Design of Feedback Control System for Water Driven Stage

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Abstract

The present paper focuses on a design of speed control system for the water driven stage. The water driven stage that is equipped with water hydrostatic bearings and water hydraulic piston mechanism has been designed for ultra-precision machine tools. The stage speed can be controlled by the flow rate supplied to the stage. Based on the derived mathematical model, a feedback control system is designed in order for regulating the speed. In particular, an influence of the external forces acting on the stage on the speed is considered. Feedback gains are then determined so that the desired control performance can be obtained. The performance of the designed feedback control system is tested via simulation.

1 Introduction

The present paper describes a design of feedback control system for the water driven stage [1]. The water driven stage was designed as a feed table of diamond turning machine. In particular, we intend to develop a small diamond turning machine that is suitable for machining small parts in size.

The stage has a water piston-cylinder mechanism, thus the water flow generates the linear motion of the stage. Specifically, the speed of water driven stage can be controlled by the flow rate. The flow control system with an appropriate feedback mechanism is thus needed to control the speed of stage, achieving constant speed regardless of the external disturbances such as cutting condition or temperature fluctuation. It is particularly important to drive the stage with low and constant speed so that fine finish surfaces can be obtained in the diamond turning applications. In the present paper, the feedback control system is thus considered with the modelling of the stage and the flow control valve. Performance of the designed feedback control system is tested via simulation.

2 Water driven stage

Figure 1 illustrates the structure of the water driven stage [1]. The table of stage is supported by water hydrostatic bearings in the vertical and horizontal directions, except for the feed direction. The stage has a piston-cylinder mechanism that is made inside the table. It is noted that the piston and cylinder has square cross-section, then the piston is formed on the upper and bottom surfaces of the guide-way. The pressure difference of the supplied water can thus be generated, makes the table drive along the stage. The speed of the stage is controlled by the flow rate. A feedback control system can be accordingly made by the flow control valve and the stage, as depicted in Fig. 2. Commercially available proportional flow control valves are experimentally used for the control system.

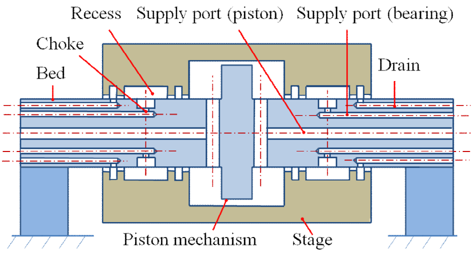

Figure 1 Structure of water driven stage

3 Modeling

Mathematical models of the stage as well as the flow control valve are derived for designing the feedback controller. Equation of motion of the stage is given by Eq. (1).

$$T_c \frac{dv}{dt} + v = \frac{AR}{c + A^2 R} q_p - \frac{F_c}{c + A^2 R} \qquad (1)$$

Here, c: viscous damping coefficient due to water, R: flow resistance at the clearance between the piston and cylinder, v: stage speed, A: area of piston, q_p: supplied flow rate into cylinder, F_c: external load forces such as cutting force, T_c: the time constant of water driven stage.

In Eq. (1), the time constant of the stage is given by Eq. (2).

$$T_c = \frac{M}{c + A^2 R} \qquad (2)$$

The relationship between the pressure difference and the leakage flow at the piston-cylinder is represented by Eq. (3).

$$q_l = \frac{1}{R}\left(p_1 - p_2\right) \tag{3}$$

The relationship between the stage speed and flow rate is given by Eq. (4), since the compressibility of water in the controlled system is negligibly small.

$$Av = q_p - q_l \tag{4}$$

Linearized pressure-flow characteristics of the flow control valve is given as Eq. (5).

$$q_p = k_u u - k_p p_c \tag{5}$$

In Eq. (5), k_u and k_p are determined by experiments.

4 Design of feedback control system

Based on the mathematical models of the water driven stage and the proportional flow control valve, a feedback control system is designed as depicted in Fig. 2. In Fig. 2, K_1 and K_2 are the gains to be determined so that the desired control performance can be obtained. The transfer function of the feedback control system can be represented by the second order system as represented by Eq. (6).

$$G(s) = \frac{1}{1 + 2\zeta \frac{s}{\omega_n} + \frac{s^2}{\omega_n^2}} \tag{6}$$

Here,

$$\omega_n = \sqrt{\frac{K_1 K}{T_{cs}}} \tag{7}$$

$$\zeta = \frac{1 + K_2 K}{2\sqrt{K_1 K T_{cs}}} \tag{8}$$

$$K = \frac{k_u A R}{A^2 R + c k_p R + c} \tag{9}$$

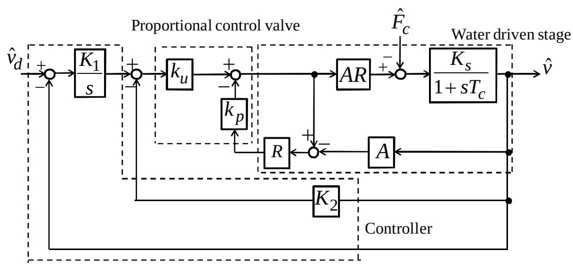

Figure 2 Designed feedback control system

In Eqs. (7) and (8), the time constant of the system composed of the stage and the valve is given by T_{cs}.

Now, the feedback gains K_1 and K_2 can be determined by specifying the natural frequency ω_n and the damping coefficient ζ. An important requirement in the controller design is to reduce the influence of the cutting force on the stage speed. The relationship between the external force and the stage speed is given by Eq. (10).

$$\hat{v}(s) = \frac{-\dfrac{K_s}{K_{s1}KK_1}s}{1+\dfrac{1+KK_2}{KK_1}s+\dfrac{T_{cs}}{KK_1}s^2}\hat{F}_c(s) \quad (10)$$

In Eq. (10), K_s: constant representing the relationship the stage speed and applied forces acting on the piston, K_{s1}: a non-dimensional constant determined by the characteristics of the stage and valve.

The gain K_1 can be determined so that the influence of the external forces on the speed of stage is fully diminished. Then the gain K_2 is determined by Eq. (8). Performance of the designed feedback control system is investigated via simulation as shown in Fig. 3. In particular, the external force of 1 N was applied to the system at the time of 4 seconds in the simulation. The response of the feedback control system is compared with that of the open loop control system as shown in Fig. 3. It is then verified that the designed controller successfully suppresses the influence of the external forces on the speed of stage.

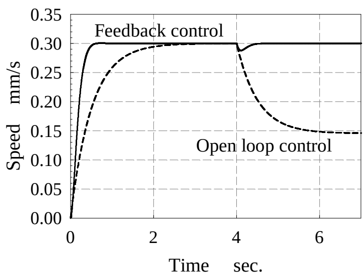

Figure 3 Simulation results

5 Summary

Feedback speed control system of the water driven stage was considered. The conventional feedback control system was designed in order to control the speed of stage. Feedback gains were determined so that the influences of the external forces, such as cutting forces, on the speed of stage can be suppressed. The designed feedback control performance was investigated through simulation. This research work is financially supported by the Grant-in-Aid for Scientific Research (C) of the Japan Society for the Promotion of Science.

Reference

[1] Y. Nakao, M. Kawakami, Design of water driven stage, Proceedings of 9th International Conference of the European Society for Precision Engineering and Nanotechnology, Vol. 1, pp. 200-203, (San Sebastian, 2009-6).