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To Improve Micro-Planar-Magnetic Generator Performance Based on Addition of Magnetic Material

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Abstract: By finite element simulation and experiment, this paper compares the performance of generators with magnetic material to generators without magnetic material (Fe) in its coil and analyzes the reason why there is difference between simulation results and experimental results. Experimental results present that under the same rotational speed, output voltage improves 60% with the addition of magnetic material in coil compared to generator without magnetic material in coil. We further discuss the feasibility to add magnetic material in coil, present the existed problems and improvement methods.

Introduction

Research on micro power generations is increasing as wireless sensor networks and wearable devices are becoming smaller and increasingly widely used. Compared with traditional electrochemical batteries, micro magnetic generators have advantages as long-time storage, no need for replacement, ease of maintenance, less pollution, etc. Besides, micro planar magneic generator owns features of short in axial dimension, high power density and high energy effeciency and so on. Hence, research communities have done research to improve performance of micro planar magnetic generators.

C.T. Pan et al [1] fabricated a 5×5×2 mm^3 generator in 4 pole-pairs and the maximum power output reached 0.412 mW at 149.3 Hz. This device had a multi-layer planar coil to increase coil enclosed area. Florian Herrault et al [2] fabricated a generator consisting of a three-phase microfabricated surface-wound copper coil and a multi-pole permanent-magnet rotor of 2 mm in diameter. The generator exhibited up to 6.6 mW of alternating current (AC) electrical power across a resistive load 1.8Ω at a rotation speed of 392 kr/min. They did research on how different magnetic materials and coil enclosed area influence the output performance. In the following year, the same research team [3] fabricated a generator with a laminated magnetic stator core to obtain power of 1.05 W at a rotation speed of 200 kr/min. Sun shao-chun et at [4] presented a three-phase stator coil which delivered 357.3 μW at 10 kr/min with a 0.23 Ω resistor load and showed how the changing rate of magnetic flux impacts the generator performance. R. Cordero1 et al [5] developed a generator composed of commercially available NdFeB permanent magnets and planar coils manufactured by photolithography. The generator was capable of producing 3.2 V and 5.8 mW of output power at a rotation speed of 4 kr/min. They further analyzed the affect of multi-layer coil. Y. J. Chen et al [6] established a generator with the size of 0.761 cm^3 which generated 218.127 mV induced voltage at 1395.34 rad/s. Besides, they did research with different shapes of coil.

According to Faraday's law of electromagnetic induction, the induced voltage can be expressed as Eq.1.

$$U(t) = -\frac{d\Phi(t)}{dt} = -S\frac{dB(t)}{dt} \tag{1}$$

where *U(t)* is the induced voltage, *Φ* represents the magnetic flux through coil, *B* means the magnetic flux density, *S* is the area enclosed by coil

Eq.1 indicates that there are three methods to improve output voltage: (1) To increase the magnetic flux density through the coil, (2) To enlarge the area enclosed by the coil, (3) To improve the change rate of magnetic flux. Generator design also focuses on the above three points.
There are two methods to increase magnetic flux density: (1) To use material with high residual magnetism as the magnet, (2) To add magnetic material in coil. Since NdFeB is widely spread and with high residual magnetism, existed micro magnetic generators usually use NdFeB as magnet, while addition of magnetic material to coil has no practical application so far. Next, we'll analyze the output performance of generator with and without magnetic material (Fe) in its coil by finite element simulation and experiment respectively.

2 Overall design

Main structure of micro-planar-magnetic generator contains a stator multilayer coil and rotor multi-pole magnets on both sides of the coil, as shown in Fig.1. Magnet provides magnetic field as energy source and when the turbine drives the magnets to rotate, they rotate relatively to the coil and magnetic flux through the coil changes and there is electromotive force produced in coil.

