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Development of Water Drive Spindle

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ABSTRACT

A water drive spindle for diamond turning machines is proposed. The spindle uses water flow for driving the rotor by a water drive motor, for supporting the rotor by water hydrostatic bearings, as well as for coolant. As water is not only incompressible and clean but also low viscosity fluid, it is considered that a high-speed and precise rotational motion will achieve in the clean environments for ultra-precision machinings. The present paper reports a structure of the spindle as well as the operational principle of the spindle. In the present paper, theoretical equations used for designing the spindle is derived. The characteristics of the spindle are studied theoretically and experimentally.

KEY WORDS

Spindle, Water Hydraulics, Water Drive Built-In Motor, Water Hydrostatic Bearing, Ultra-Precision Machining

INTRODUCTION

A high-speed hydraulic motor has been presented in our studies[1]-[3]. The performances of the motor have been studied theoretically and experimentally. In the experiments, the developed motor was driven by oil. However, the motor was designed so that it can be driven by not only oil flow but also air or water flow.

Based on the studies concerning the high-speed hydraulic motor, a water drive spindle is developed in the present study. A final goal of the present study is to apply the water drive spindle for the ultra precision machine tools, such as a diamond turning machine or a diamond grinding machine.

The spindle for the ultra-precision machine tools is required the following performances: (i) high rotational speeds, (ii) precise rotational motion with small run-out, (iii) large stiffness of the bearings and (iv) small thermal deformation of the spindle.

In order to attain the precise rotational motion, conventional spindles for the ultra-precision machine tools are commonly equipped with the air static pressure bearings and the electric built-in motor. In fact, precision machining can be performed by the conventional spindle with a precision guide way and a single crystal diamond cutting tool.

Now, a further improvement of the machining accuracy is required. As a result, an advanced spindle is needed to achieve higher machining accuracy. From such viewpoint, the air static pressure bearings are not necessarily suitable to design the spindle with a large stiffness, because of the compressibility of air. Another problem of the conventional spindle is the heat generation at the built-in motor that induces the thermal deformation of the spindle.

In order to increase the stiffness of the static pressure bearings, the bearings are, in general, designed as follows: (i) the clearance of the bearings is small, (ii) the area of the bearing surfaces where the pressure acts is large. Accordingly, even small thermal deformation of the spindle, due to the heat generation at the built-in motor, will cause the mechanical contacts between the rotor and casing, which usually causes serious problems.

It is considered that a solution for designing advanced spindle is to use water for the lubricant fluid of the static pressure bearings, because water is the incompressible fluid with low viscosity. In addition, it will be also advantageous to use water for the coolant as well as the lubricant fluid, because the thermal conductivity of water is higher than that of air and oil.

In addition to the effective utilization of the water flow for the lubricant and coolant, the present paper proposes to use the water flow for driving the spindle. A basic design for driving the spindle, named as the water drive motor, has been studied in our previous studies[1]-[3]. The water drive motor can be easily built in the rotor in place of the electric built-in motor.

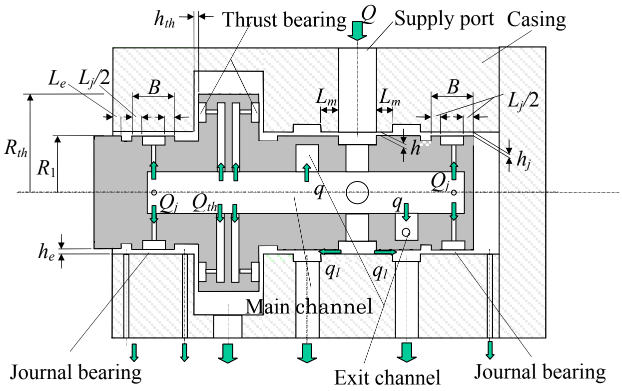
The present paper first describes the operational principle of the spindle as well as theoretical equations of the spindle that are essential for the design of the spindle. Spindles that have different rated powers and rotational speeds are studied theoretically and experimentally.

WATER DRIVE SPINDLE

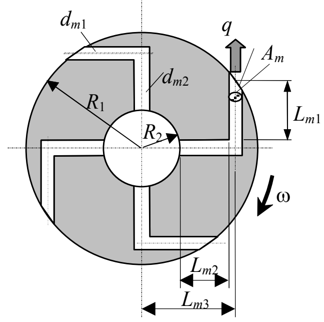
A structure of the water drive spindle is illustrated in Fig. 1. The spindle rotor is supported by the water hydrostatic bearings in the radial and axial directions and it has several flow channels inside the rotor. In order to lead water into the rotor, relatively large channels in the radial directions are present in the middle of the rotor. Water flows inside the rotor, because the main channel passes through the center of the rotor in the axial direction and several flow channels are fabricated for passing the water out from the main channel. The spindle is designed so as to use the water flow effectively to achieve the following three spindle functions.

