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Proposal of disturbance-compensating and energy-saving control method of air turbine spindle and evaluation of its energy consumption☆

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ABSTRACT

This paper introduces a disturbance-compensating and energy-saving control method of an air turbine spindle equipped with a rotation control system designed for use in ultra-precision milling. As one of the key components, our proposed pneumatic regulating device, called a high-precision quick-response pneumatic pressure regulator (HPQR), is used to control the air supply pressure of the air turbine spindle precisely and quickly. The rotation feedback control system including the HPQR and a disturbance force observer, which avoids changes of rotation speed due to disturbance forces applied to the air turbine spindle, is explained. In addition, a pneumatic energy assessment method using a device called an "air power meter" is explained. The effectiveness of the proposed method is demonstrated through the experimental results.

1. Introduction

Energy savings are in demand in many technology fields. In the field of fluid power, some reports have pointed out that fluid power transmits a large amount of energy with low efficiency [1], so techniques or devices contributing to energy saving must be established. Establishment of an energy assessment method has also been a great concern. Among the research on pneumatics [2,3], a novel device measuring the work-producing potential of compressed air has been proposed and developed [4].

This research focuses on air turbine spindles with aerostatic bearings. Air turbine spindles with aerostatic bearings are widely used in ultra-precision machines, such as aspherical lens generators, due to their beneficial properties that include high precision, high speed, low friction, and low vibration [5]. However, air turbine spindles have been affected by the following problems:

1. *Vulnerable to disturbance*: The rotation speed of the spindle tends to decrease when a disturbance force (e.g., cutting force) is applied to the spindle.
2. *Slow speed controllability*: It takes a while to stabilize the rotation speed when starting up or changing the target speed.

To solve these problems, the authors have been researching a quick, robust rotation control method for the air turbine spindles used in ultra-precision machining [6–8]. By using the proposed rotation control system with the disturbance force observer, the robustness and the controllability improved. However, comparison of the energy consumption between the conventional method and the proposed control method had not been done before now. In mechanical systems, improvement of the controllability is often achieved in a trade-off with efficiency. However, our goal has been to establish a quick, robust, and energy-saving rotation control method for the air turbine spindles used in ultra-precision machining. Therefore, an energy assessment was necessary.

In this paper, the design and fabrication of a new air turbine spindle equipped with a rotation control system for use in ultra-precision milling are explained. The structures of the fabricated pressure-controlling device and the controller are also explained. A pneumatic energy assessment method is then used to measure

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Nomenclature

E_i	energy consumption (kJ)
$\dot{E}_i$	air power (kW)
K_{GI}	integral gain (V/kg)
K_{ph}	proportional gain ((kg/s)/Pa)
K_v	flow rate gain of the SP valve ((kg/s)/V)
k_α	gain of the air turbine (min^{-1}/Pa)
G_{in}	input flow rate (kg/s)
G_{out}	output flow rate (kg/s)
N	rotation speed (min^{-1})
N_{ref}	rotation speed reference (min^{-1})
P	pressure (Pa)
P_a	ambient pressure (Pa)
P_{ref}	pressure reference (Pa)
P_{cmp}	compensation pressure (Pa)
Q	volume flow rate (m^3/s)
t	time (s)
T	time constant (s)
T_o	time constant of the observer (s)
T_t	time constant of the air turbine (s)
R	gas constant (J/(kg K))
V	volume of chamber (m^3)
θ	temperature in chamber (K)

the performances of rotation controllability and the energy consumption of the proposed method and the conventional method. The two methods are compared, and the results are discussed.

2. Fabrication of the HPQR

Some studies have reported the relations among supply pressure, flow rate, rotation speed, and output torque of the air turbine spindle [9]. However, because methods to control the air supply pressure and the flow rate are imprecise and too slow, it has not been possible to control the rotation speed and the output torque of the air turbine spindle. To address these problems, we developed the high-precision, quick-response pneumatic pressure regulator (HPQR) [10] and applied the HPQR to the rotation feedback control of an air turbine spindle [6–8].

Fig. 1 and Table 1 show a photograph and a list of the components of the fabricated HPQR, respectively. The HPQR is a pressure regulator that can control the supply pressure very quickly and precisely. The HPQR consists of the following: spool-type servo valve (SP valve; Festo, MPYE-5-1/8LF-010B), isothermal chamber, pressure differentiator (PD sensor; Tokyo Meter, DTP-8), pressure sensor (Toyoda, PD-64S500K), and digital signal processor (DSP) controller (MTT, s-BOX). The SP valve has five ports, but it is used as a three-port (supply, control, and exhaust) servo valve; the two unused ports are plugged. The isothermal chamber is filled with metal wool, which creates a nearly isothermal state in the chamber. The isothermal chamber has a volume V of 0.001 m^3 (1 L). The PD sensor measures the pneumatic pressure differential with high precision and quick response.

