TORQUE MEASUREMENT METHOD USING AIR TURBINE FOR MICRO DEVICES

Hitoshi Ota*, Luming Li*, Munehisa Takeda*, Hiromu Narumiya*, Takao Ohara**, Koji Namura*
*Advanced Technology R&D Center, Mitsubishi Electric Corp.
**Manufacturing Engineering Center, Mitsubishi Electric Corp.
1-1, Tsukaguchi-Honmachi 8-Chome, Amagasaki, Hyogo, 661-8661 Japan

ABSTRACT

The authors have developed a general-purpose system that can measure very low torques in the order of 10^{-7} Nm. The new method proposed here uses wind pressure to apply a load to a turbine attached to the output shaft of the device. It can therefore be used for all rotating micro-devices. The use of wind pressure reduces the loss during measurement, and makes it possible to measure low levels of torque easily by simply attaching the turbine to the device. In the present study, the measuring principle of the new system was verified. In addition, a prototype micro-motor 1.6 mm in diameter was fabricated and used to demonstrate that the new system was able to measure torques in the order of 10^{-7} Nm while the motor was in operation.

INTRODUCTION

Researchers have recently been active in developing actuators from ten micrometers to a few millimeters in sizes for use in ultra-small devices [1, 2]. With a reduction in the device size, the output power from micro-devices diminishes. Torques developed by these devices are estimated to be lower than 10^{-6}Nm [3]. The development of highly efficient devices therefore requires an adequate method of evaluating very low levels of output power and torque. To obtain practical levels of output a micro-device must be rotated at high speed [4]. It is thus necessary to establish a method of measuring torque during high-speed operation.

A traditional method of measuring the torque of a micro-motor winds a micro-spring around the motor shaft [5,6]. Another method uses a cantilever to measure the reaction force produced as a load is applied to the rotor shaft [3]. As the device under measurement becomes smaller, however, it becomes more difficult to measure, for there is a considerable increase in the loss caused in the mechanical contact between the motor and the measuring equipment due to the applied load to the motor. When using a load sensor made of springs or other material, the transmission of external vibrations must be prevented. The measuring system therefore requires a complex structure. To avoid these problems, the newly developed method is designed to reduce the measurement loss. Also, the equipment used has a simple structure. The new method was used to measure torques lower than 10^{-6} Nm. It uses wind pressure to apply a load to a turbine attached to the output shaft of the device. A prototype micro-motor 1.6 mm in diameter was fabricated [7], and its torque was measured using the new measurement method.

TORQUE EVALUATION METHOD

Measurement principle

The new method uses wind pressure to apply a load to the motor without mechanical contact. Figure 1 shows the measurement principle. First, four-vane impulse turbine is attached to the motor's output shaft. A flange is accommodated around the turbine. As shown in Figure 1, the flange has four air holes corresponding to the number of turbine vanes. While the motor is rotating, a load is applied to it by sucking air from the air holes and thereby applying a wind pressure to the turbine. When air is sucked, the differential pressure occurs between the inside of flange and atmosphere (the out side of flange). Applied load to the motor is calculated multiplying the area of air hole by the differential pressure. However, circumferential air leaks between the turbine and the flange, and as a result, the pressure loss is caused. It is difficult to obtain losses analytically. Therefore, the motor torque is calculated using experimental constant and the mean radius of the four turbine vanes as indicated in equation (1).

$$T = \Psi \times 4 \times S \times \Delta P \times r \quad [\mathrm{Nm}] \quad (1)$$

Where,
Ψ: experimental constant
S: area of air holes [m^2]
ΔP: differential pressure in the chamber [Pa]
r: mean radius of the turbine vanes [m]

The experimental constant was determined experimentally using a commercially available DC motor with known torque characteristics. The torque of this motor was measured to establish the relationship between the pressure and torque, from which the constant Ψ was determined. The torque of the micro-motor was measured using the same turbine.

In this method, air is sucked in order to get stable flow condition. The air holes are arranged at intervals of 90 degrees to ensure that couples of forces are applied to the turbine. Therefore, no extra load acts upon the motor bearing. When the holes are arranged as shown in Figure 1, the load acts clockwise. Thus, the motor must be turned counter-clockwise. An impulse turbine was chosen because it prevents great variations in turbine efficiency due to changes in wind speed.

