and goods transportation. However, drones have a short flight time because their batteries need to be small in size for mounting on the drones. To increase the efficiency of the drone motor, it is important to reduce the power consumption. Motor efficiency can be achieved by increasing the motor size, but a drone motor needs to be compact and high powered for mounting on a drone. To increase the output power, the rated torque and rotational speed of the motor need to be increased. It is desirable to increase the rated rotational speed because an increase in the torque tends to increase the motor size.

The motor loss is classified into copper loss, iron loss, and stray load loss ([11]). Studies have shown that coil winding and the use of low-loss core materials are effective in reducing the copper loss and the iron loss ([8], [9]). However, there are few reports on the eddy current losses for the winding, which accounts for most of the stray load loss. The eddy current loss generated in the winding depends on the fundamental frequency of the excitation current and the carrier frequency of the pulse width modulation inverter. The drone motor has high fundamental and carrier frequency because it has to be small in size with a high output. The influence of the eddy current loss generated in the winding becomes large ([5], [4]). Furthermore, the conductor resistivity increases with the temperature rise of the coil during operation. Therefore, it is effective to increase the heat dissipation of the armature and to lower the armature resistance to increase the efficiency.

Therefore, we considered placing a magnetic sheet on the winding to reduce the eddy current loss and the copper loss of the drone motor. The magnetic sheet consisted of a composite material with magnetic powder and silicone rubber. The loss improvement effect by controlling the magnetic flux was reported on a converter or a power transmission coil ([6], [3]). Therefore, we proposed to reduce the eddy current loss caused by the leakage flux on the field side being linked to the winding by arranging a magnetic sheet on the winding. Furthermore, the magnetic sheet had high thermal conductivity; therefore, the heat dissipation of the winding could be improved and the increase in electrical resistance could be suppressed. This paper reports the results of simulations and experiments on the effect of the placement of the magnetic sheet on the windings to increase the efficiency of the drone motor.

2. Structure

2.1. Drone motor

Fig. 1 shows the structure of the drone motor. The drone motor is an outer rotor type, and its rated output was 318 W. There were 14 poles and 12 slots. The stator height excluding the coil end was 13 mm; the stator outer diameter was 48 mm. The outer diameter of the mover was 57.3 mm, and the gap length was 0.3 mm. The coil was a concentrated winding with a round wire. The rotor was the surface permanent magnet type.

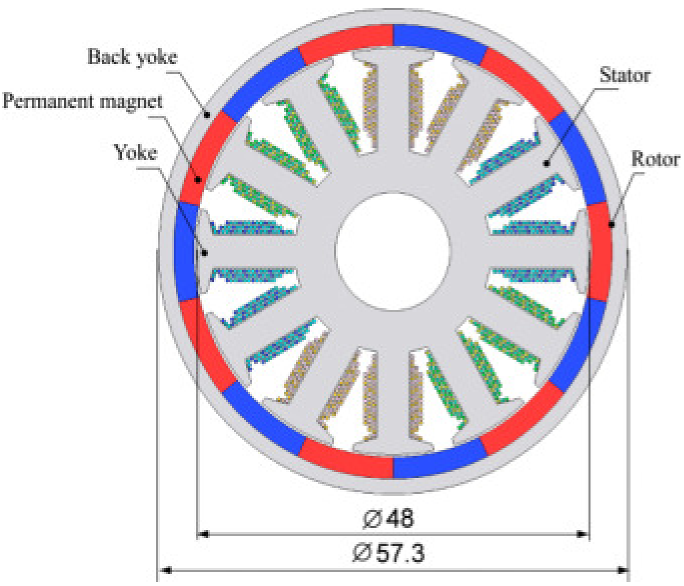

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Fig. 1. Structure of the drone motor (unit: mm).

