Laminar Flow Actuation on Ultraprecision Stage Positioning

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Introduction

Laminar flow actuation is a preferred method in Quiet Hydraulics. Quiet Hydraulics has several advantages in ultraprecision machine design. In ultraprecision machine design, every engineer has to face two main challenges. One is thermal stability and the other is vibration. For instance, temperature variation of 1 milli-degree C can easily lead to 10 nm dimensional changes for a machine larger than 1 m. Vibration is also one of the major factors that determine the precision of a machine. The most efficient temperature control for any machine tool is through liquid showering, which maintains temperature stability at least an order of magnitude better than any other means. Hydraulic components are the easiest to integrate with liquid showering system. However the turbulence in most orifice-restricted hydraulic components creates a potential source of vibration. Therefore we applied the quiet hydraulics principles to design hydraulic systems with low Reynolds number to assure laminar flow operation conditions.

At the Stanford Quiet Hydraulics Lab, we have successfully integrated a laminar flow flapper valve into our quiet hydraulics testbed as the actuation means of the carriages. The overall integration results showed the standard deviation of the carriage positioning is 11.7 nm. In this presentation, we will focus on the laminar flow actuation system. The laminar flow actuation system includes a customized laminar flow flapper valve, a newly designed manifold, and a stictionless piston. A mathematical model of the laminar flapper valve is proposed. From the model we can investigate the properties of laminar flow flapper valves. The differences between the model and the experimental data are discussed in detail. Although we had modeled the laminar flow valve at component level, system integration result showed the model is neither too complicated for the controller design nor oversimplified to leave out important dynamics.

Despite the fact that almost all hydraulic components have nonlinear dynamics, because of the way we design the actuation system, the overall system including the laminar flow actuation actually showed very little nonlinearity. We can close the control loop with a simple linear controller design. The results show that the laminar flow actuation has wide dynamic range, low disturbance. It is a very good candidate for ultraprecision actuation.

Laminar Flow Actuation

At the Stanford Quiet Hydraulics lab, we have developed an ultraprecision diamond turning machine as a testbed to implement precision engineering principles. The Quiet Hydraulics testbed has two carriages for tool post and spindle motor. Each carriage adopts Kraakman way design with built-in provision for straightness and yaw correction. Therefore, the carriage positioning system can assume a straight traveling path. In order to be free from stiction from the seals, we have the hydraulic fluid run in open loop. By controlling the temperature of the fluid, the overall system is thermally stable, and the fluid can also take away heat generated from the inefficiency of hydraulic components.

The main components of the carriage positioning system are a laminar flow valve, a flow manifold, and a piston with hydrostatic bearings. The actuator we chose is a laminar flow flapper valve modified by Woodward HSC from one of their three-way flapper valves. The fundamental differences between most hydraulic valves and a laminar flow valve are the efficiency and the temperature sensitivity. Most hydraulic valve designs would minimize the viscous loss to increase their efficiency, therefore, they are designed to be operated in turbulent flow region with internal orifices to regulate the flow and sharp edges at the flapper area to induce turbulence. Because of the turbulent flow, the dependence on the viscosity of the fluid is reduced. Since viscosity of fluid is a function of temperature, by reducing the effect of viscosity, a turbulent flow valve can be more robust to environmental changes. However, in ultraprecision applications, the power consumption is not a concern but the precision is. With tight control on the liquid temperature, a laminar flow flapper valve that eliminates the possible vibration source from the turbulence of the liquid flow is a much better candidate for higher precision applications. The basic difference in design between an ordinary flapper valve and a laminar flow flapper valve is shown in figure 1.

Generally, the laminar flow at the flapper area can be characterized by the following equation,

$$R = \frac{\Delta p}{q} = \frac{6\mu \ln(D_o/d_i)}{\pi h^3} \tag{1}$$

where R is the flow resistance defined by the pressure difference, Δp, divided by the flow rate, q, μ is the viscosity of the fluid, D_o and d_i are the outer and inner diameter of the nozzle tubes, and h is the gap between the flapper to the nozzle. For laminar flow, the flow rate of the valve is proportional to the pressure drop, as we observed in figure 2. However, in experiments, we did not see the resistance change of the flapper valve varies as inverse proportional to h cubed. That is due to the viscous loss in the flow passages inside the valve is no longer negligible. The effective resistance of the valve will be,

$$R = R_p + (h_0/h)^3 R_0 \tag{2}$$

where R_p is the passage resistance, h_0 is the gap of flapper valve at the neutral position and the corresponding flapper resistance is R_0. If we define,

$$k = R_p/R_0 \tag{3}$$

we can have a better description of the resistance changes with command input shown in figure 3.

The model of flapper valve is further proven valid with the integral results done at system level. The physical model of the carriage positioning system is shown in figure 4. With the mathematical model of the flapper valve, we can simulate the open loop response. In figure 5, the comparison of the simulated response and the experimental data is presented. Note that the resonance at around 18 Hz is the structural resonance determined by the linkage stiffness.

The laminar flow flapper valve shows very good linearity. Therefore we can close the positioning loop with a simple controller design. A PID+Notch controller is employed. Figure 6 shows the step response of the closed-loop stage positioning system.

Discussion

There are several factors limiting the precision of stage positioning. The quiet hydraulics testbed has a wide dynamic range. The total travel is about 15 cm, while the precision target is at nanometer level. There are not a lot of sensors that can cover such a big dynamic range. The sensor output format also seems easier if we use A-quad-B signal. In this application, we have the choice of using A-quad-B, 32-bit digital words, or communication from PC's ISA bus. At the time of application, the A-quad-B signal is most ready to implement, as long as the controller allocates enough memory for decoder. But using A-quad-B signal prevents us using the finest resolution of the sensor, which is 0.3 nm. For this research the sensor resolution is about 5 nm.