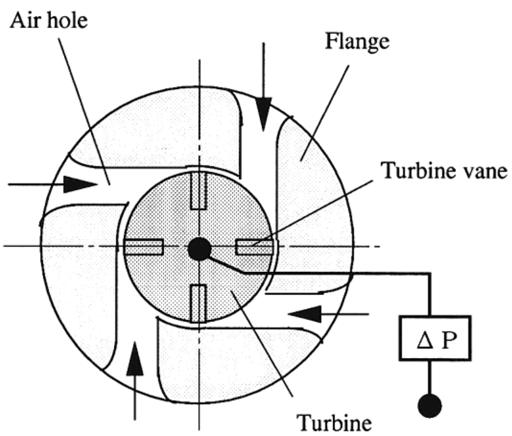


Fig. 1 Measurement method

Torque evaluation equipment

The torque evaluation equipment was fabricated according to the measurement principle shown in Figure 1. Figure 2 shows a schematic representation of the equipment.· It consists of a turbine for applying wind pressure to the motor, a flange, chambers, a vacuum cleaner, a wind-pressure regulating valve, a pressure sensor for measuring pressure in the chamber, and an optical sensor for measuring the rotational speed. As shown in Figure 2, the flange is arranged between two chambers. The flange has air holes for sucking air. The turbine was attached to the motor and put into the flange. To apply a load to the motor, air was sucked using the vacuum cleaner and wind pressure was thereby applied to the turbine. It was considered that, should a differential pressure be produced between the two chambers, the motor would be attracted to the cleaner chamber, generating an extra load in the direction of the motor shaft. To avoid this possible problem, a vent was provided between the chambers.

Dimensions of turbine and flange

Figure 3a shows the dimensions of the impulse turbine. A turbine 6 mm in diameter having four 2 x 2 mm vanes is attached to the motor. The mean radius of the turbine vanes is 2 mm. As shown in Figure 3b, the gap between flange and turbine is 0.1 mm. The air holes have a diameter of 1.5 mm. The outer end of the turbine is fitted with a 0.25 mm thick cover to reduce leaks in the axial direction of the turbine vanes. Glossy targets are fixed to the cover surface. These targets are used to measure the motor's rotational speed. The optical sensor shown in Figure 2 measures the intensity of the reflected light, and is usually used to obtain the displacement of the object from the tip of the sensor. As the highly reflective targets on the cover pass the sensor, they produce pulse outputs in the sensor. The motor's rotational speed can be obtained by measuring the frequency of the these output waves using a frequency counter.

Procedures

The test was carried out as follows. First, the turbine was attached to the motor shaft. The motor and turbine was attached to a micro-stage for alignment, which was then positioned in the motor chamber. When the center of the turbine vanes is out of alignment with the center of the air holes, it is assumed that the same level of wind pressure produces a weaker force on the turbine vanes. The micro-stage was adjusted to ensure that the turbine was placed at the center of the air holes. The center positions of turbine and air hole were determined as follows. The micro-stage was adjusted to align the cover surface with the edge of the air holes (shown in Figure 3b). And then, the motor was moved 0.3 mm in the X direction indicated by the thick arrow in Figure 3b. Next, the optical sensor for measuring the motor's rotational speed was installed in the cleaner chamber. While rotating the motor, the sensor stage position was adjusted to maximize the output level of the optical sensor.