2.2. Magnetic sheets

The magnetic sheet was produced by mixing a magnetic powder and two-component silicone rubber; then, the material was baked and stretched thinly. Two effects are expected by sticking the magnetic sheet to the winding. First, the magnetic powder contained in the magnetic sheet prevented interlinking with the winding by controlling the path of the leakage flux from the rotor. This helps to reduce the current density bias and the eddy current losses of the windings. Second, the magnetic sheet had high heat conductivity; therefore, this improved the heat dissipation of the winding. We expected to decrease the electrical resistance by suppressing the temperature rise during energization.

In Section 3, we confirm the efficiency improvement effect that accompanies the reduction of eddy current losses by pasting a magnetic sheet in the simulation. In Section 4, we confirm the improvement in efficiency associated with the improvement in the heat dissipation of the winding and the reduction of the eddy current loss in the experiment.

3. Simulation

3.1. Simulation conditions

Fig. 2 shows the analysis model of the drone motor with the magnetic sheet. The magnetic sheet is placed at the outer periphery of the winding. This helps to prevent leakage flux from the rotor that has entered the slot from being linked to the winding. Also, the eddy current loss in the winding can be reduced. Table 1 shows the analysis conditions. The windings of the analytical model use the conductor specifications to determine the current density distribution. For obtaining the resistance, inductance, copper loss, torque, and iron loss in this simulation, we used two-dimensional magnetic field transient analysis of JMAG-Designer. The fundamental frequency of the excitation current was 933 Hz because there were 14 poles, and the rotational speed of the rotor was 8000 rpm. The thickness of the magnetic sheet was 0.1 mm.

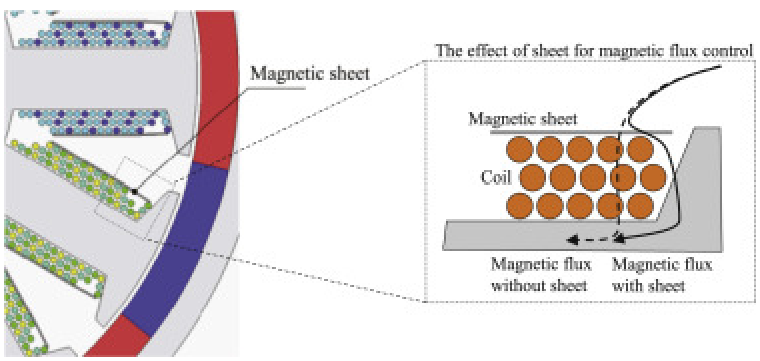

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Fig. 2. Analysis model of the drone motor with magnetic sheet.

Table 1. Simulation conditions.

Item	Contents
Software	JMAG-Designer (x64) Ver.17.0
Analysis	Two-dimensional magnetic field analysis
Solution	FEM
	Copper: 1/10 or less of the skin depth,
Mesh size	Magnetic layer : 10 mm,
	Air : Automatic
Analysis area	Analysis in 10 times the analysis model
Rotor speed	$N_r = 8000$ rpm
Current	$I = 30\ \mathrm{A_{max}}$
	Copper : $(r = 1.72 \times 10^{-8}\ \mathrm{W\ m}, m_r{}' = 1, m_r{}'' = 0)$
Material	Magnetic composite material : $(m_r{}' = 20, m_r{}'' = 0)$
	Air : $(r = \infty\ \mathrm{W\ m}, m_r{}' = 1, m_r{}'' = 0)$

3.2. Simulation results

Fig. 3 shows the magnetic flux lines and current density distribution. The magnetic flux partially leaked when the mover linked to the winding was reduced by disposing the magnetic sheet. The bias of the current density was slightly reduced because the flux linkage to the winding was reduced. The analysis results are shown in Table 2. The electrical resistance with the magnetic sheet was reduced by 3.2% because of the reduced current density bias. The copper loss with the magnetic sheet was reduced by 1.8%. Furthermore, the iron loss and the torque were almost unchanged, and there was almost no adverse effect of sticking the magnetic sheet. The efficiency improved by 0.2% because of the reduction of copper loss. Eddy current losses due to wire interlinkage will be larger in more high-speed motors or open slot motors because they have larger skin effects and proximity effects, and there is large leakage flux from the mover. In such cases, the efficiency improvement because of the magnetic sheet is further enhanced.