(i) Water drive motor The spindle rotor has bend-shaped channels of small diameter, named as the exit channels, connecting between the main channel and the outer surfaces of the rotor. As illustrated in Fig. 1, the exit channels are located at two cross sections of the rotor. These exit channels enable the water flow to pass out from the inside of the rotor. The direction of the water flow changes significantly in the exit channels. Consequently, the torque used to spin the rotor is generated by the large change in the angular momentum of the water flow.

(ii) Water hydrostatic bearings Water hydrostatic journal and thrust bearings are designed as follows. Recesses are formed on the outer surfaces of the rotor. In addition, chokes of the bearings are located between the recesses and the main channel. Hence, the lubricant



(a) Spindle structure



(b) Exit channel

Fig. 1 Water drive spindle

water can pass out from the main channel through the chokes and the recesses in the radial and axial directions. This generates the static pressure distributions around the rotor to support the rotor.

(iii) Water cooling In addition to the working and lubricant fluid, water can be used as a coolant, to minimize the thermal deformation of the spindle. The thermal conductivity of water is higher than that of oil and air, which is an advantage for achieving better cooling performance.

THEORY

Primary configurations of the spindle are given in Figs. 1(a) and (b). The output torque T_l generated by the water flow rate q through one of the exit channels can be expressed by Eq. (1).

$$T_l = 2n\rho q\left(\frac{l_{m3}}{A_m}q - R_1^2\omega + R_2^2\omega\right) - 2\mu\pi R_1^3\omega\left(\frac{2L_m}{h_m} + \frac{2L_j}{h_j} + \frac{L_e}{h_e}\right) - \frac{\mu\pi}{h_{th}}\left(R_{th}^4 - R_1^4\right)\omega \tag{1}$$

Here, ρ is the density of the water, μ is the viscosity of water and n is the number of the exit channels at a cross section of the rotor.

The pressure drop in the exit channels is dominant compared to that in the other channels. Hence, the relationship between the supply pressure p_s and the flow rate q can be represented as

$$q = \frac{A_m}{\sqrt{\kappa}}\sqrt{\frac{2p_s}{\rho}} \tag{2}$$

where,

$$\kappa = 1 + \lambda\frac{l_{m1} + l_{m2}}{d_m} + \zeta_1 + \zeta_2 \tag{3}$$

In Eq. (3), λ is the friction factor and ζ_1 and ζ_2 are the resistance coefficients of the exit channels. The leakage flow in the clearance between the casing and the rotor can be represented as

$$q_l = \frac{\pi h_m^3 R_1}{6\mu L_m}p_s \tag{4}$$

Thus, the flow rate of the water drive motor is given by

$$Q_m = 2\left(nq + q_l\right) \tag{5}$$

The stiffness of the journal bearing can be given by

$$K_j = \frac{2BR_1}{h_j}\overline{P}_j p_{jr} \tag{6}$$

where, $\overline{P}_j$ is a characteristic parameter determined by the pressure distribution on the journal bearing surface and p_{jr} is the recess pressure of the journal bearing. The flow rate of the journal bearing can be represented by

$$Q_j = \frac{\Theta_j h_j^3}{\mu}p_{jr} \tag{7}$$

where, Θ_j is a coefficient expressing the pressure flow relationship at the journal bearing surface.

Similarly, the stiffness and the flow rate of the thrust bearing are given by

$$K_{th} = \frac{3\Pi_{th} A_{th}}{h_j} p_{thr} \quad (8)$$

$$Q_{th} = \frac{2\Theta_{th} h_{th}^3}{\mu} p_{thr} \quad (9)$$

where, p_{thr} is the recess pressure of the thrust bearing, and Π_{th} is a characteristic parameter determined by the pressure distribution on the thrust bearing surface, and Θ_{th} is also a coefficient expressing the pressure flow relationship at the thrust bearing surface. These coefficients $\overline{P}_j$, Θ_j, Π_{th} and Θ_{th} in Eqs.(6)-(9) can be obtained by solving the Reynolds' equation.

The total flow rate of the spindle is given by

$$Q_t = Q_m + 2Q_j + Q_{th} \quad (10)$$

Finally, the total efficiency of the spindle can be represented as

$$\eta = \frac{T_l \omega}{p_s Q_t} \quad (11)$$

DESIGNED SPINDLE

For designing the spindle, the rated performances, such as the output power, rotational speed and bearing stiffness, are specified. Accordingly, a designer has to determine the spindle dimensions so that the designed spindle attains, at least, the given rated performances. In addition, the designer is required to determine the optimum dimensions, which maximize the total efficiency of the spindle given by Eq. (11). In the present study, software for determining the optimum parameters has been developed based on the equations derived in the previous section.