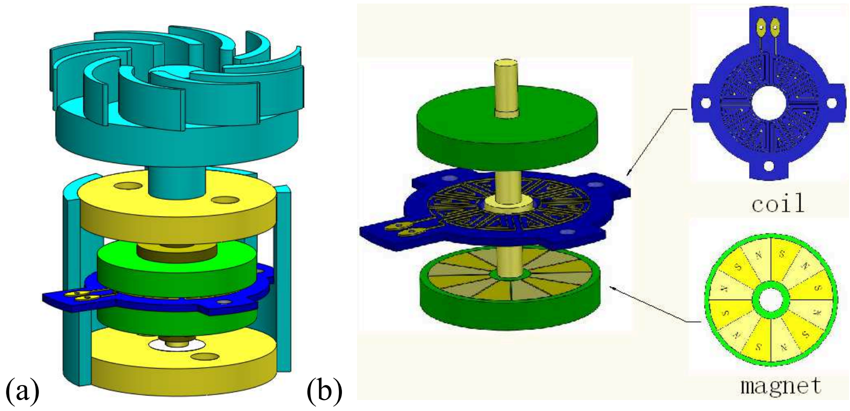

Fig.1 Micro planar magnetic generator (a) overall structure (b) main structure

To compare the performance of generator with magnetic material to generators without magnetic material in its coil, we designed comparison programs as follow,
(1)Add an iron film in the middle of coil and the structure is: coil+ adhesive+ iron film+ adhesive+ coil, as shown in Fig.2(a).
(1)Add paper in the middle of coil which has the same thickness of iron film and the structure is: coil+ adhesive+ paper+ adhesive+ coil, as shown in Fig.2(b).
In this design, coil is double layer and thickness of coil, iron film, adhesive is 0.1mm, 0.3mm, 0.04mm respectively, and the total structure thickness is 0.58mm.

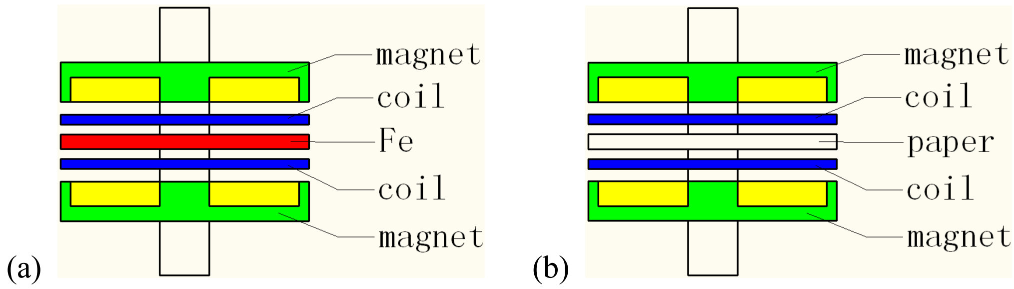

Fig.2 (a) Model with magnetic material in coil (b) Model without magnetic material in coil

Then we compared the performance of generators with magnetic material to generators without magnetic material (Fe) in its coil by finite element simulation and experiment respectively.

3 Finite element analyses

We carry out finite element analysis (FEA) simulations using Ansoft Maxwell software and compare the magnetic distributions of the prototypes with magnetic material to generators without magnetic material in its coil.

3.1 Simulation model

A circumferential cross section in the three-dimensional magnetic structure of the generator is expanded into a plane as a two-dimensional (2D) model, as shown in Fig.3(a). Width of the magnet is defined as the average of outer arc and inner arc of a three-dimensional magnet. After model building, material allocating, boundaries definition, mesh and corresponding post-processing operation, we obtained magnetic flux distribution as shown in Fig.3(b).