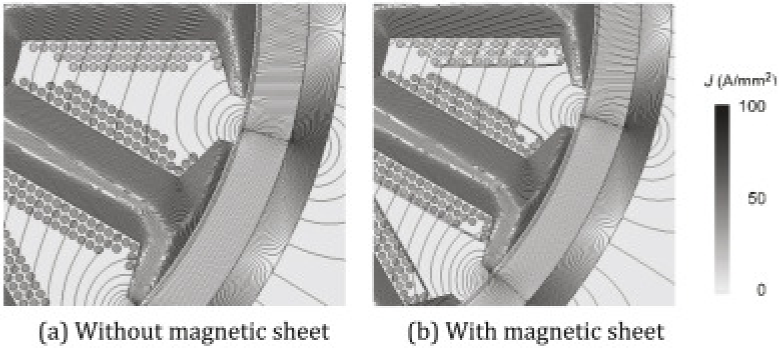

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Fig. 3. Flux line and distribution of current density.

Table 2. Simulation results.

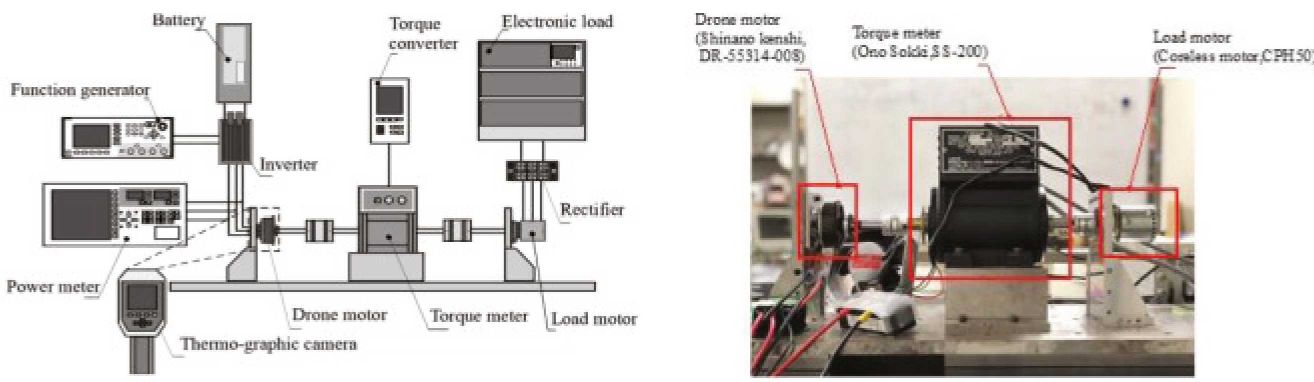
Item	Without magnetic sheet	With magnetic sheet
Resistance (Ω)	19.0	18.4
Copper loss (W)	33.4	32.8
Iron loss (W)	42.7	42.5
Torque (N m)	0.78	0.78
Efficiency (%)	88.3	88.5

4. Experiment with magnetic sheet

4.1. Experimental configuration

Fig. 4(a) shows the overall experimental structure. The drone motor, torque meter, and load motor are connected on the same shaft via a coupling (see Fig. 4(b)). The power supply was a drone battery. The speed of the drone motor was controlled by inputting a pulse wave using a function generator. A coreless brushless DC motor was used as the load motor, and the regenerative energy was consumed by the electronic load. The electronic load was used in the constant resistance mode, and the resistance was adjusted to achieve the desired torque.

