Airflow energy harvesting through diamagnetically levitated magnet rotor

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Abstract. An airflow energy harvester by using diamagnetic levitation technology to generate electricity is presented in this paper. The energy harvester consists of a lifting magnet, an upper pyrolytic graphite plate, a magnet rotor, two centrosymmetric nozzles, induction coils, and a lower pyrolytic graphite plate. The lifting magnet is used to exert an upward force on the magnet rotor, so the levitated magnet rotor can stably levitate. In order to study the output characteristics of the energy harvester, two streams of airflow are applied to the magnet rotor to form a force couple. The relationship between the induced voltage and the airflow rate was analyzed and tested by simulation and experiment. In this paper, the flow rate was controlled by the mass flow controller, and the output voltage under different airflow rates was recorded. It was found that the peak induced voltage of the coil could reach 2.8 V when the flowrate was 3000 sccm.

1. Introduction
In recent years, with the development of wireless sensor network (WSN), a growing number of wireless sensors have been used in remote places. Due to the lifespan limitations of conventional batteries, developing permanent and zero-maintenance batteries is a hot research topic. There are various energy sources in nature, such as solar energy [1,2], vibration energy [3,4] and airflow energy [5,6]. Among these energy sources, airflow has been receiving widespread attention as a ubiquitous energy source. The most common airflow energy harvester is the wind turbine [7,8]. Holmes et al. studied a micro airflow energy harvester whose rotor area is down to about 1.5 m², and a maximum output power up to 4.3 mW when the average wind velocity is 10 m/s [9]. Zhu et al. proposed a cantilever-based electromagnetic airflow harvester, which can get output power over 90uW when the flow speed exceeds 2 m/s [10]. Diamagnetic levitation technology [11-13] has been widely used in energy harvester due to its zero friction characteristics.

An airflow energy harvester used diamagnetic levitated structure was reported in this paper. An elaborate magnet rotor used airflow to float in the diamagnetic levitation structure. The stability of the energy harvester was verified by testing its output characteristics under a series of airflow rates.

2. Structure model
The structure model of the airflow energy harvester is shown in figure 1. A lifting magnet, two centrosymmetric nozzles, an upper pyrolytic graphite plate, a magnet rotor, six induction coils, and a lower pyrolytic graphite plate make up an airflow energy harvester. Three blades of the magnet rotor evenly distributed along the edge. Six planar spiral coils form two layers of special-shaped coils, and the special-shaped coils are overlapped together. Every layer of special-shaped coil consists of three planar spiral coils, and the planar spiral coils evenly distributed around the central axis of the magnet rotor on the bottom of the top of the lower graphite and correspond to the blades of the rotor. An attracting force of the lifting magnet is to counteract the gravity of the rotor, and the upper and lower...
HOPG plates help to keep the magnet rotor in equilibrium by exerting repelling force. Two streams of airflow acting on the magnet rotor to form a force couple. The magnet rotor can be driven to rotate between the two HOPG plates by the airflow, and the induced electromotive force will be generated within the coils. The magnet rotor is levitated and driven to rotate without physical contacting with other components which contribute to improving energy conversion efficiency.

**Figure 1.** Structure model of the airflow energy harvester.

Table 1 shows the necessary compositions and parameters of the airflow energy harvester. The vertical distance between lifting magnet and levitated rotor is 82.5 mm. The planar spiral coils are wound with 0.07 mm copper wire, with 3.2 mm inner diameter and 12 mm outer diameter. The levitation gap between the two HOPG plates and the levitated rotor are both 0.8 mm. And resistance of each coil is 40.3 Ω. The gravity of the magnet rotor is 0.2387 N.

**Table 1.** Parameters for the airflow energy harvester.

| Component  | Material         | Dimensions(mm) |
|------------|------------------|-----------------|
| Lifting magnet | NdFeB(N52)      | Ø25×10          |
| HOPG plate  | HOPG             | Ø25×2           |
| Coil        | Copper           | Ø0.07           |
| Magnet rotor| NdFeB(N52)       | Ø18×3           |
| Nozzle      | PVC              | Ø0.4(inner diameter) |

### 3. Theoretical analysis

#### 3.1. Diamagnetic levitation analysis

Since the magnet rotor is balanced in the vertical direction, the magnet rotor can be stably levitated between two HOPG plates. The repelling force of the diamagnet substances can be regarded as a diamagnetic force in magnetic fields $H$. The following equation can calculate the diamagnetic force [14].

$$ \mathbf{F}_d = \mu_0 \chi_m \int_V \nabla \mathbf{H} \cdot d\mathbf{V} $$

(1)

Where $\mu_0$ is the relative magnetic permeability, $\chi_m$ depends on the magnetic susceptibility, $V$ is the volume of diamagnet.

$$ G = F_L + F_D - F_E $$

(2)

Where $F_L$ is the upward attractive force from the lifting magnet, $F_D$ is the upward diamagnetic force from the lower HOPG plate, $F_E$ is the downward diamagnetic force from the upper HOPG plate.
3.2. Driving force and air resistance calculation
The airflow rate is converted into airflow velocity.

\[ v_0 = \frac{Q}{\pi r_0^2} \]  \hspace{1cm} (3)

Where \( r_0 \) is the radius of the nozzle, \( v_0 \) is the outlet velocity of the airflow.