In the present study, two spindles with different rated performances, named as Spindle 1 and Spindle 2, are designed using the software. The rated performances of the spindles, such as the output power P_r; the rotational speed N_r; the stiffness of the journal bearing K_{jr}; and the stiffness of the thrust bearing K_{thr}, are specified as follows:

(i) Spindle 1: P_r =50 W, N_r =10,000 rpm, K_{jr} =47 N/μm and K_{thr} = 12 N/μm

(ii) Spindle2: P_r =40 W, N_r =4,000 rpm, K_{jr} =85 N/μm and K_{thr} = 33 N/μm

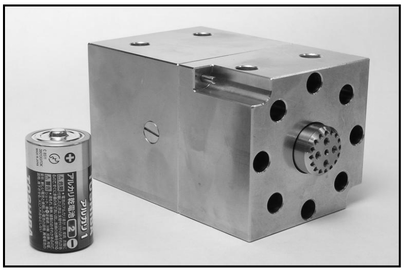


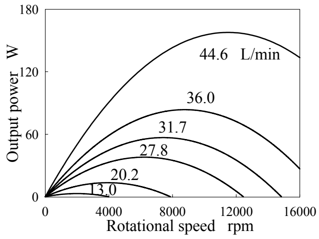
Fig. 2 Developed water drive spindle

The developed spindle is shown in Fig. 2. Figures 3(a) and 4(a) show calculated output power. For example, Fig. 3(a) shows the output power of the Spindle 1. In this case, it is observed that the rated performance can be obtained when the total flow rate is 31.7 *l*/min. Similarly, the output power of the Spindle 2 becomes 40 W at 4,000 rpm by supplying the flow rate of 33.4 *l*/min, as shown in Fig. 4(a).

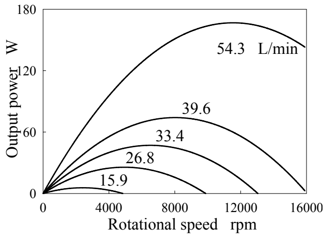
The total efficiency of the spindles are given in Figs. 3(b) and Figs. 4(b) as well. A disadvantage of the spindle is that the total efficiency is particularly low. It has been shown that a primary reason is the large pressure drop in the exit channels [3].

EXPERIMENTS

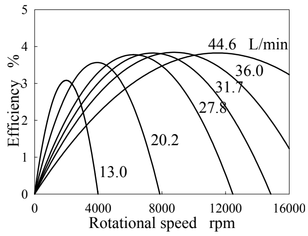
Experimental setup A schematic of the experimental setup is shown in Fig. 5. A water-piston pump was used to supply water to the spindle. A rotational speed of the spindle was measured by the pulse frequency from a photoelectric sensor that outputs one pulse per a rotation



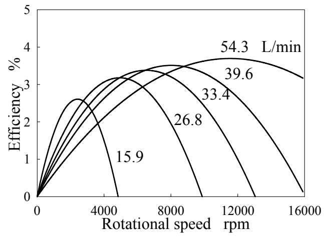
(a) Output power



(a) Output power



(b) Efficiency



(b) Efficiency

Fig. 3 Spindle characteristics (Spindle 1)

Fig. 4 Spindle characteristics (Spindle 2)

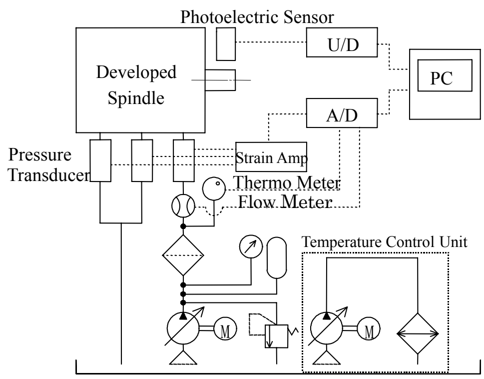


Fig. 5 Experimental setup

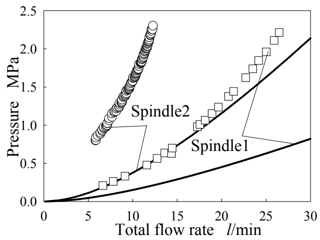


Fig. 6 Q_t vs. p_s

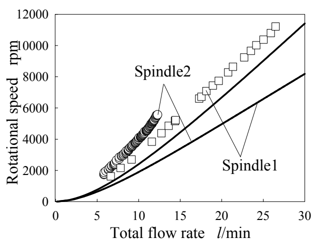


Fig. 7 Q_t vs. N

of the rotor. A water temperature control unit was equipped with a reservoir tank of water. Tap water was used for the experiments. During the experiments, the water temperature was controlled in the range from 19.8 to 20.8 degrees Celsius.