The magnetic sheet was prepared according to the procedure shown in Fig. 5. The raw material for the magnetic composite material was manufactured in steps by mixing amorphous 1 (particle size 2.6 μm), amorphous 2 (particle size 10 μm), and silicone rubber in the ratio of 5: 15: 1.49 by vacuum stirring. The magnetic composite material is dropped on a polyethylene terephthalate (PET) sheet, and the air bubbles were removed by a shaker. The vacuum evacuation is performed using a vacuum desiccator. Again, it was vibrated by a shaker to remove all air bubbles. The PET sheet was sandwiched and pressurized to the desired thickness. The magnetic sheet was completed by baking with the PET sheet. The complex permeability was measured using an impedance analyzer (16454A) and a terminal adaptor (42942A) and was found to be $\mu' = 19.4$, $\mu'' = 0.25$. These values were close to the characteristics used in the simulation. Fig. 6 shows the stator of a drone motor with magnetic sheets. A two-component acrylic adhesive was used to attach the magnetic sheet to the winding of the motor.



(a) Overall structure (b) Motors connection

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Fig. 4. Experiment configuration.

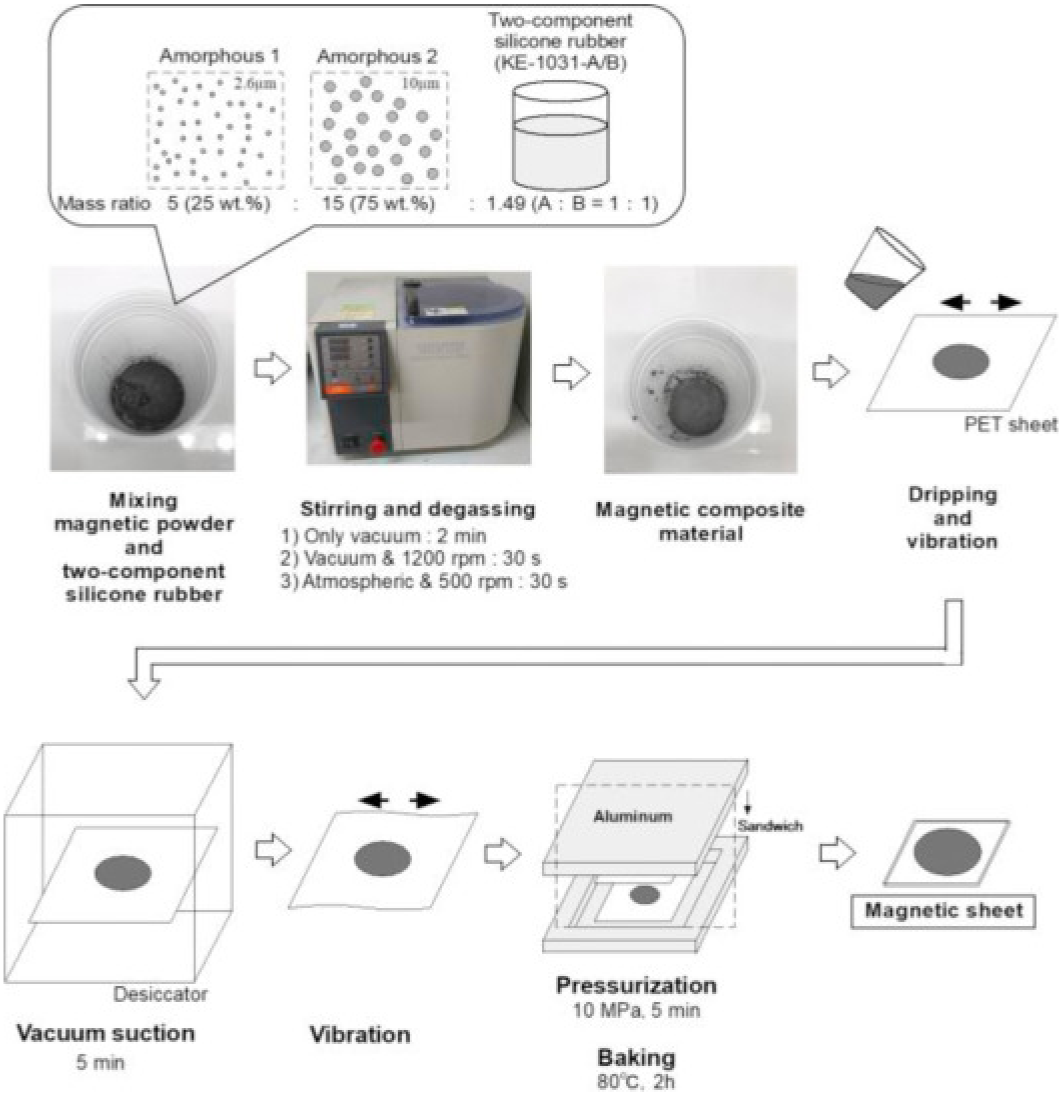

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Fig. 5. Production of magnetic sheets.

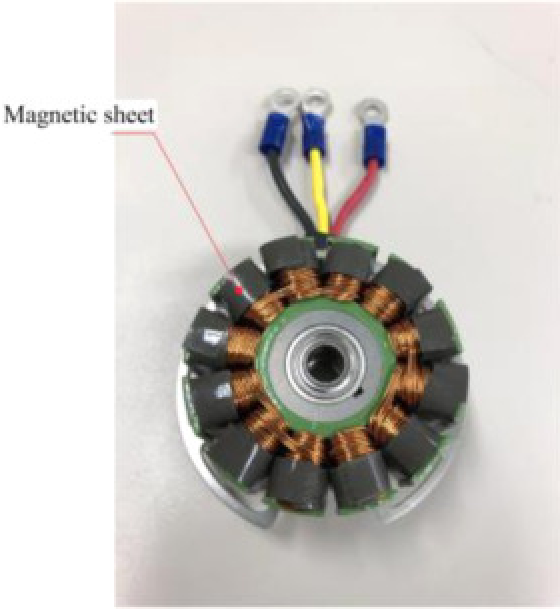

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Fig. 6. Drone motor with magnetic sheets.

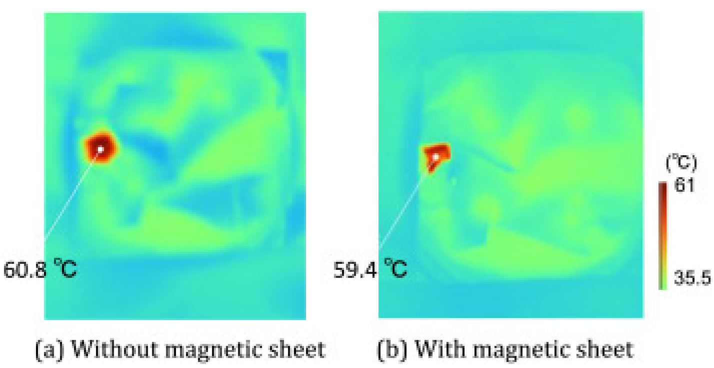

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Fig. 7. Temperature distribution of drone motor 9 min after the start of operation.

