SPINDLE MOTOR DRIVEN BY FLUID ENERGY FOR ULTRA-PRECISION MACHINE TOOL

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1. Introduction

The present paper describes a high-speed motor driven by fluid power, primarily fluid flow energy. The motor can be effectively built into spindles for an ultra-precision machine tool and a micro-manufacturing system. Conventional spindle motors are driven by electric power, whereas the proposed motor is driven by fluid energy. Pure water, which is used in semi-conductor manufacturing plants, can be used as a working fluid for the motor. Therefore, the motor can be also used as an actuator for the semi-conductor plants as well as the ultra-precision machine tools.

The spindle devices used by dentists are the high-speed motors driven by fluid energy. In manufacturing fields, similar spindles have been designed to create small drilling holes, such as 0.6 mm in diameter [1]. An air-turbine is formed on the outer surface of the spindle and it is used as a motor. In this case, the air-turbine spins the spindle in excess of 100,000 rpm. However, making turbine structure for the spindle is relatively difficult, which is a disadvantage of the motor. In contrast, the spindle of the proposed motor has simple channels, which replace the turbine, in the spindle. Consequently, the structure of the proposed motor becomes rather simple than that of conventional high-speed motors using the air-turbine.

In the present paper, we first introduce the motor structure and the principle of the motor operation. We then derive a mathematical model of the motor to represent motor characteristics. A motor design procedure is established based on the derived mathematical model. Example of optimum parameters determined by the design procedure is shown and then the calculated performances of the designed motor are illustrated.

2. Proposed Motor

Figure 1 illustrates the schematic drawing of a cross section of the spindle, where a small and bend channel called a flow-out channel is present. The flow-out channels are located at two cross sections of the spindle. The working fluid in the flow-out channels flows from the center of the spindle to the outside of the spindle. The bend shaped-channels change significantly the fluid flow directions in the flow-out channels. Consequently, the torque used to spin the spindle is generated by the large change in angular momentum of the fluid flow.

Figure 2 illustrates the structure of the motor proposed in the present study. The spindle is supported by appropriate bearings. The working fluid, such as water or air, is supplied to a supply port in the casing of the motor. In order to lead the working fluid into the spindle, relatively large channels are present in the middle of the spindle. The working fluid flows inside the spindle because

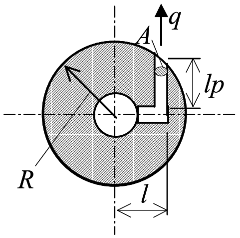

Fig. 1 Cross section of the spindle

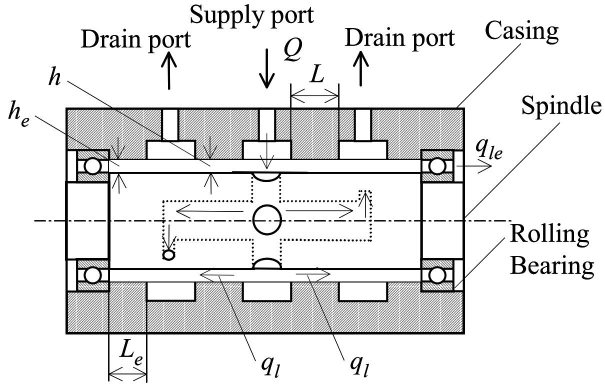

Fig. 2 Structure of proposed motor

the main channel passes through the center of the spindle in the axial direction. At both ends of the main channel, the flow-out channels are located between the main channel and the outside of the spindle. The working fluid in the flow-out channels flows through drain ports in the casing.

As show in Fig. 2, the proposed motor has an extremely simple structure. In addition, since no large mechanical frictional force acts on any of the moving parts of the motor, the motor can be driven by water flow by selecting appropriate materials for the motor elements. Particularly, the proposed motor can also be driven by pure water used in semi conductor manufacturing plants. Therefore, we can also design the high-speed motor for the actuators for machines in the semi conductor manufacturing plants as well as the spindle motor of the ultra-precision machine tools.