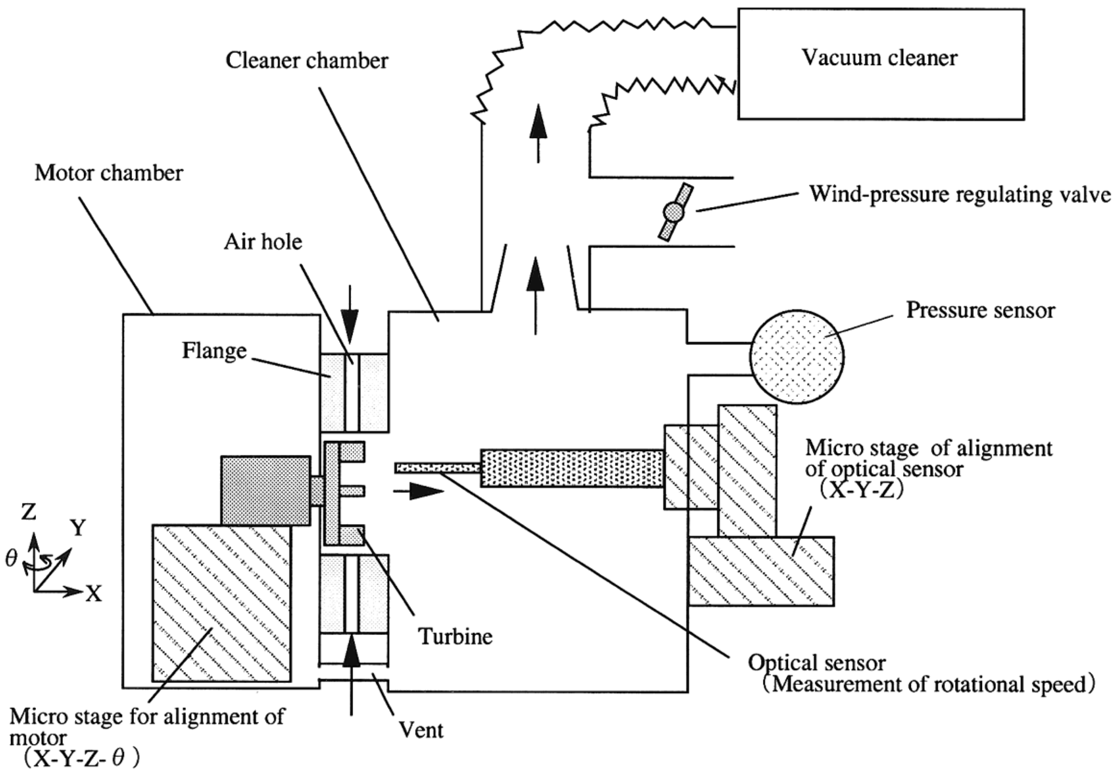
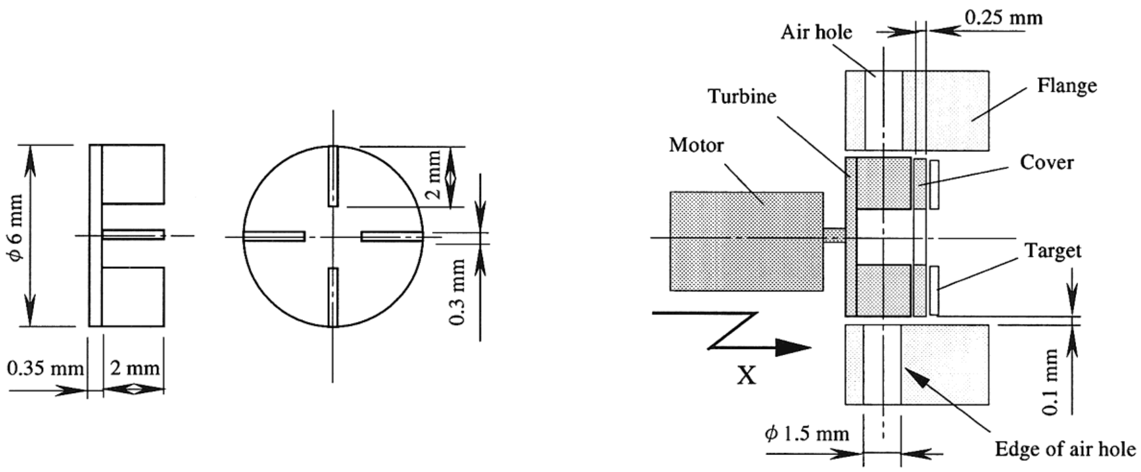


Fig. 2 Schematic of experimental equipment



(a) Dimensions of the turbine

(b) Schematic of experimental setting of motor with turbine

Fig. 3 Schematic of a turbine

After the motor and sensor were correctly positioned, the motor torque was measured. First, the motor was rotated at a specified rotational speed. Then, with the pressure regulating valve open, the cleaner was activated. With the activation of the cleaner, the air around the measuring system flows from the air holes through the cleaner chamber to the cleaner outlet, as shown by the arrows in Figure 2. The motor's rotational speed was monitored using a frequency counter. The pressure regulating valve was closed gradually to increase the airflow rate. As the airflow collides with the turbine vanes, the vanes are subjected to the differential pressure between the atmosphere and the cleaner chamber. A load is thus applied to the motor.

