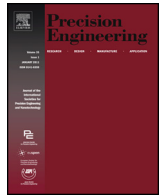




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Rotational speed control system of water driven spindle considering influence of cutting force using disturbance observer

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ABSTRACT

The water driven spindle has been developed for use in an ultra-precision machine tool for producing precision parts. In order to achieve high machining accuracy and generate high-quality surfaces, precise rotational accuracy and a constant machine tool spindle speed are necessary in ultra-precision machine tools. However, the rotational speed of the spindle inevitably changes due to the influence of the cutting forces during machining process. In order to deal this problem, this paper describes the development of a rotational speed control system. In particular, the control system is designed such that the influence of the cutting forces is effectively reduced. In this paper, mathematical models of the water-driven spindle and the flow control valve are introduced to develop a feedback control system. The effectiveness of the developed feedback control system is then verified through simulation and experimental tests. In addition, the disturbance observer is added to the designed feedback control system in order to minimize the influence of the cutting forces. Turning tests are then carried out in order to verify the effectiveness of the disturbance observer. As a results, the developed feedback control system with the disturbance observer is verified to successfully reduce the change in the rotational speed.

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1. Introduction

Recently, a wide variety of precision parts, such as various types of lenses and mirrors for cameras and optical instruments, have been produced by ultra-precision machining. In ultra-precision machining, single-point diamond cutting or turning is mainly carried out to achieve high-accuracy and high-quality machined surfaces. Ultra-precision machining can achieve surface accuracies on the order of tens of nanometers or better. In order to accomplish ultra-precision machining, precise rotational motions, high-bearing stiffness and high-thermal stability are required for the spindle of the ultra-precision machine tool. For these reasons, the spindle of an ultra-precision machine tools is generally equipped with hydrostatic bearings. In many cases, air or low viscosity oil is used as the lubricating fluid of the hydrostatic bearings [1–5]. However, air hydrostatic bearings cannot achieve high bearing stiffness due to the compressibility of air. Therefore, upsizing of the bearing surface of the spindle is necessary in order to design air bearings having the required characteristics. As a result, the size of the spindle body becomes excessively large. Although oil

hydrostatic bearings can solve the problems associated with air hydrostatic bearings, the higher viscosity of oil leads to the heat generation during spindle operation, degrading the thermal stability.

The water-driven spindle was developed in order to cope with these problems [6,7]. This spindle has a water-driven mechanism and water hydrostatic bearings. An advantage of using water for the hydrostatic bearings is that water is an incompressible fluid. Accordingly, it makes possible to design hydrostatic bearings with higher bearing stiffness with small bearing size. Furthermore, the water supplied for the hydrostatic bearings can be used as an effective cooling media for the water driven spindle because of the large thermal conductivity and specific heat of water. For these reasons, the water-driven spindle achieves both of important performances of high-bearing stiffness and high-thermal stability.

In this study, the characteristics of the developed water-driven spindle are investigated theoretically and experimentally. Furthermore, single-point diamond turning tests are carried out using the water-driven spindle.

The rotational speed of the water-driven spindle is found to vary due to the influence of cutting forces during machining operation. The variation in the rotational speed of the spindle during turning operations changes the cutting speed, which degrades the machined surface quality. To cope with the problem, the rotational

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Nomenclature

T_m	Driving torque produced by supplying water flow to exit channels [Nm]
T_r	Torque due to the viscosity of water between rotor and casing (radial direction) [Nm]
T_{th}	Torque due to the viscosity of water between rotor and casing (thrust direction) [Nm]
T_l	External load torque due to cutting forces [Nm]
I	Moment of inertia of rotor [$\text{kg} \cdot \text{m}^2$]
ω	Angular velocity [rad/s]
L_m, L_j, L_e	Length of each part of rotor [m]
h_m, h_j, h_e, h_{th}	Gap of each part between land of bearings and casing [m]
$r_l, r_{th1}, r_{th2}, r_{th3}$	Radius of each part of rotor [m]
A_m	Sectional area of exit channel [m^2]
q_m	Water flow rate per one of exit channels [m^3/s]
ρ	Density of water [kg/m^3]
μ	viscosity of water [Pa·s]
κ	Loss coefficient of exit channel [–]
λ	Friction factor [–]
$\zeta_{in}, \zeta_{out}, \zeta_b$	Loss coefficients of inlet, outlet or bend of exit channel [–]
n_e	Number of exit channel per cross section [–]
N	Rotational speed [min^{-1}]
T_c	Time constant [s]
p_s	Supply pressure [Pa]
p_c	Control pressure [Pa]
u	Input voltage to flow control valve [V]
q_l	Leak flow rate [m^3/s]
q_j, q_{th}	Flow rate through radial or thrust hydrostatic bearings [m^3/s]
Q	Total supplied flow rate [m^3/s]
R_{bl}	Resultant flow resistance of flow channels [$\text{Pa} \cdot \text{s}/\text{m}^3$]
R_{ex}	Flow resistance of exit channel [$\text{Pa} \cdot \text{s}/\text{m}^3$]
R_{th}	Flow resistance of thrust bearing [$\text{Pa} \cdot \text{s}/\text{m}^3$]
R_{lth}	Flow resistance between land and casing [$\text{Pa} \cdot \text{s}/\text{m}^3$]
R_{cth}	Flow resistance of restrictor [$\text{Pa} \cdot \text{s}/\text{m}^3$]
N_{cth}	Number of restrictors [–]
w_{rth}, w_{lth}	Lengths of recess or land [m]
d_{cth}	Diameter of restrictor [m]
k, n	Flow rate coefficient and exponent of flow control valve [$\text{m}^3/\text{s}, -$]
K_{sv}	Gain of steady-state spindle speed [rad/(s·V)]
K_p	Proportional gain of rotational speed control system [s·V]
K_i	Integral gain of rotational speed control system [V]
T_o	Time constant of disturbance observer [s]