3. Mathematical Model

In order to design the proposed motor, a mathematical model is needed to determine optimum dimensions of the motor elements. Therefore, a mathematical model to establish design procedure for the motor is derived in this section. As described in the previous section, the flow-out channels are created in the cross sections of the spindle. The flow rate in each channel is then expressed as q, and the angular velocity of the rotor is expressed as ω. If the pressure at the outlet port of the casing is assumed to be zero, the output torque, T, generated by the fluid flow through the flow-out channels can be expressed as

$$T = 2n\rho q\left(\frac{l}{A}q - R^2\omega\right) \tag{1}$$

where n, A and ρ are the number of the flow-out channels in a cross section, the area of the cross section of the flow-out channel and the density of the fluid, respectively.

The negative torque due to fluid viscosity becomes significant as the rotational speed of the spindle increases due to the presence of fluid in the small gap between the casing and the spindle. If a Newtonian fluid is used for the motor, this negative torque can also be represented as

$$T_{f1} = \frac{2\mu\pi L R^3}{h}\omega \tag{2}$$

$$T_{f2} = \frac{2\mu\pi L_e R^3}{h_e}\omega \tag{3}$$

where μ is the coefficient of viscosity of the fluid. T_{f1} and T_{f2} represent the negative torques acting on the spindle between the inlet port and the outlet ports and at the end of the spindle, respectively.

If we consider the steady state of the motor, the motor torque can be expressed as

$$T_l = 2n\rho q\left(\frac{4cR}{\pi d^2}q - R^2\omega\right) - 2\frac{2\mu\pi L R^3}{h}\omega - \frac{2\mu\pi L_e R^3}{h_e}\omega \tag{4}$$

where $l = cR\ (0 < c < 1)$.

When the fluid flows into the motor, a pressure drop is produced primarily by the flow in the flow-out channels. Assuming that the flow channels from the inlet port to two outlet ports are designed symmetrically. Then, the supply pressure for the motor can be represented as

$$p_s = \left(1 + \lambda \frac{l_p}{d} + \zeta_1 + \zeta_2\right) \frac{\rho q^2}{2A^2} \tag{5}$$

where λ is the friction factor of the flow-out channels and ζ_1 and ζ_2 are the resistance coefficients[2] for flow in bends and for flow in the sudden contraction at the flow-out channels. If we write

$$\kappa = 1 + \lambda \frac{l_p}{d} + \zeta_1 + \zeta_2 \tag{6}$$

Eq. (5) becomes

$$p_s = \frac{8\kappa \rho q^2}{\pi^2 d^4} \tag{7}$$

The second term in Eq. (6) is neglected in the calculations for the design of the motor described in the following section, because this term is negligible compared to the other terms.

The leakage flow in the gap between the casing and the spindle can be described as follows

$$q_l = \frac{\pi h^3 R}{6 \mu L} p_s \tag{8}$$

Thus, the total flow rate is given by

$$Q = 2(nq + q_l) \tag{9}$$

4. Motor Design

The mathematical model derived in the previous section shows that the torque of the proposed motor can be controlled by the flow rate q in the flow-out channel. From the Eqs. (4), (7) and (8), it is found that the motor characteristics are extremely influenced by the following parameters; (1) the radius of the spindle, (2) the gap size between the casing and the spindle and (3) the diameter of the flow-out channels.

Since a large radius of the spindle makes the magnitude of the first term in Eq. (4), which represents the positive torque of the motor, increase, whereas the negative torque in the other terms also increases. Large gap sizes, h and h_e, are effective to reduce negative torque due to the viscosity of the fluid between the spindle and the casing. However, the leakage flow q_l in the gap increases as the gap size becomes large. The small diameter of the flow-out channels increases the positive torque, however, it decreases the efficiency of the motor due to the loss of the fluid flow energy. Therefore, optimum values for these parameters must be exist. Determination of the parameters is essential in designing a motor. In the present study, based on the derived mathematical model, we develop software to determine the optimum parameters so as to maximize the efficiency of the motor.

As an example of the design, the motor of the rated rotational speed of 20,000 rpm are designed. In this design, the maximum flow rate of the pump supplying the water to the motor was assumed to be 20 *l*/min. Determined optimum conditions for various output power of the motor are shown in Fig. 3. Figure 4 shows the torque characteristics of the designed motor with the rated power of 40 W. Characteristics of the power and the total efficiency of the motor are given in Figs. 5 and 6, respectively. The total efficiency of the motor is approximately 12 % at maximum. The maximum efficiency of the motor is less than that of the conventional electric motors. However, the magnitude of the energy loss is less than 300 W because the motor output is small.