A preliminary test was conducted, using a commercially available motor, to obtain the experimental constant Ψ occurring in equation (1). A DC motor 4.4 mm in diameter was used. Figure 4 shows the turbine installed on the motor. The component indicated by the upward arrow is the cover. The cover surface is fitted with two targets which enable the optical sensor to measure the rotational speed. While the differential pressure is increased gradually at every 50 Pa approximately, changes in the motor's rotational speed were measured. The measurements were continued until the motor stops.

TEST RESULTS

Results of test using a commercially available motor

Figure 5 shows the DC motor's rotational speed as a function of pressure, using the turbine position as a parameter. The graph reveals that rotational speed reduces almost linearly with an increase in the pressure. At turbine positions 0.6 and 0.7 mm, i.e., when the bottom of turbine is moved close to the center of the air holes, the pressure is higher than that of the other turbine positions. This is because when the air holes align with the bottom of turbine, air easily leaks in the axial direction of the turbine and small area of turbine vanes are subjected to wind pressure. It is therefore necessary to apply extra pressure to generate the specified level of pressure.

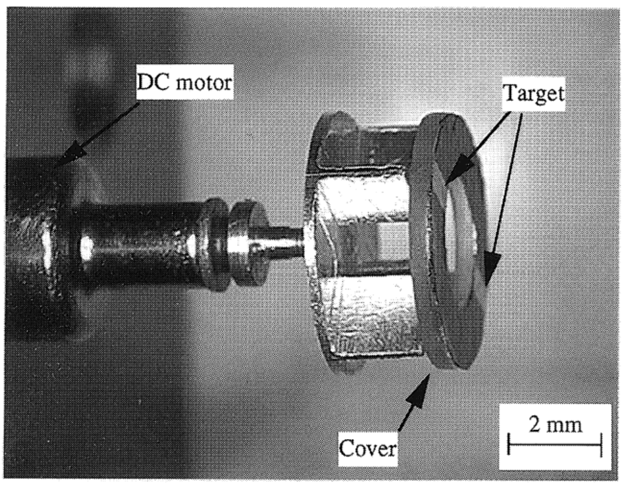


Fig. 4 Photograph of DC motor with turbine

Using the results obtained in Figure 5, the experimental constant Ψ in equation (1) was calculated. First, using equation (2), torque To was obtained from the measured value of ΔP:

$$T_O = 4 \times S \times \Delta P \times r \quad \text{[Nm]} \quad (2)$$

Then we have the value of the constant as follows:

$$\Psi = T_D \div T_O \quad (3)$$

where T_D is the known torque of the DC motor.

Figure 6 shows the experimental constant Ψ as a function of the turbine position. Here Ψ is maximized at 0.3 mm, where the center of the turbine vanes aligns approximately with the center of the air holes. At the turbine positions of 0.6 and 0.7 mm, the values of Ψ are small. This can be explained in the same manner as for the results shown in Figure 5: air leaks make it

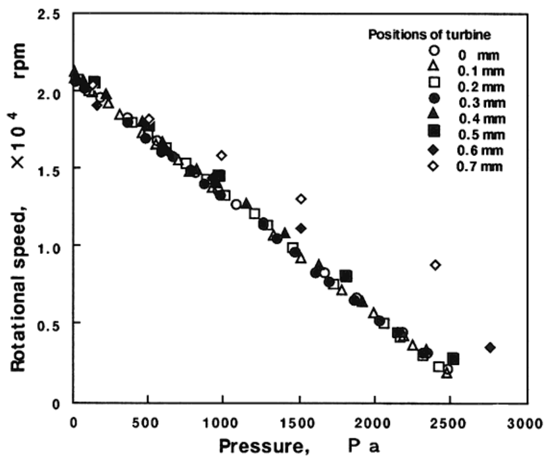


Fig. 5 Rotational speed as a function of pressure (DC motor)

necessary to apply an extra pressure to generate the same level of load on the turbine. These results reveals that air leaks can be minimized by first aligning the cover surface with the edge of the air hole and then moving the turbine by 0.3 mm. However, Changes in the values of Ψ are small between 0.1 -0.4 mm positions. The motor is easily placed in these positions. Therefore, accurate positioning procedure is not necessary in this method.