Experimental results As shown in Fig. 6, the highest supply pressure was approximately set to 2.3 MPa in both experiments. Figure 7 shows the relationships between the total flow rate and the rotational speed N. The results show the spindles can reach their rated spindle speeds.

The solid lines in Figs. 6 and 7 represent calculated rotational speed and supply pressure, i.e. pressure drop in the exit channels. It is observed that the supply pressure calculated with Eq. (2) differs significantly from the pressure measured in the experiments. It is considered that the friction factor and the resistance coefficients[4] used for the calculations did not represent well the actual pressure flow relationships.

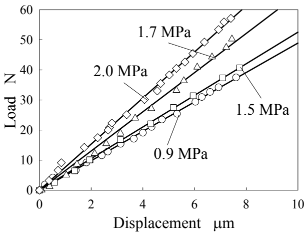
The calculated rotational speed also differs from the experimental results. As it is obvious from Eq. (1), once the primary dimensions of the spindle were determined, the flow rate q becomes the significant factor that determines the rotational speed. Furthermore, the flow rate q is determined by the recess pressures p_{rth} and p_{rj}, and Θ_j, Θ_{th} as well as the supply pressure p_s. The recess pressures p_{rth} and p_{rj} are determined by the pressure flow relationships of their chokes and Θ_j, Θ_{th}. Therefore, the results show that the characteristic values have to be measured in order to obtain better calculation results.

Stiffness of the water hydrostatic bearings was measured and then compared with the designed values. The relationships between the displacement and the load are shown in Fig. 8(a) and Fig. 9(a). The characteristics were measured for several supply pressures. The relationships between the supply pressures and the stiffness are shown in Fig. 8(b) and Fig. 9(b), respectively. We can observe that the stiffness increases in proportion to the increase in the supply pressures. At the rated operational condition, measured stiffness of the thrust bearing was 32 N/μm, which agrees well with the theoretical value of 33 N/μm.

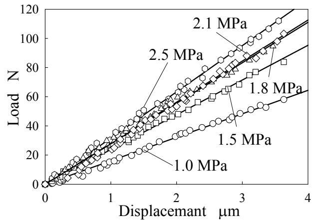
Stiffness of the journal bearings was measured as 7.7 N/μm. In the experiments, however, the loads were applied to an end of the rotor, which induces the moment effects on the bearings. Removing the moment effects from the original measured data, the stiffness in the radial direction becomes 49.0 N/μm per journal bearing. Since two journal bearings are present at both ends of the rotor, the total stiffness of the bearings in the radial direction becomes 98.0 N/μm. In contrast, the theoretical value of the stiffness was 87.9 N/μm. It is considered that the difference between the measured and theoretical values comes from the influence of the pressure flow relationships of the water hydrostatic bearings.

CONCLUSIONS

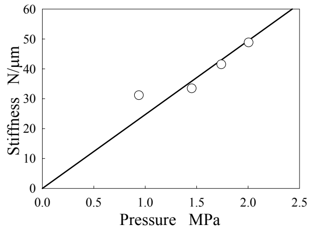
A water drive spindle for diamond turning machines was presented in this paper. The water drive spindle is designed so as to use water flow for driving, supporting and cooling the spindle. In the present paper, theoretical equations that are essential in designing the spindle were introduced. The characteristics of the spindle were studied through theoretical calculations and experiments. Two water drive spindles with different rated performances were designed and tested. The results showed that both of the spindles rotate at over the rated spindle speeds. It was shown that calculated performances of the spindles were not good agreed with the experimental results, due to luck of the experimental data on the pressure flow relationships of various flow channels of the spindle. Stiffness of the water hydrostatic bearings were also measured and the results were good agreed with the design values.



(a) Displacement vs. load

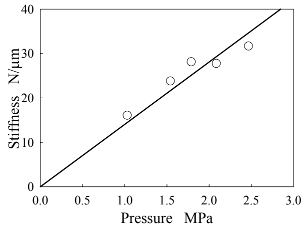


(a) Displacement vs. load



(b) p_s vs. stiffness

Fig. 8 Bearing stiffness (journal bearing)



(b) p_s vs. stiffness

Fig. 9 Bearing stiffness (thrust bearing)

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