A MICROFLUIDIC-ELECTRIC PACKAGE FOR POWER MEMS GENERATORS

Florian Herrault, Chang-Hyeon Ji, Seong-Hyok Kim, Xiaosong Wu, and Mark G. Allen Georgia Institute of Technology, Atlanta, Georgia, USA

ABSTRACT

This paper reports the design, fabrication, and measurement results of a compact, multi-functional package for air-driven, rotary, electromagnetic MEMS generators. The fully integrated device includes a polymer-based fluidic housing, its associated turbine supported by a small, off-the-shelf, high-speed ball bearing, and a permanent-magnet (PM) generator with electroplated copper windings. The fluidic-electric package has an overall volume of approximately 1.1cm³, and weighs 1.5g. It withstands pressures up to 85kPa, can support rotational speeds up to 203,000 rpm, and generates an electrical output power of 0.8mW, indicating that this packaged machine is applicable to small, low-power systems.

1. INTRODUCTION

There is high expectation for a new generation of MEMS-scale power generation systems as current electronic devices become more compact and energy demanding. However, the miniaturization, and fabrication of fully integrated systems capable of converting an external source of energy (e.g. from high-pressure sources or small-scale combustion engines) into an electrical energy is still challenging. Compact, air-driven, standalone type generators require high mechanical strength to sustain high-pressure flows, and precision machining to assemble and align each element. To achieve these structures, relatively complex fabrication techniques such as etching and stacking silicon wafers, and selective laser micromachining of polymer sheets followed by lamination, have been investigated. In spite of the fabrication challenges, several successful approaches to power generation have been demonstrated. Stevn et al. have fabricated a MEMS electroquasistatic induction turbine-generator, and demonstrated a maximum output power of 192µW under driven excitation [1]. Holmes et al. have integrated a 7.5mm diameter permanent-magnet generator, an axial-flow polymer turbine, and a silicon-based package, and achieved an output power of 1.1mW at a rotational speed of 30,000rpm, which corresponds to an input flow rate of 35L/min, and a pressure of 0.8kPa [2].

To achieve reasonable levels of output power from ultracompact power MEMS typically requires high rotational speeds. The rotating system of high power density generators must be supported by low friction bearings in order to achieve such speeds. One approach is to consider microfabricated air bearings as described in [1]. Recent research efforts on the integration of more conventional metal ball bearings into microfabricated systems for high-speed applications are promising [3]. However, long-term operation is still under investigation.

We previously presented a 55cm³, self-contained, flow-powered microgenerator system for watt-level applications [4]. Despite relatively large electrical power output, the size and weight of this device are drawbacks for applications that require small footprint and light weight, such as portable electronics. More recently, we reported the fabrication and characterization of ultraminiaturized permanent-magnet generators that demonstrated milliwatt-scale power capability at high rotor speeds (~400,000rpm) [5]. As an ongoing effort of scale reduction and integration, we present in this paper the development of a combined microfluidic-electric, compact package for micropower generation. Using an external source of pressure, the device generates electrical output power in the milliwatt range. Such machines could potentially be applied to backup battery chargers, RF MEMS, or sensing devices in an environment where high-pressure, gas streams are available.

2. SYSTEM DESIGN

The packaged system combines fluidic, mechanical, magnetic, and electrical functionalities. It first converts stored energy from a source of compressed gas into mechanical energy via a radial-flow turbine. This energy is next transformed into electrical energy through a 2mm diameter, microfabricated, axial-flow, and permanent-magnet (PM) generator. For such small devices, rotational speeds in excess of 100,000rpm are required to generate appreciable output power. A three-dimensional rendering of the microfluidic-electric package is presented in Figure 1.



Figure 1. Schematics of the microfluidic-electric package: (a) 3-D cross view, (b) 3-D view.

An external source of pressure is used to spin the radial-flow turbine and the multi-pole PM rotor, creating a time-varying magnetic field [6]. Hence, AC voltages are induced in the three-phase stator windings, and electrical power is delivered when these windings are connected to a load. The microfluidic-electric package requires precise machining tolerances and high mechanical stability to maintain an air gap on the order of 100µm between the high-speed magnetic rotor and the stator. Moreover, the package must withstand high input pressures, and direct the gas flow towards the turbine blades. Because of the milliwatt-scale output power level, the resistance of the electrical connections must be very small to minimize electrical losses.