4.2. Results

The motor was driven at the maximum rotational speed with the electronic load set to 1 Ω for the rotation resistance. Measurements start after reaching the maximum rotational speed. Fig. 7 is the temperature distribution by the thermo shot for the highest winding temperature. Fig. 7(a) and (b) show the case without and with the magnetic sheet, respectively. The temperature of the winding in both cases reached the maximum approximately 9 min after starting the measurement. The maximum temperatures without and with the magnetic sheets were 60.8 °C and 59.4 °C, respectively; these temperatures were maintained during the operation. The temperature rise was suppressed by using the magnetic sheet. Fig. 8 shows the time transition of the measurement result. Fig. 8(a) shows the graph for the rotational speed. The rotational speed was the same for approximately 16 min, but the rotational speed without the magnetic sheet decreased with the passage of time. The rotational speed could not be maintained because the battery capacity had dropped. Fig. 8(b) shows the torque. There was no change in the torque because of the magnetic sheet. The torque without the magnetic sheet dropped sharply after 16 min because of a decrease in battery capacity. The electrical resistance with the magnetic sheet was reduced by 2.6% (see Fig. 8(c)). This happened because of two reasons: the reduction of eddy current loss in the winding and the suppression of temperature rise due to the high thermal conductivity of the magnetic sheet. From the simulation results, we can see that the latter effect is large, as described in Section 2.