The viscosity of the fluid in the gap and the loss of the fluid flow energy in the flow-out channels are the primary reasons for the low efficiency of the motor. Since the small gap is inevitable to reduce the leakage flow in the gap, it is difficult to reduce significantly the negative torque due to the fluid viscosity. In contrast, we can reduce the energy loss

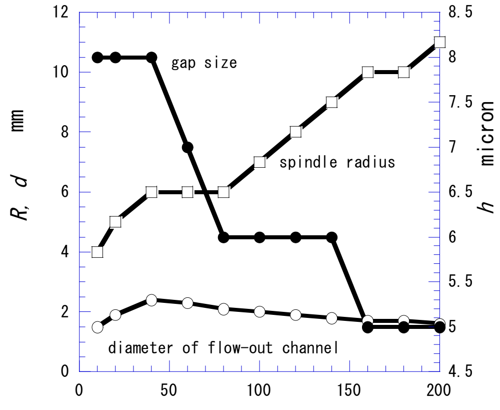

Fig. 3 Optimum parameters

(Rated rotational speed : 20,000 rpm)

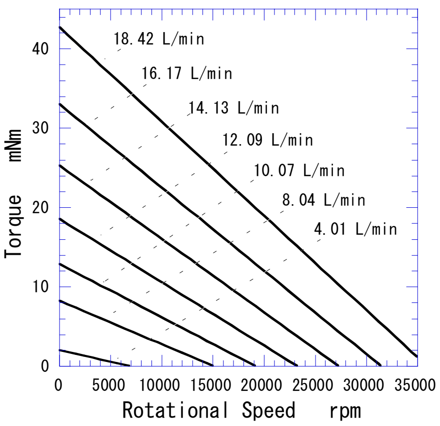

Fig. 4 Torque characteristics

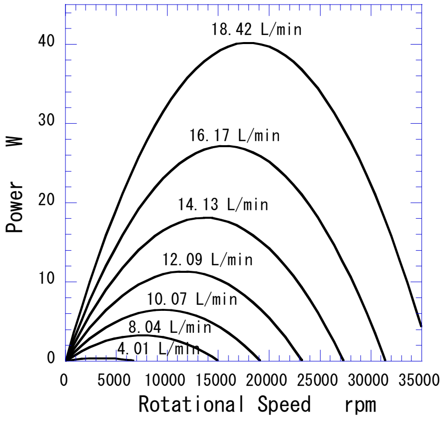

Fig. 5 Motor power

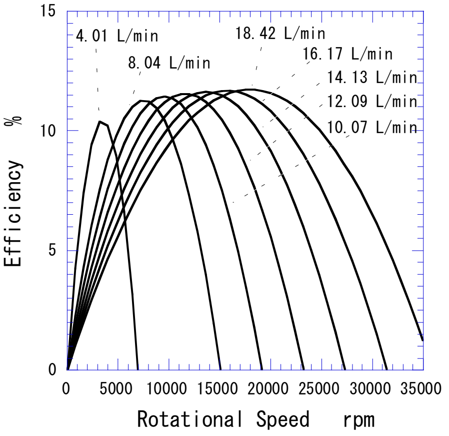

Fig. 6 Motor efficiency

of the working fluid flow in the flow-out channels by designing optimum geometry of the channels.

5. Summary

In this paper, a high-speed motor driven by various fluids such as water and air was proposed. The motor can be effectively built into the spindle of ultra-precision machine tools and the micro-manufacturing systems. In addition, since pure water can be used to drive the motor as the working fluid, the motor can be applied as the actuators used in semi-conductor manufacturing plants.

In order to determine the optimum parameters of the motor, a mathematical model was derived and then designed example was presented. A calculated motor efficiency was approximately 12 % at maximum. In order to improve the efficiency of the motor, the influence of geometry of a flow-out channel on energy loss will be considered in future work.

Acknowledgement

This research work is financially supported by the Grant-in-Aid for Scientific Research (C) of Japan Society for the Promotion of Science.

References

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