As the rotor measures 2mm in diameter, high-speed ball bearings that have comparable dimensions are selected. The housing is scaled around the size of the silicon stator die, and contains the rotating system. The turbine is designed based on the diameter of the bearing. In this initial effort, the detailed shapes and dimensions of the blades and channels have not been optimized for efficiency: instead, with an eye toward future mass-manufacturing, the turbine is reduced to six straight blades that span 60°. The inlet and outlet ports are aligned with each other, and face the outer part of the turbine blades to increase the torque of the rotor. A miniature, off-the-shelf, ball bearing set (SSRI418Z5MCM5, National Precision Bearing, Inc.) is utilized for stability at high rotational speeds and long-term operation.

The ultraminiaturized PM generator is a three-phase, four-pole, three-turn/pole, axial flux, synchronous machine. The stator consists of electroplated surface-wound copper coils on a silicon substrate, and the 2mm diameter rotor includes neodymium iron boron (NdFeB) permanent magnets and an iron cobalt vanadium (FeCoV) soft magnetic back iron. Detailed fabrication and characterization of ultraminiaturized PM generators have been previously reported using a test setup [5], and have demonstrated output power across a resistive load of approximately 3.6mW at a rotational speed of 392,000rpm.

3. SYSTEM FABRICATION

The housing, along with the turbine and its integrated magnetic rotor are fabricated by stereolithography (SLA). This fabrication technique consists of selectively curing a liquid resin with a laser beam via a specific 3-D computer-aided-design (CAD) pattern, in order to build 3-D polymer structures. SLA is commonly used for rapid prototyping, and is compatible with subsequent micromolding for mass production at reduced cost. SLA processes have certain advantages over conventional micromachining such as large structure height, ability to fabricate integrated microfluidic channels, or complex 3-D structures with features on the sidewalls, at the expense of the precision achievable with conventional micromachining. The x- and y- resolution of the SLA machine used to fabricate the package is 100µm. Although the SLA process is serial in nature, as mentioned above the subsequent use of micromolding can overcome this limitation. Further, judicious choice of the polymer for the package enables overall light weight, yet sufficient robustness to withstand high input pressures. The mass density of the epoxy-acrylate polymer material in this work is 1.13g/cm³.

An exploded view of the machine and package is shown in Figure 2. The stator pads are wire-bonded onto pressed magnet wires that are attached to the SLA backplate, and in turn brought out to external electrical connections. The PM pieces and the back iron disc are inserted into the rotor housing integrated at the bottom of the turbine. The ball bearing is inserted into the back of the fluidic housing.



Figure 2. View of the power generation system before assembly.

All the parts are assembled by inserting alignment posts from one element into complementary recesses in the facing element. Both posts and recesses were formed during the layer fabrication process. The rotor assembly is press-fit and adhesively bonded to the inner surface of the bearing. The alignment and the air gap are set in this manner without any additional precautions. The assembled system is shown in Figure 3.



Figure 3. View of the assembled microfluidic-electric package.

The main dimensions of the air-driven magnetic power generation system are summarized in Table 1. The system has an overall volume of 1.1 cm^3 , and a weight of 1.5 g.

The encapsulated ultraminiaturized PM generator accounts for 10% of the total volume of the system.

	Diameter (active area)	2.00
Magnetic	Air gap	0.10
Generator	Total height (rotor + stator)	1.60
	Die size	8.50
Turbine	Diameter	6.35
I ui bille	Height	2.60
	Outer diameter	6.35
Bearing	Inner diameter	3.10
	Height	2.35
Housing	Width	10.60
	Length	10.60
	Height	9.86

Table 1. Dimensions of the air-driven magnetic power generation system (in mm)

4. SYSTEM CHARACTERIZATION Fluidic Characteristics

To test the fluidic characteristics of the package and turbine, the rotational speed of the 2mm diameter rotor is measured as a function of input pressure, as represented in Figure 4. The pressure required to start the turbine is approximately 25kPa, and is higher than the minimum pressure at which the machine operates steadily. In practice, the pressure is first increased above 25kPa, and then decreased to measure the rotational speed of the turbine below the starting threshold. At higher pressures, instabilities occur in the rotating system, which causes the rotor to crash on the stator.