Fig. 9 shows the efficiency of the motor. The efficiency is the ratio of input to output. The input power of the motor is measured by a power meter, and the output is the product of the torque and rotational speed. With the magnetic sheet, the maximum efficiency was improved by 1.5%. To improve efficiency, it is useful to stick the sheet to the winding. Furthermore, if the magnetic sheet can be stuck to the deepest part of the slot, the heat radiation effect and the efficiency improvement effect can be enhanced.

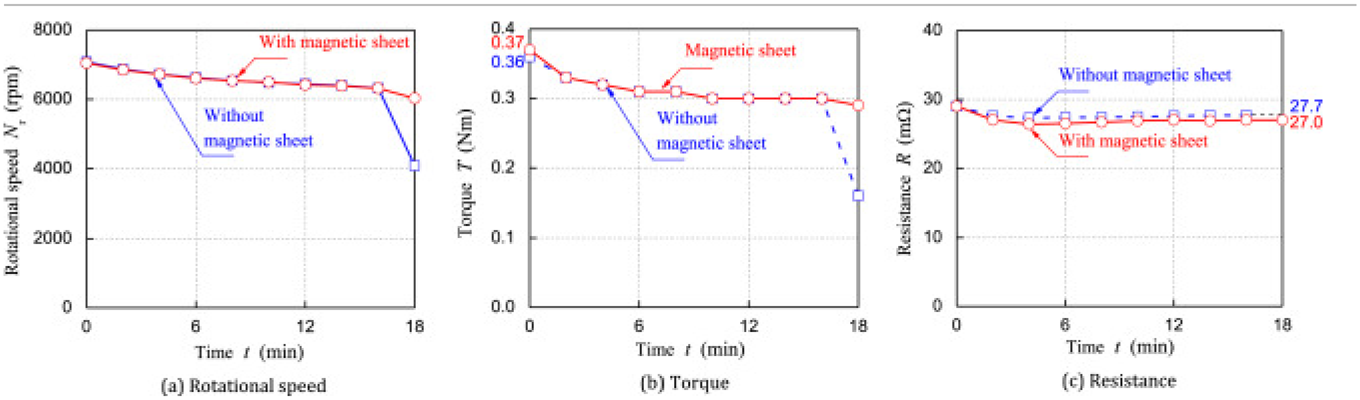

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Fig. 8. Experimental results.

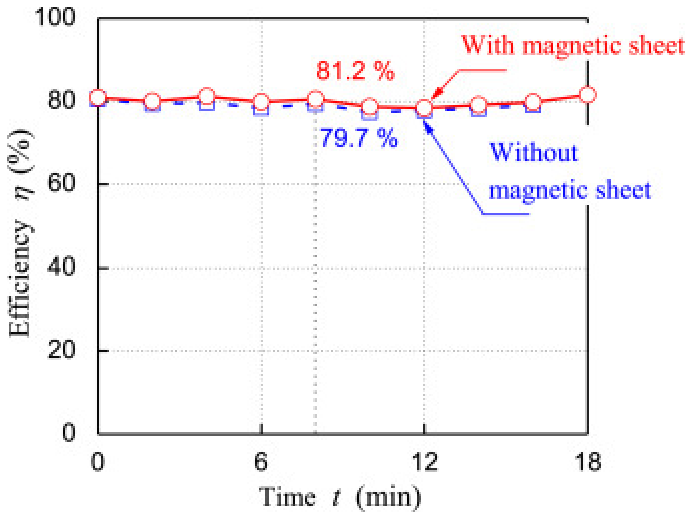

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Fig. 9. Motor efficiency.