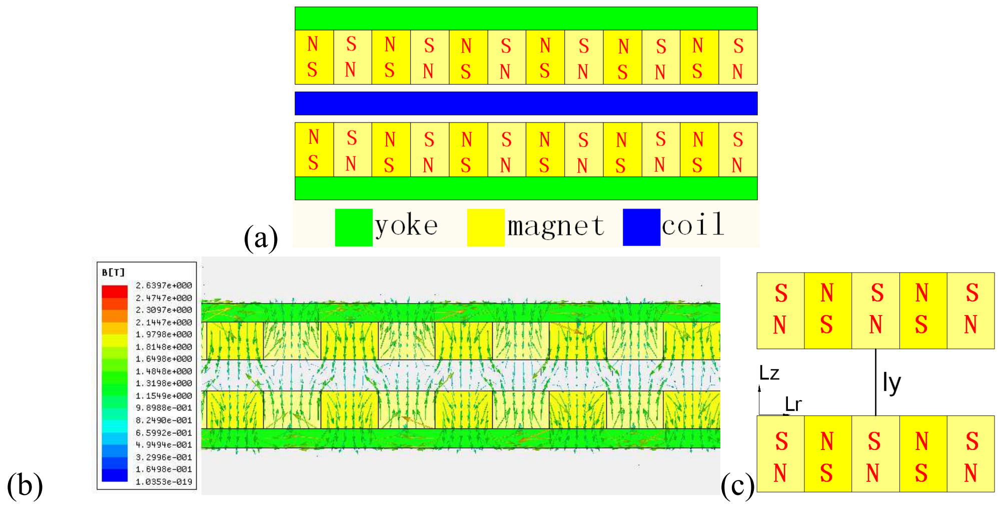

Fig.3 (a)Simulation model (b)Magnetic flux distribution (c)Model coordinate

Fig.3(b) shows that magnetic field in the magnetic gap is not uniform. There is circumferential component Lr besides axial component Lz. Along the middle line ly there is only axial component and no circumferential component. As the distance from ly increases, axial component decreases and circumferential component increases. Axial component is the effective value. Magnetic flux distribution on ly is shown in Fig.4.

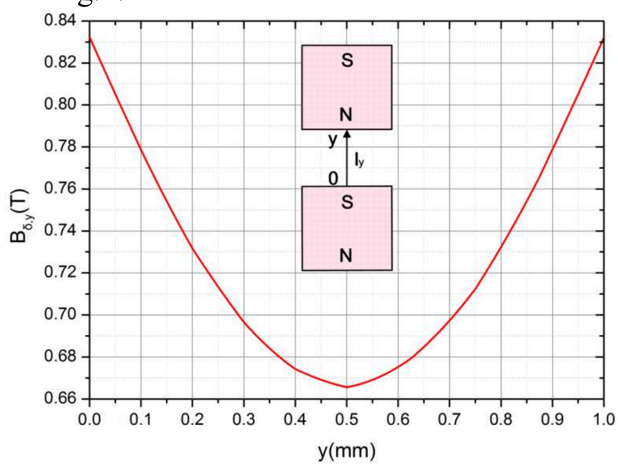

Fig.4 Magnetic flux density distribution along the middle line ly

Fig.4 indicates that magnetic density is the strongest on surface of magnet and weakest in the middle of the gap. We can get magnetic density in the magnetic gap with this simulation method.

3.2 Comparison between magnetic flux distribution of generators with and without magnetic material

According to the simulation method above, we can get the magnetic flux distribution of generator with and without magnetic material in coil, as shown in Fig.5.

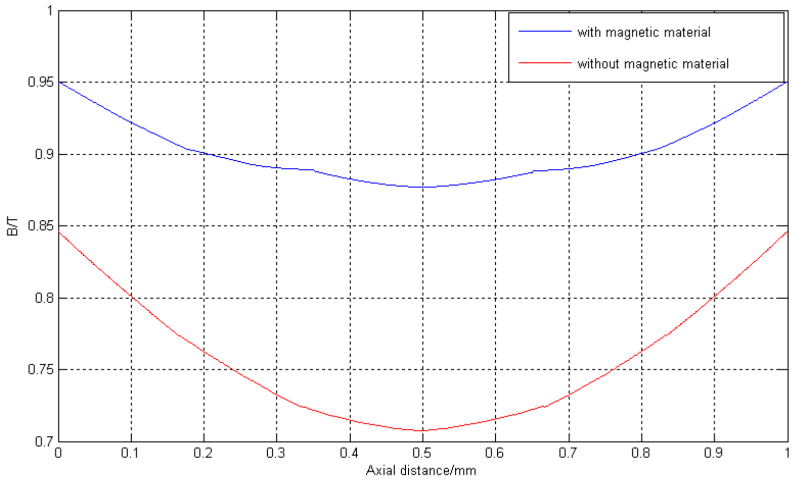

Fig.5 Magnetic flux density distribution of generators with and without magnetic material

Fig.5 shows that addition of magnetic material increases magnetic density in the gap effectively. Thickness of gap is 1mm, coil is double layer. The layers of the upper coil are located at 0.24mm and 0.28mm from the upper magnetic surface. The layers of the lower coil are located at 0.72mm and 0.76mm from the upper magnetic surface. And we can get the magnetic flux density of different layers of coil from Fig.5.

