Development of MEMS Air Turbine Micro Generator with Ball Bearing Mechanism and Magnetic Material

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Abstract. This paper proposes an electromagnetic type MEMS air turbine generator combining an air turbine fabricated by MEMS process and a magnetic circuit by multilayer ceramic technology. Introducing ball bearing system for the turbine, two types of turbine rotor, a planar type and a rim type, were evaluated. The rim type achieved 290,135 rpm at the inlet flow of 2.4 L/min and the pressure of 0.3 MPa. The magnetic circuit was fabricated by multilayer ceramic technology. The circuit consist of Ni Cu Zn ferrite and silver 100 turn helical coil. The internal resistance was 2 Ω. The dimensions of the combined generator were 7.40 mm, 8.47 mm and 5.82 mm, respectively. When the load resistance was 8 Ω, the generator showed the maximum output. The maximum power was 2.41 mVA.

1. Introduction

Miniaturization of a power supply is important issue. A lithium ion secondary battery has been mainly used. However, the energy density has reached its theoretical limit. Therefore, miniature electric generators have been studied as the candidate to replace the battery. MEMS (Micro Electro Mechanical Systems) process has been used to achieve the miniaturization. MEMS process is based on the IC production process, and it produces a micro structure. The research of MIT UMGT (Ultra Micro Gas Turbine) which used the MEMS process was reported [1]. There are two methods for the MEMS power generation; an electrostatic type and an electromagnetic induction type. Since the structure is easy to fabricate by MEMS process, most of them are the electrostatic type [2]. However, its output power is small due to the charge saturation and the high internal impedance. On the contrary, the electromagnetic induction type is expected to achieve the high output power [3]. This type requires a complex magnetic circuit, and also, it does not contain a magnetic core usually. Therefore, the magnetic flux divers. To collect the magnetic flux, the area of the coil becomes wide, and then, the conductor loss increases.

We focused on the multilayer ceramic technology to form the miniature three-dimensional magnetic circuit. The multilayer ceramic technology provides the monolithic structure that has the helical coil and magnetic core. We previously developed the electromagnetic induction type MEMS air turbine generator combining with the multilayer ceramic magnetic circuit. The fluid-dynamic bearing system was adopted because of the low friction. However, its shaky motion reduced the rotational speed. Also, the gap between the magnet and the magnetic circuit was long because the flow path layer for the bearing should have been set between them. The maximum output power was 1.41 µVA [4].
In this paper, a miniature ball bearing is employed for the MEMS air turbine. It keeps the stable rotation. Moreover, by introducing a shaft, the permanent magnet can be separated from the turbine rotor. And then, the gap between the magnet and the magnetic circuit can be narrow. Two type rotors are fabricated with regard to the rotor structure, a planar type and a rim type. The rotational motion of these air turbines are evaluated, and then, the output power of the rim type is measured. The maximum power and the power loss are discussed.

2. MEMS Air Turbine
Developed MEMS turbines are shown in Figure 1 and Figure 2. The ball bearing of the planar type was arranged at the bottom of the rotor. A Compressed air flows from side inlet and to top outlet. The bleads is formed on the disk. The dimensions of the fabricated turbine were 5.23, 5.20, 4.51 mm length, width and height, respectively.

![Figure 1. The schematic diagrams and the photograph of the planar type air turbine.](image1)

Two ball bearings were used for the rim type. The bearings are placed above and below the rotor. The compressed air flows from side inlet to side outlet. The blade are formed on the side wall of the rotor. The dimensions of the rim type were 5.24, 5.37, 4.64 mm length, width and height, respectively.

![Figure 2. The schematic diagrams and the photograph of the rim type air turbine.](image2)

Rotation measurements were performed using hall elements. A comparison of the rotational speed is shown in Figure 3. The flow rate varied from 0 to 1.0 L/min. at pressure of 0.3 MPa. Experimental result revealed that the rim type system had a superior potential to the planar type.

