Design, fabrication and characterization of an air-driven micro turbine device

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Abstract. Micro turbine is one of the important components in a micro gas turbine engine. This paper reports on the development and investigations of a micro turbine device driven by compressed air, which consists of three layers of silicon wafers and two layers of acrylic plates. The rotor has an outer diameter of 8.4 mm with a thickness of 0.76 mm. The key challenges to develop a successful high-speed turbine device are geometry design and fabrication of micro blade profiles as well as air-bearings. The micro air bearings have been designed, and a deep reactive ion etching (DRIE) process has been used for fabricating micro journal bearings with high aspect ratio. The micro turbine has reached a rotating speed of 9,000 rpm during test.

Keywords: micro gas turbine engine, turbine device, DRIE, air bearing

1. Introduction
A MEMS (Microelectromechanical systems) -based micro gas turbine engine 1-3 will be one of the promising solutions to provide high density power source for portable electronics, micro robots and micro satellite-related systems. A micro gas turbine engine consists of a radial inflow turbine, a centrifugal compressor and a combustor. The micro turbine is one of the critical components in a micro gas turbine engine, since it is used for outputting power as well as for rotating the compressor.

The critical aspects for a turbine testing-device include blades profile and micro air bearings. A typical conventional rotor has a dimension of a few millimeters along its axial direction. However, the axial dimension of a MEMS-based turbine is limited to less than half a millimeter due to process limitation. This will result in a journal air bearing with low aspect ratio (bearing Length/Diameter, L/D). A short journal bearing implies that it is supporting a thin disk rather than a shaft. Furthermore, a
journal air bearing is defined by a narrow trench, then the ratio of \( W/D \) (Width/rotor Diameter) \(^{4,5}\) will affect the performance of a journal bearing. Both a low aspect ratio of \( L/D \) and a high ratio of \( W/D \) will lead to low capability and low stability of a journal bearing.

This paper reports on the development of a silicon-based micro turbine device. Instead of using exhausted gas from a micro combustor, the turbine is driven by compressed air at room temperature. The performance of the turbine at room temperature will be different from that driven by hot exhausted gas. This research aims mainly to realize a prototype of turbine device based on DRIE process, and then to investigate the basic behavior of the turbine test rig.

2. Design of Micro Turbine Device

Fig. 1(a) shows the schematic design of a micro turbine test rig for MEMS-based gas turbine engine. The turbine consists of three layers of silicon wafers and two acrylic plates for tubing and clamping. Fig. 1(b) shows the exploded view of the turbine with the acrylic plates omitted. There are three flow paths, which are for rotor driving, journal air bearing and thrusting air bearing, respectively. The 3\(^{rd}\) wafer provides a platen of 10 \( \mu m \) deep for the rotor and the flow paths for driving air as well as for air bearings. The blades profile for both the rotor and stator are fabricated from the 2\(^{nd}\) layer of wafer. The 1\(^{st}\) wafer provides the air outlet and a platen of 10 \( \mu m \) deep for the rotor. Silicon wafers of 0.4 mm thick are used for 1\(^{st}\) and 3\(^{rd}\) wafers. A wafer of 0.76 mm thick is used for the 2\(^{nd}\) wafer, from which both the rotor and stator are fabricated. Fig. 2 (a) shows the profile design for both rotor blades and stator guide vanes. The rotor has 17 blades with outer and inner diameters of 8.4 mm and 4.4 mm, respectively. The stator has 23 blades for guide vanes; the outer and inner diameters of the guide vanes are 10.5 mm and 8.5 mm, respectively. The blade height is designed to be half of the wafer thickness.

The velocity vectors that express the relative flow of driving air at middle section of blades have been investigated using simulations based on three-dimensional computational fluid dynamics (CFD). It can be seen from the velocity vectors shown in Fig. 2(b) that the airflow velocity in the boundary layer gradually increases from zero to the main flow velocity. The angle of airflow at rotating blade inlet matches the blade profile; no obvious flow separation region is found at airfoil forepart. This ensures the improvement of efficiency and augmentation of output power. The designs shown in Fig. 2 are under the condition that the turbine is driven by exhausted gas from a combustor. When it is driven by compressed air, its performance such as rotation speed and output power will be slightly decreased.