Figure 4. Rotor speed as a function of input pressure for microfluidic-electric package, and commercial turbine.

For comparison, the rotor speed of a commercial turbine (HNG-100H, Handpiece Parts and Products, Inc.), which has been used to test the ultraminiaturized PM generators in the experimental setup reported in [5], is also plotted as a function of the input pressure.

This commercial turbine uses a set of two ball bearings similar to the one used in the multi-functional package. The pressure-speed curves of the two turbines compare favorably over the range 0-200krpm. While higher rotational speeds than 200krpm are achievable with the off-the-shelf turbine, its starting pressure, which is around 53kPa, is higher than that of the combined package. In addition, a slightly higher input pressure is required to spin the rotor at the same operating speed, confirming the good design of the fluidic package. The size of the commercial turbine, packaged in a cylinder of a diameter of 8.6mm, and a height of 9.6mm, is larger than the system turbine-bearing reported in Table 1.

Electrical Characteristics

The single-phase resistances of the stator coils are measured before and after packaging as shown in Table 2. The resistance exhibits approximately a 25% increase and a 3% phase-to-phase discrepancy after assembly, which is attributed to the aluminum bond wires. This connection scheme shows improvement (i.e. lower resistance) over the one reported in [5] that uses a ceramic package.

Table	2.	Resistance	of the	e winding	phases	before	and	after
			р	ackaging	5			

Phases	Winding resistance (mΩ)	Packaged device resistance (mΩ)
A	426	536
В	430	531
С	429	513

The open-circuit voltages induced by the multi-pole spinning rotor in the three phases of the stator windings are shown in Figure 5. Such symmetric and sinusoidal waveforms indicate that the rotor and stator are accurately aligned, suggesting that the precision of SLA fabrication techniques are sufficient for this application. At a rotational speed of 92krpm, the device exhibits a single-phase open-circuit voltage of 30mV peak-to-peak (= $10.6 \text{mV}_{\text{rms}}$).



Figure 5. Open-circuit voltage waveforms of the three phases of the PM generator at a rotational speed of 92krpm.

The single-phase, RMS (Root-Mean-Square) voltage delivered by the microfluidic-electric package is then measured as a function of rotational speed and electrical frequency, as shown in Figure 6. Both, the open-circuit voltage (V_{oc}) and the load voltage (V_{load}) measured across a resistive load of approximately 0.6 Ω , are plotted. As expected, the output voltage increases linearly with the rotor speed [5, 6].



Figure 6. Output voltage measurements as a function of rotor speed and electrical frequency.

Comparing the open-circuit voltage generated by the microfluidic-electric package with the open-circuit voltage measured as a function of the air gap from a similar 4-pole, 3-turn/pole, and NdFeB microgenerator confirms that the air gap between the rotor and stator in the package is approximately 100 μ m, as expected by the 3-D design. When powered by an 85kPa pressure source, the rotor spins at 203,000rpm, and the machine generates an open-circuit voltage of 25.5mV_{rms} per phase.

The single-phase, RMS load voltage measured across a matched load resistance is used to calculate the RMS output power. The data are plotted as a function of the rotor speed and electrical frequency in Figure 7.



Figure 7. Measured single-phase RMS power as a function of rotor speed and electrical frequency.

Therefore, the three-phase microgenerator exhibits a total RMS output power of three times the one measured across a single phase. Hence, 0.8mW of average electrical power is achieved at a rotational speed of 203,000rpm, which corresponds to a power-to-weight ratio of 0.5mW/g, and a power density of 0.7mW/cm³.

5. CONCLUSION

An air-driven, microfluidic-electric package has been designed by combining a micromachined permanent-magnet generator, and a polymer-based rotating turbine and housing fabricated by stereolithography. The system has a volume of 1.1cm³, and weighs 1.5g. When driven by an 85kPa pressure source, the device demonstrates a maximum output power of 0.8mW at a rotational speed of 203,000rpm. These promising results indicate that this microfluidic-electric package is suitable for low power applications. Higher system power densities can be achieved not only by optimizing the dimensions of the rotating system to decrease the required input pressure and/or increase operational speed, but also increasing the percentage of space occupied by the electrical power generation means within the package

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