![Figure 3. A comparison of the rotational speed of turbines.](image3)

3. Multilayer Ceramic Magnetic Circuit
The schematic diagrams of the multilayer ceramic magnetic circuit is shown in Figure 4(a) (b). The magnetic material was Ni Cu Zn ferrite with the permeability of 900. After the firing at 900 degrees Celsius, the four pieces were bonded and the closed magnetic circuit was obtained. The total number of coil turns were 100. The dimensions of the fabricated circuit were 7.40, 8.47, 2.36 mm, length, width and height, respectively. The measured DC resistance were 2 Ω.
4. Results and Discussions

The fabricated the MEMS air turbine generator is shown in Figure 4(c). The dimensions of the generator combined with the micro air turbine and the multilayer ceramic magnetic circuit were 7.40, 8.47, 5.82 mm, length, width and height, respectively. Compressed air was introduced into the MEMS air turbine, and the output waveform was observed. The maximum rotational speed was 290,135 rpm when the inlet flow was 2.4 L/min, and the pressure was 0.3 MPa. The load resistance dependence of the output voltage and the output power is shown in Figure 5. When the load resistance was 8 Ω, the voltage and the maximum power was 139 mV, 2.41 mVA, respectively. The output waveform is shown in Figure 6 at the load resistance is 8 and 1000 Ω.

![Diagram of multilayer ceramic magnetic circuit](image)

**Figure 4.** The schematic diagrams of the multilayer ceramic magnetic circuit and the photograph of the assembled generator.

![Waveform graphs](image)

**Figure 5.** Relations between load resistance and output voltage and output power. 2.4 L/min, 0.3MPa

![Waveform graphs](image)

**Figure 6.** The output waveform at the load resistance is 8 and 1000 Ω.

When the load resistance $R_L$ is connected to the generator and the current $I$ flows through the circuit, the output voltage $V=R_LI$ is given by the following equation. At this time, the influence of the voltage drop due to the self-inductance $L$ and the internal resistance $r$ of the magnetic circuit are considered.

$$V = R_LI = N \frac{\mathrm{d}\phi}{\mathrm{d}t} - i\omega LI - rI$$

(1)

$\phi$ means the magnetic flux passing through the magnetic circuit of the generator. $N$ is turn number of the coil. The value of $L$ measured at the equivalent frequency of 290,135 rpm, with an impedance analyser Agilent 4294A was 241 $\mu$H. When 1 kΩ of $R_L$ is connected, the current flowing the circuit is sufficiently small and the voltage drop due to self-inductance and internal resistance is small. Therefore,
the output voltage is approximated by \( \frac{d\phi}{dt} \). The surface magnetic flux density of the permanent magnet is 0.159 T, and the magnitude of the magnetic flux on the magnet surface is 0.375 \( \mu \)Wb. If the all flux enter in the circuit, the amplitude of the output voltage is calculated to be 570 mV. In comparison with Figure 6 (b), 36% of the flux contributes to the actual power generation. It is considered that other magnetic flux leaks without entering the magnetic circuit. On the other hand, when \( R_L = 8 \) \( \Omega \), the reactance of \( \omega L \) is calculated 7.3 \( \Omega \). The values of \( \omega L \) and \( r \) are close to \( R_L \). Therefore, their influence appears. The absolute value of the output voltage is estimated as follows.

\[
|V| = \frac{N \frac{d\phi}{dt} R_L}{\sqrt{(R_L + r)^2 + \omega^2 L^2}}
\]

(2)

When calculated from equation (2), \(|V|\) becomes 367mV. Considering the contribution rate 36% of the magnetic flux to this result, it almost coincides with Figure 6(a).

When the current flows, the magnetic circuit occurs braking torque to the permanent magnet. In Figures 6(a) and 6(b), the rotational speed is almost equal. Therefore, it is considered that the braking torque by current is enough small in this system. The magnetic flux density from the magnetic circuit is estimated as follows.

\[
B = \mu_0 \mu_r NI
\]

(3)

\( \mu_0 \) is the vacuum permeability, \( \mu_r \) is the ferrite relative permeability , 900. \( B \) is calculated 1.96mT. When the magnetization of the permanent magnet and the magnetic flux density occurred by the magnetic circuit are perpendicular, the braking torque becomes maximum. If all of the magnetic flux contributes, the braking torque is estimated to about 42.9 pNm. This value is considered to be a sufficiently small value.

5. Conclusion

Two types of turbines with the ball barring were manufactured and the rotational speed was compared in this study. As a result, the rim type rotates faster than the flat planar type. Then, the electromagnetic type MEMS air turbine generator using the rim type was fabricated. The appearance size of the generator was 7.40, 8.47, 5.82 mm, length, width and height, respectively. The DC conductor resistance of multilayer ceramic magnetic circuit was 2 \( \Omega \). The load resistance dependence of the output voltage and the output power was measured. The maximum power of the generator was 2.41 mVA. Moreover, the measured voltage and power were compared to the theoretical value that was calculated taking account of the internal resistance and the self-inductance.

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