The control body as shown in the figure 2(a) satisfies the momentum equation [15].

Figure 2. Schematic diagram of the interaction between air flow and magnet rotor.

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\begin{align*}
\oint p \cos(n,x) dS + \iint \rho f_x d\tau - F_x &= \frac{\partial}{\partial t} \iint \rho u d\tau + \iint (u \cdot n) u \rho dS \\
\oint p \cos(n,y) dS + \iint \rho f_y d\tau - F_y &= \frac{\partial}{\partial t} \iint \rho v d\tau + \iint (v \cdot n) v \rho dS \\
\oint p \cos(n,z) dS + \iint \rho f_z d\tau - F_z &= \frac{\partial}{\partial t} \iint \rho w d\tau + \iint (w \cdot n) w \rho dS
\end{align*}
\]  \hspace{1cm} (4)

Where \( S \) is the area of control surface, \( p \) is the fluid stress, \( n \) is the unit vector of the outer normal, \( \tau \) is the volume of control body, \( \rho \) is the density of the fluid, \( F \) is an external force of acting on the control body, \( f \) is the mass force, \( u \, v \, w \) is the flow rate of the fluid.

The force on the control body can combine with equation (4) in the y direction.

\[ F = \iint (v \cdot n) v \rho dS \]  \hspace{1cm} (5)

The torque produced by the two centrosymmetric nozzles.

\[ T = 2FL \]  \hspace{1cm} (6)

Where \( L \) is the vertical distance from the nozzle to the axis of rotation.

Air resistance is mainly composed of viscous resistance and windward resistance. The air resistance force on the rotor can be calculated in two parts as shown in the figure 2(b)

Viscosity resistance of the upper and lower surfaces.

\[ f_{ii} = -\mu A \frac{v}{2h} = -\mu A \frac{W_r}{2h} \]  \hspace{1cm} (7)

\[ M_i = 2 \int_{R_0}^{R} \mu A \frac{W_r^2}{2h} dr = \frac{\mu A W_r}{3h} (R^3 - R_0^3) \]  \hspace{1cm} (8)

Where \( \mu \) depends on the dynamic viscosity of the fluid, \( A \) depends on the surface area, \( h \) depends on the levitation gap.

Windward resistance of side walls.
\[ f_2 = -b \nu_i = -b w r_i \] (9)

\[ M_z = \int_R^R 3 b w r^2 dr = -b w (R^3 - R_0^3) \] (10)

Where \( b \) depends on the performance of the fluid.

The rotor is in equilibrium when the driving force and resistance are equal in magnitude.

\[ T + M = 0 \] (11)

Peak induced voltage.

\[ E = n B S w = \frac{6 \rho h L n B S \sin \theta}{\pi \nu_0^2 \left[ u A (R^3 - R_0^3) + 3 h b (R^3 - R_0^3) \right]} Q^2 \] (12)

### 3.3. Simulated analysis

Finite element software COMSOL Multiphysics 5.3 is used to simulate and analyze the flow field. Figure 3(a) shows the streamline diagram of airflow. Parametric scanning of flow rate is used to obtain the torque of the rotor under different airflow rate. The relationship between airflow rate and torque shows in figure 3(b). The airflow is mainly divided into two streams when it is acting on the blades of the magnet rotor. One stream of airflow moves clockwise along the arc of the blades and the other one moves counterclockwise along the arc of the blades, which is consistent with the physical model of the torque analysis we performed.

![Flow field simulation analysis.](image)

### 4. Experiment

An experiment model is established to test the output characteristics in figure 4(a). And the detail of airflow energy harvester is shown in figure 4(b).

In the experiment, a nitrogen cylinder with constant pressure as a gas source and connected to the centrosymmetric nozzles. Two mass flow controllers (AITOLY MFC300) were used to control the gas flow with the computer software. An oscilloscope (Tektronix TDS2012B) was used to measure the voltage and frequency of the induced current.
The relationship between peak output voltage of the coils and airflow rate shows in figure 5. It was found that the energy harvester began to generate an induced voltage when the flowrate was 60 sccm. The relationship between airflow rate and the output voltage was a quadratic curve when the airflow rate was smaller than 2800 sccm. The analytical curve was highly consistent with the experimental data. The voltage increased continuously when the airflow rate was larger than 2800 sccm, while the correlation function no longer conformed to the quadratic curve. Since the measuring scale of the mass flow controller is 0~3000 sccm, the peak induced voltage of the coil could reach 2.8 V when the flowrate was 3000 sccm and the magnet rotor still rotated stably at the same time.

Figure 5. Induced voltage with various airflow rates.

5. Conclusions
An airflow energy harvester by using diamagnetic levitation technology was proposed and investigated in this paper. The energy harvester could respond to a flowrate as low as 60 sccm. When the airflow rate was smaller than 2800 sccm, the relationship between the airflow rate and the output voltage is a quadratic curve with a coefficient of determination 0.9994. While the flowrate was 3000 sccm, the output reached 2.8 V. The experiment results demonstrated the possibility of the airflow energy harvester with a diamagnetically levitated magnet rotor. Future work includes optimizing the layout of the rotor, coil size, and nozzle position to improve the dynamic characteristic of the magnet rotor.

6. References
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