Table.1 Magnetic density at different layers of coil

Location of coil	0.24mm	0.28mm	0.72mm	0.76mm	Magnetic flux density average[T]
Magnetic flux density without magnetic material in coil[T]	0.750203	0.739149	0.739149	0.750207	0.744677
Magnetic flux density with magnetic material in coil [T]	0.895735	0.891489	0.890901	0.895018	0.8932858

Magnetic flux distribution of generators with and without magnetic material in its coil is obtained by finite element method. Then put these values into Eq.1, we can get the output voltage with various rotational speed.

4 Experimental results

In experiment, rotor is driven by motor and output voltage of generators with and without magnetic material in coil is tested. Comparison between experimental results and simulation results is shown in Table.2 and Table.3.

Table.2 Experimental results without magnetic material in coil

No.	Rotational speed [kr/min]	Output voltage [V]	Output voltage / Rotational speed in experiment [V/kr]	Output voltage / Rotational speed in simulation [V/kr]	Simulation error [%]	Simulation error average[%]
1	0.879	0.2	0.228		2.79	
2	1.965	0.42	0.213696		9.48	
3	2.572	0.58	0.225504		3.74	
4	2.629	0.56	0.213024	0.233947	9.82	6.56
5	3.962	0.88	0.222112		5.33	
6	5.507	1.2	0.21792		7.35	
7	5.967	1.3	0.21788		7.37	

Table.3 Experimental results with magnetic material coil

No.	Rotational speed [kr/min]	Output voltage [V]	Output voltage / rotational speed in experiment [V/kr]	Output voltage / rotational speed in simulation [V/kr]	Simulation error [%]	Simulation error average[%]
1	0.779	0.30	0.3852		-27.15	
2	1.238	0.48	0.38784		-27.64	
3	1.754	0.58	0.3306		-15.11	
4	2.439	0.80	0.328	0.280634	-14.44	-19.62
5	2.495	0.82	0.328656		-14.61	
6	3.056	1.08	0.353376		-20.58	
7	4.980	1.70	0.34136		-17.79	

Experimental results present that under the same rotational speed, output voltage improves 59.6% with the addition of magnetic material in coil compared to coil without magnetic material.

When there is no magnetic material in the coil, the error between simulation and experiment is 6.56% which indicates that the simulation method is feasible. While when there is magnetic material added in the coil, error between simulation and experiment is -19.62%. Simulation result is less than experimental result with bigger errors and that's because: (1) Definition of iron material is different with the one used in experiment, (2) In experiment, magnetic material is attracted by the magnets and the coil is on the one side of the gap instead of in the middle as the model in simulation. In the middle of the gap, the magnetic flux density is smallest, so attracted on one side of the gap, the coil is in an area with a bigger magnetic flux density and the output voltage is increased.

However, magnetic material attracted by the magnet and located on one side of the gap increases frictional resistance and incurs difficulty in rotational speed increasing. Meanwhile, there's hysteresis torque and eddy current loss produced between rotating magnets and static magnetic material. Last, since there's negative correlation between magnetic flux density and gap thickness, adding magnetic material increases gap thickness and decreases output voltage. Further we should thinner the magnetic material and that would improve the output performance.

5 Conclusions

Addition of magnetic material in coil increases magnetic flux density in the gap and improves output performance effectively. We further discussed the feasibility to add magnetic material in coil, presented the existed problems and improvement methods. In the future, we will analyze how different magnetic material and shapes influence output performance and solve the problem of frictional resistance caused by addition of magnetic material. Addition of magnetic material improves output performance considerably and deserves further research.

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