The torque of the DC motor was calculated using the value of Ψ obtained in Figure 6 and Equation (1). The results for the turbine positions 0.2, 0.3, and 0.4 mm are shown in Figure 7. This calculation employed a Ψ value of 0.64, the average for a turbine position of 0.3 mm (Figure 6). Figure 7 shows that slight errors are caused between the DC motor's known and measured torque values between 0.2 - 0.4 mm. These changes correspond to the variations of Ψ and the error was within 4 %.

Measured torque characteristic of micro-motor

Finally, the torque of the prototype micro-motor was measured. Figure 8 shows the external appearance of the micro-motor, and Figure 9 shows the external appearance of the motor fitted with the turbine. The motor is 1.6 mm in diameter and 2.2 mm in length. The three-phase alternating-current motor is fabricated using a permanent magnet rotor with two magnetized poles [7]. As shown in Figure 9, a turbine of the same size as the one used to measure the torque of the DC motor was attached to the micro-motor and placed in

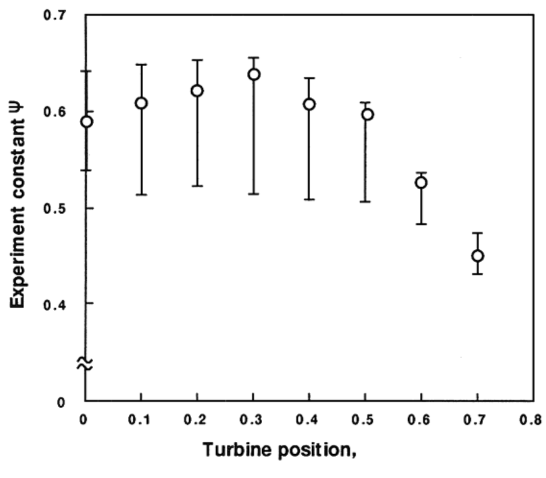


Fig. 6 Experiment constant Ψ as a function of the turbine position

the flange. As an example of measured results, Figure 10 shows the relationship between rotational speed (around 16,000 rpm) and pressure. Until the pressure reaches a certain value, the motor rotates at a speed synchronized with the rotation frequency. When pressure surpasses a certain level, the micro-motor steps out and comes to a halt. This result represents the characteristics of synchronous motor, i.e., the motor rotates at synchronized speed only, and when the excessive load is applied, the motor stops quickly.

Figure 11 shows the torque values calculated using a Ψ value of 0.64 and the pressure value immediately before the motor stops. The torque declines with an increase in rotational speed. This is attributed to an increase in the mechanical loss in the bearings at high speed.

These results indicate that the new torque measurement

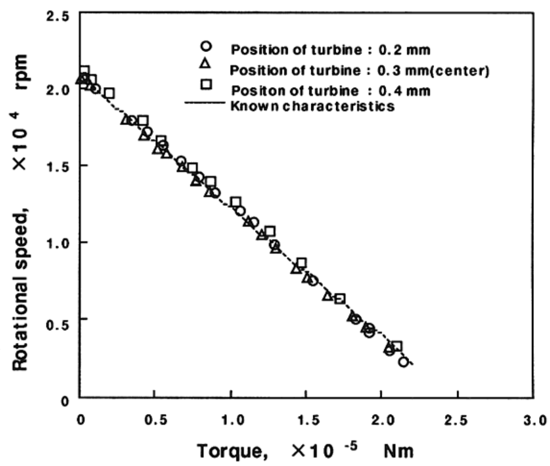


Fig.7 Rotational speed as a function of torque (DC motor)