In turbine design, micro holes with a diameter of 0.24 mm are distributed on a 6 mm diameter circle to provide hydrostatic thrust bearing. Hydrostatic journal bearing is provided via 8 holes (0.5 mm in diameter) distributed on an 11 mm diameter circle. The radial clearance of a journal bearing will be defined by the width of a trench between the rotor and stator. A trench of 20 \( \mu m \) wide and 380 \( \mu m \) deep with an aspect ratio of 19 is expected. However, fabrication of such journal bearing using standard DRIE (deep reactive ion etching) process is a critical challenge.

![Fig.1 Design of micro turbine testing device](image-url)
3. Fabrication

The DRIE based on ICP (Inductively Coupled Plasma) is the major process for fabricating the turbine device. For the design depicted in Fig. 1, all wafers contain patterns that need to be fabricated from both sides and etched through. Process parameters including plasma source power, bias power and process pressure have been optimized to realize high aspect ratio etch and to obtain straight sidewalls. Fig. 3(a) shows the roughness of thrust bearing surface on 3rd wafer measured using a Zygo interferometer. It can be seen that the peak-to-peak flatness over a 3.6 mm scanning-length is 150 nm, and the local roughness is about 10 nm. Fig. 3(b) illustrates the inner sidewall of the stator fabricated on the 2nd wafer. The measurement demonstrates that its surface roughness is less than 0.2 μm. The surface roughness and roundness of the sidewall are important because a journal bearing is defined by the clearance between two sidewalls of stator and rotor, respectively. Fig. 4(a) demonstrates the optical microscope image of the assembled stator-rotor pair from topside. Fig. 4(b) illustrates the journal bearing from bottom side. The radial clearance is about 20 μm, which is acceptable for the turbine testing-device. Process optimization for fabricating micro air journal bearing with precise radial clearance will be performed in future investigation.
4. Measurement of Rotation Speed

The three layers of turbine components are aligned via four pinholes and then clamped between two acrylic plates for testing. Fig. 5 shows the instrumentation for measuring the rotation speed of the turbine test rig. The turbine device is assembled in an acrylic package. The package is then connected to a gas distribution system, which consists of a compressed air source, pressure transducers, valve regulators and mass flow meters. The turbine is driven by compressed air, the rotation of which can be recorded by a high-speed video camera or an optical fiber sensor. The maximum recording rate of the high-speed video camera is 2,000 frames per second (fps). Fig. 6 illustrates one measured result from the camera, which demonstrates the rotation speed (rpm) at different flow rates (slpm; standard liters per minute). The interval for data sampling is 2 seconds. It can be found that the maximum speed has reached to 9,000 rpm at a flow rate of 8.8 slpm.

An optical fiber sensor with RS232 serial link to a computer is also used to measure the rotation speed of the developed turbine device. The optical fiber sensor is a reflective type transducer, whose output signal is proportional to the reflectivity of target surface and the gap distance from the sensor tip to the target. Considering that the sensor output will vary with variations of the target reflectivity, an ink-mark is printed on the rotor to make a reflectivity difference. Fig. 7 demonstrates the measured signal from fiber sensor, which is an intuition demonstration of rotation cycles at 3516 rpm. The spectrum analysis of the signal based on Fast Fourier Transform (FFT) has been performed as well. The FFT result shows two strong peaks at close frequencies, which indicates that the rotation speed is not uniform during operation while the flow rate is being kept constant. The factors resulting in the unsteady rotation are still under investigations. The possible reasons might be (1) the contact of the rotor with 1st wafer or 3rd wafer, or (2) the low stability of journal air bearing. Hence, future strategy of this research is to improve the stability of both thrust bearing and journal bearing and then to increase the rotation speed of the turbine device.
5. Summary
A micro turbine device has been designed and fabricated using MEMS-based micromachining technology. The micro turbine test rig consists of three layers of silicon wafers and two layers of acrylic plates, which has been assembled and tested using compressed air as driving force. The micro turbine has reached a rotating speed of 9,000 rpm when the flow rate of the compressed air is 8.8 slpm. Measurements using both high-speed video recorder and optical fiber sensor indicate that the rotation speed is not stable during operation. The future challenges are to improve the rotation stability as well as the rotation speed.

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