5. Conclusion

A magnetic sheet was placed around the winding to increase the efficiency of the drone motor. In the magnetic field analysis simulation, the increase in electrical resistance was suppressed so that the flux of the rotor interlinks with the winding by using the magnetic sheet. The electrical resistance was reduced, and the efficiency was improved by 0.2%. In addition, we could improve the heat dissipation of the winding because of the high thermal conductivity of the magnetic sheet. In the experiments that use a drone motor, the increase in electrical resistance was suppressed, and the maximum efficiency was improved by 1.5%. Our results prove that the pasting of the magnetic sheet was effective for improving the motor efficiency.

Acknowledgments

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References

[1] de Almeida Aníbal T., Ferreira Fernando J.T.E., Baoming Ge
Beyond induction motors—Technology trends to move up efficiency
IEEE Trans. Ind. Appl., 50 (3) (2014), pp. 2103-2114

CrossRef View Record in Scopus Google Scholar

[2] Dorrell D.G., Knight A.M., Popescu M.
Performance improvement in high-performance brushless rare-earth magnet motors for hybrid vehicles by use of high flux-density steel
IEEE Trans. Magn., 47 (10) (2011), pp. 3016-3019
View Record in Scopus Google Scholar

[3] S. Endo, Y. Bu, T. Mizuno, 2018. Weight reduction and high efficiency of wireless power transmission coil using magnetocoated aluminum plate. In: Proc. EVS 31 & EVTeC 2018, No.C1-3, pp. 1-6.
Google Scholar

[4] Ishak D., Zhu Z.Q., Howe D.
Eddy-current loss in the rotor magnets of permanent-magnet brushless machines having a fractional number of slots per pole
IEEE Trans. Magn., 41 (9) (2005), pp. 2462-2469
CrossRef View Record in Scopus Google Scholar

[5] Iwasaki S., Deodhar R.P., Liu Y., Pride A., Zhu Z.Q., Bremner J.J.
Influence of PWM on the proximity loss in permanent-magnet brushless AC machines
IEEE Trans. Ind. Appl., 45 (4) (2009), pp. 1359-1367
CrossRef View Record in Scopus Google Scholar

[6] Konno Y., Yamamoto T., Kawahara S., Torishima K., Bu Y., Mizuno T.
Examination of high Q factor inductor with vacant space for a non-isolated DC–DC converter
IEEE Trans. Magn., 54 (11) (2018), Article 8401504
Google Scholar

[7] Lu S.
A review of high-efficiency motors: Specification, policy, and technology
Renew. Sustain. Energy Rev., 59 (2016), pp. 1-12
Article Download PDF CrossRef View Record in Scopus Google Scholar

[8] Makita S., Takahashi E., Nashiki M., Doki S.
New motor having a simple structure with three-dimensional magnetic circuit and loop windings
IEEJ Trans. Ind. Appl., 134 (3) (2014), pp. 363-369
CrossRef View Record in Scopus Google Scholar

[9] Ohta M., Yoshizawa Y.
Improvement of soft magnetic properties in (Fe0:85B0:15)100-xCux melt-spun alloys

Mater. Trans., 48 (9) (2007), pp. 2378-2380
CrossRef View Record in Scopus Google Scholar

[10] Trianni A., Cagno E., Accordini D.
A review of energy efficiency measures within electric motors systems
Energy Procedia, 158 (2019), pp. 3346-3351
Article Download PDF View Record in Scopus Google Scholar

[11] Yamazaki K., Watanabe Y.
Stray load loss Calculation of induction motors using electromagnetic field analysis
IEEJ Trans. Ind. Appl., 128 (1) (2008), pp. 56-63
CrossRef Google Scholar

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