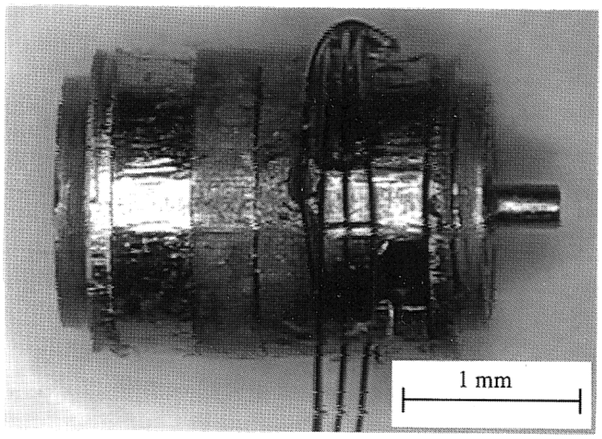


Fig.8 Photograph of micro-motor

method makes it possible to measure very low torques in the order of 10^{-7} Nm easily. It permits measurement of these levels of torque by simply attaching the turbine to the output shaft of the device under measurement.

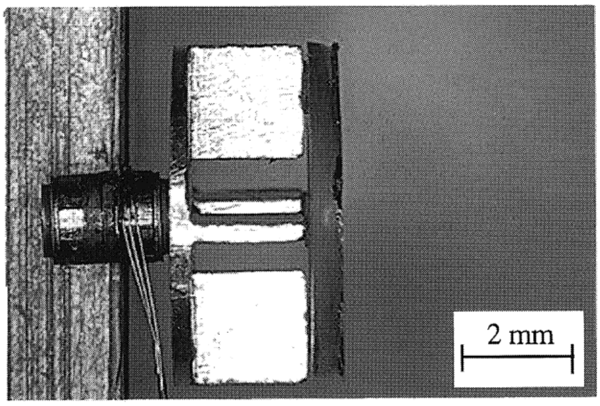


Fig.9 Photograph of micro-motor with turbine

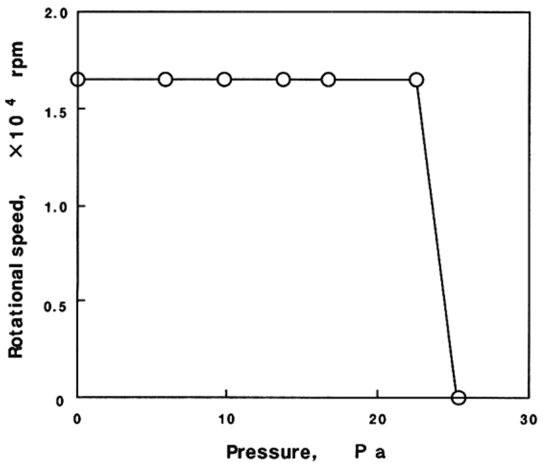


Fig.10 Rotational speed as a function of pressure (Micro-motor at the rotational speed of 16,000rpm)

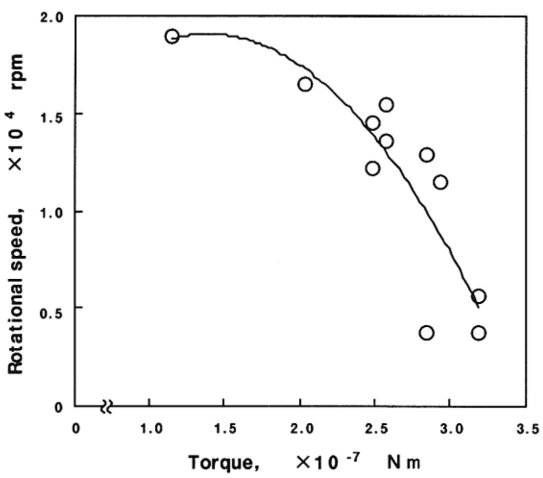


Fig.11 Experimental results of micro-motor torque

CONCLUSION

To evaluate very low torques in the order of 10^{-7}, a new measurement method has been proposed which uses wind pressure to apply a load to the device under measurement. The validity of measurement method is investigated by measuring torque of DC motor which has known characteristics, and it is clarified that the torque characteristics can be obtained by measurement of the differential pressure. Torque measurement of a 1.6 mm-diameter micro-motor demonstrated that torques in the order of 10^{-7} Nm can be measured during motor operation. Since the load sensor is not necessary in this method, compared with the cantilever method using load sensor and other traditional approaches, it is less vulnerable to disturbances including vibration caused by experimental circumstance. Therefore, it makes the measurement of very low torques much easier.

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