The other limitation comes from the linkage stiffness. In this research, the mechanical design of the linkage is not optimized for its performance. A linear force transmission mechanism is a more important concern. Thus, limited by the structural stiffness at 18 Hz, we only tried to close the positioning loop at 4 Hz. From the steady-state error spectrum, we can see that the noise less than 20 Hz has great contribution to the overall noise level. Once the bandwidth is increase the precision of the stage positioning should improve.

The previous two effects are not hard to mend. We can upgrade the machine tool controller so that it can be installed in a stand-alone chassis with proper electric shield to reduce line noise. Furthermore we can upgrade the input interface of the machine tool controller to take 32-bit digital words directly from the sensor, we can both increase the loop update rate and sensor resolution. Thus, we can reduce the quantization error. We can also increase the bandwidth of the system by modifying the linkage design or modifying the controller. Therefore, the low frequency components of the error will be greatly reduced.

From the integration result, we are very confident about the laminar flow actuation in the applications of ultraprecision machines.

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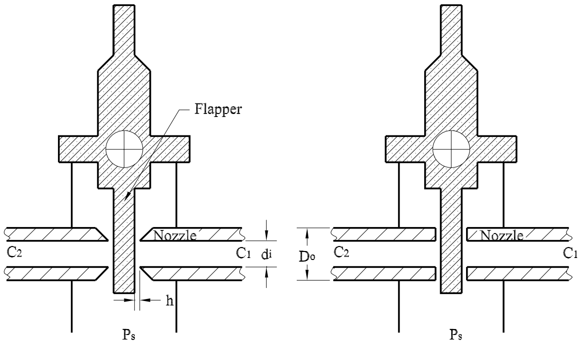

Figure 1. Turbulence flow flapper valve design vs. laminar flow flapper valve design

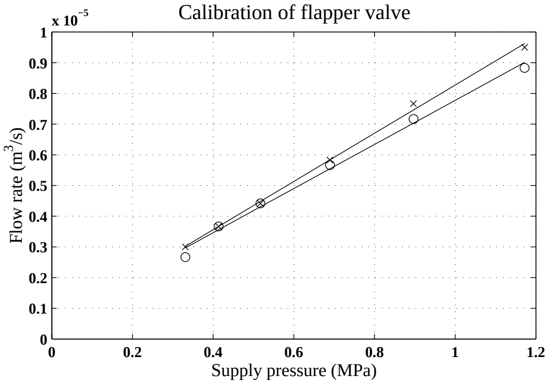

Figure 2. Nominal resistance of a laminar flow flapper valve

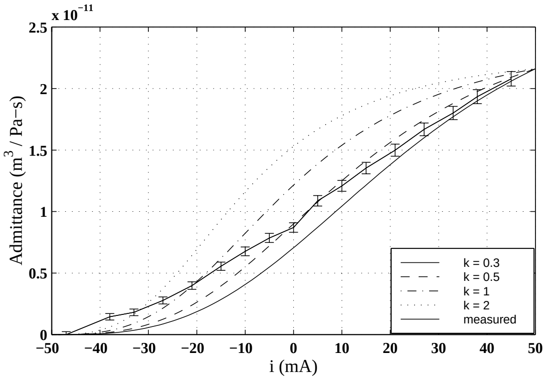

Figure 3. Effective admittance of the laminar flow flapper valve. Only one port is shown.

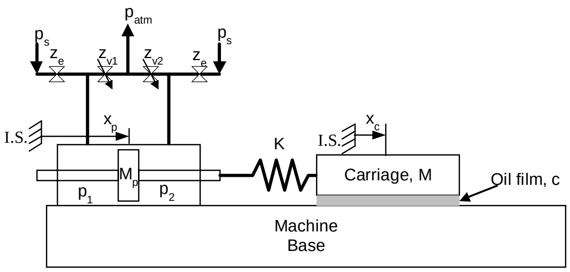

Figure 4. Stage positioning system

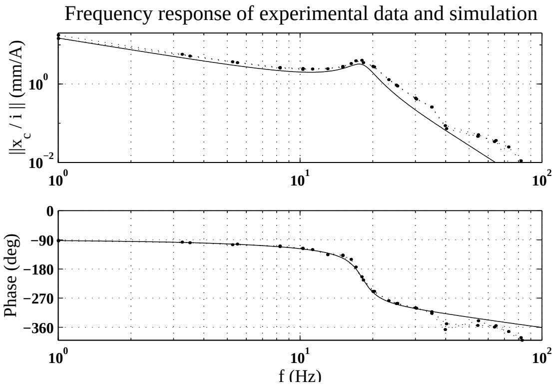

Figure 5. Open loop response of stage positioning system, simulation and experimental data

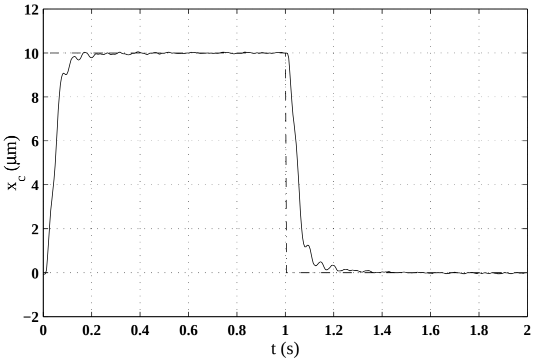

Figure 6. Step response of stage motion