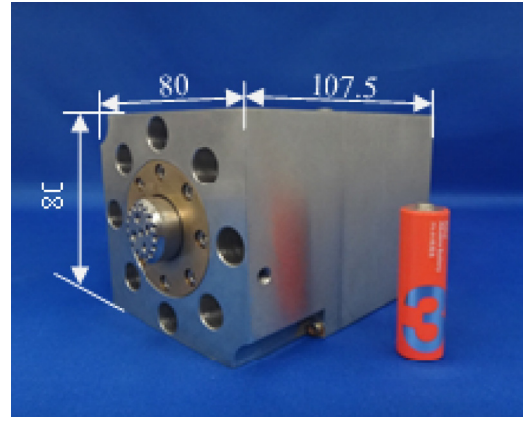


Fig. 1. Water-driven spindle.

Finally, a disturbance observer is added to the newly designed feedback control system in order to minimize the change in the rotational speed due to the influence of the external load torque by the cutting process.

2. Water-driven spindle

2.1. Structure of water-driven spindle

Fig. 1 shows the water-driven spindle, and Fig. 2(a) shows a schematic diagram of the water-driven spindle. In this figure, the symbols represent the dimensions in length that will be used in the mathematical models. The rotor of the spindle, shown in Fig. 2(b), has the water driven mechanism. The water to drive the rotor is supplied from an external water pump. The water enters the bent flow channels (referred to hereinafter as exit channels) of the spindle rotor. The exit channels produce torque to spin the rotor by changing the angular momentum of the water flowing through the channels. In addition, the spindle has water hydrostatic bearings to support the rotor in the radial and thrust directions. The recesses of the hydrostatic bearings are fabricated on the outer surfaces of the rotor. The spindle is driven by water flow power without the need for an electric motor which may generate heat and cause thermal deformation of the spindle. Moreover, the water flow can be used as a coolant to prevent thermal deformation of the spindle.

2.2. Mathematical model of water-driven spindle

The mathematical model of the water-driven spindle is derived as presented in Eq. (1), and the equation of motion of the water-driven spindle is obtained in terms of the driving torque T_m produced by supplying water flow to the exit channels, the torques T_r and T_{th} due to the viscosity of the water between the rotor and the casing, and the external load torque T_l due to, for instance, cutting forces. In Eq. (1), I is the moment of inertia of the rotor.

$$I \frac{d\omega}{dt} = T_m - T_r - T_{th} - T_l \quad (1)$$

The above equation can be rewritten as a function of the flow rate q_m into the exit channels and the angular velocity ω as follows.

$$I \frac{d\omega}{dt} = a q_m^2 - b q_m \omega - c \omega - T_l \quad (2)$$

In Eq. (2), a , b , and c are coefficients given respectively by the following equations.

$$a = 2n_e \rho \left(\frac{l_{m1} + r_m}{A_m} \right) \quad (3)$$

speed control system with consideration of the influence of the cutting forces must be needed.

The purpose of this study is to develop the rotational speed control system for the water-driven spindle. First, the mathematical models of the water-driven spindle and the flow control valve are introduced. The mathematical model indicates that the rotational speed can be controlled by the flow rate through the flow channels. A feedback control system is then developed based on the mathematical models.

Next, the designed feedback control system is tested through simulations and experiments. Turning tests are carried out using a single-point diamond-cutting tool with the water-driven spindle with developed control system.

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