The purpose of the HPQR is to maintain the pressure in the isothermal chamber at a set value. The important requirement is that, irrespective of upstream or downstream disturbances,

Table 1
Components of the HPQR.

S.P. valve	Festo MPYE-5-1/8LF-010B
Pressure sensor	TOYODA PD64S500K (resolution: 50 Pa)
P.D. sensor	TMC DTP-8
Isothermal chamber	Volume: 1 L about 5% of Copper wire

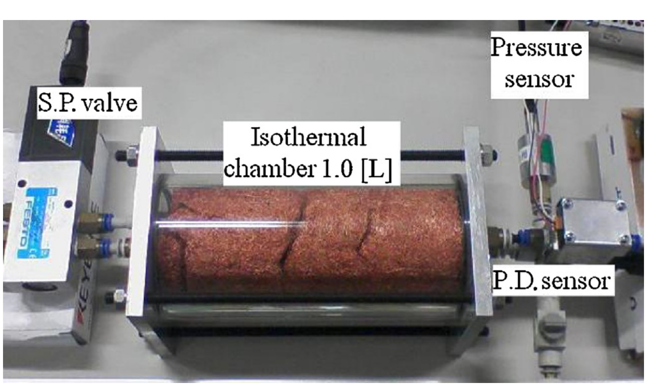

Fig. 1. Photograph of the HPQR.

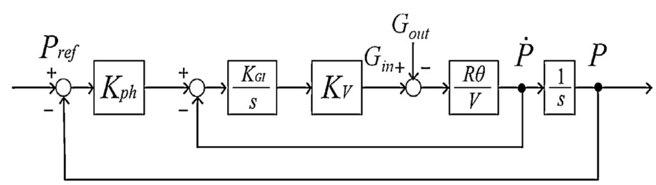

Fig. 2. Block diagram of the HPQR.

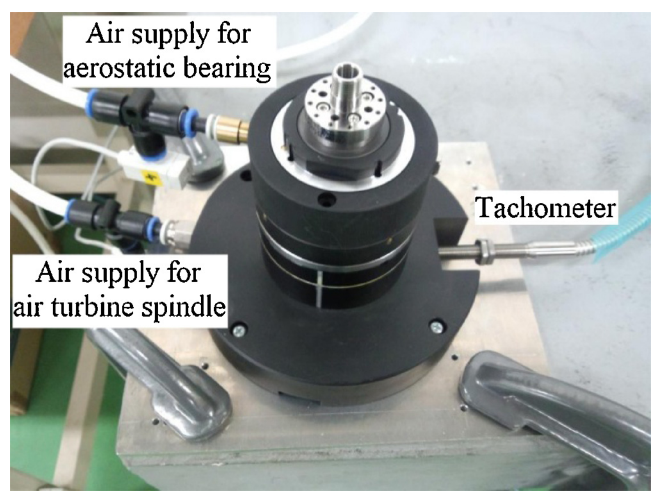

Fig. 3. Photograph of newly developed air turbine spindle.

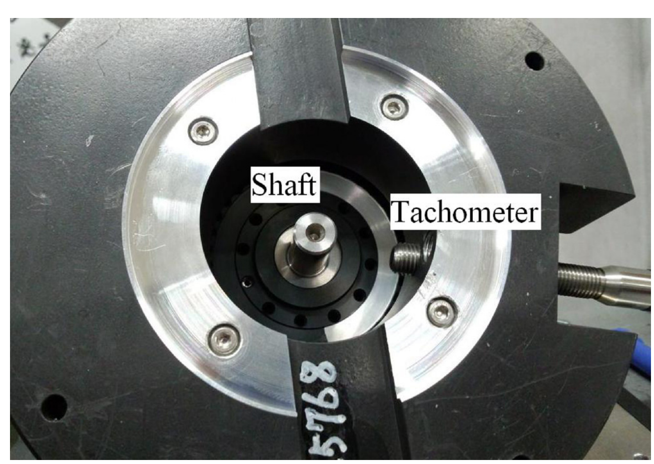

Fig. 4. Bottom view of the newly developed air turbine spindle.