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# Study of Pneumatic Servo Loading System in Double-Sided Polishing

N Qian, J Ruan and W Li

The MOE Key Laboratory of Mechanical Manufacture and Automation  
Zhejiang University of Technology, China, 310014

E-mail: qning940@sohu.com

**Abstract.** The precise double-sided polishing process is one of the main methods to get the ultra-smooth surface of workpiece. In double-sided polishing machine, a loading system is required to be able to precisely control the load superimposed on the workpiece, while the polishing is being carried out. A pneumatic servo loading system is proposed for this purpose. In the pneumatic servo system, the servo valve, which acts both the electrical to mechanical converter and the power amplifier, has a substantial influence on the performance of the loading system. Therefore a specially designed pneumatic digital servo valve is applied in the control system. In this paper, the construction of the pneumatic servo loading system in double-sided polishing machine and control strategy associated with the digital servo valve are first addressed. The mathematical model of the system established and the hardware of the pneumatic servo system is designed. Finally, the experiments are carried out by measuring the practical load on the workpiece and the quality of the surface finish. It is demonstrated that the error rate of load is less than 5% and a super-smooth surface of silicon wafer with roughness Ra 0.401 nm can be obtained.

## 1. Introduction

The precise double-sided polishing process is one of the main methods to get the ultra-smooth surface of these materials. It is usually carried out by a so-called double-sided polishing machine, primary parts of which involved several sub-systems, including polishing plate driving, pneumatic loading and electronic control etc.. Among them the pneumatic loading system is required to be able to precisely control the load superimposed on the workpiece, while the polishing is being undertaken. Pneumatic servo loading system can provide high precise and smooth force control. But conventional pneumatic servo valve is very costly and can only work reliably under cleaning conditions. Pneumatic servo control can also be achieved by utilization of the pneumatic proportional valve, which is relative more contaminated-proof. However, the pneumatic proportional valve is subject to nonlinearities, such as saturation and hysteresis due to the proportional solenoid, which is used to drive the valve spool. The commercial products of the proportional valve usually presented a hysteresis error rate of 5%-8%. So its controlling characteristic is comparatively unsatisfactory. In this paper, a pneumatic servo loading system is proposed and a pneumatic digital servo valve is designed for this servo loading system. The construction of the pneumatic servo loading system in double-sided polishing machine and control strategy associated with the digital servo valve are first addressed. The mathematical model of the system is established and the hardware circuit of the pneumatic servo loading system is also designed. Finally, the experiments are carried out.

## 2. Pneumatic servo loading system in double-sided polishing machine

### 2.1. Installation of pneumatic servo loading system.

Pneumatic servo loading system, which contains low friction cylinder, load cell, pneumatic digital servo valve, signal collection and control board, servo valve controller, single-chip, and is showed clearly in figure 1. And the signal collection and control board contains many modules, such as A/D, D/A, signal transmitter and so on. Double-sided polishing machine is showed in figure 2. The rod of the low friction cylinder is connected with a high-stability load cell, which is attached the top polishing plate, is on the topside of the machine, so that the force can be accurately detected.

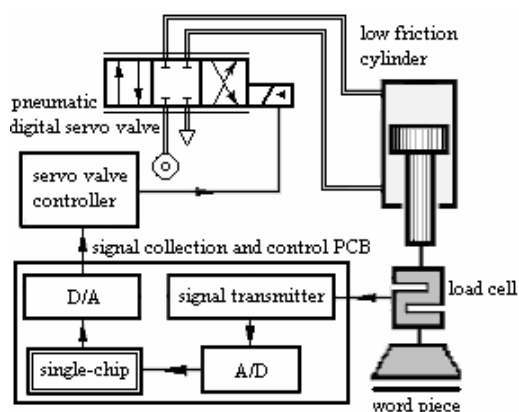


Figure 1. pneumatic servo loading system.



Figure 2. double-sided polishing machine.

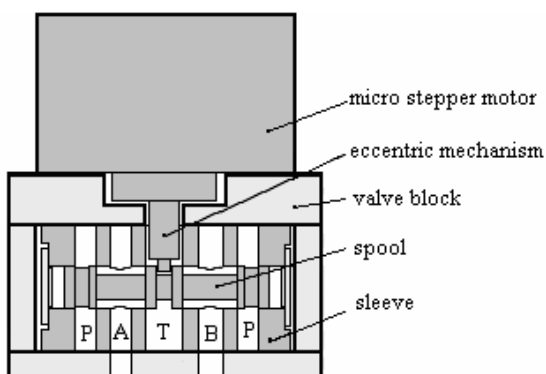


Figure 3. structure of pneumatic digital servo valve.

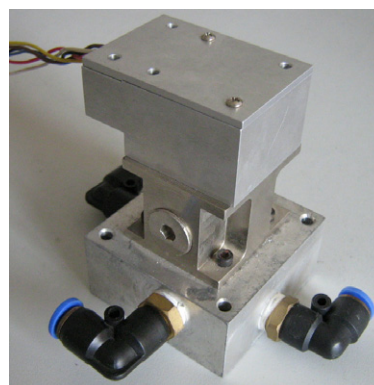


Figure 4. pneumatic digital servo valve.

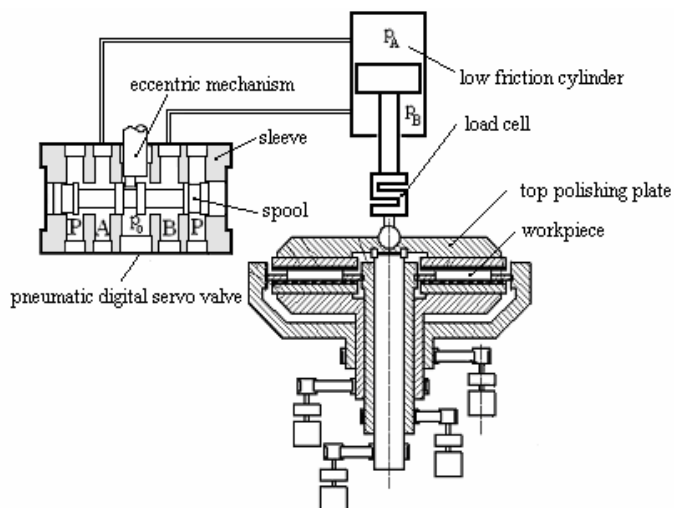


Figure 5. principle of pneumatic servo loading system.

## 2.2. Working principle of pneumatic servo loading system.

After running the initialization program in the digital servo valve controller, the spool of the digital servo valve will come to stay at central position and the cylinder rests on the original position. When the polishing machine works, the computer sends signal to digital servo valve controller after D/A conversion. Then the stepper motor rotates a corresponding angle according to the signal received by the controller. The rotor of the stepper motor is connected with the eccentric mechanism, so the rotary displacement is translated into the displacement of the spool and the valve is operated (Figure 3 is the structure of digital servo valve, and real valve is displayed in Figure 4). It is supposed that chamber A of the valve is connected to the top chamber of the cylinder and chamber B is connected to the bottom. When the machine works, computer sends signals to the valve controller, and the valve opens. Thus, chamber A is connected to high-pressure gas (chamber P), and chamber A is connected to atmosphere (chamber T). And the cylinder exports force, which is determined by the voltage signal (the placement of the cylinder is showed in figure 2). At the same time, the real value of force is transmitted to the computer by the load cell. So a close loop system is realized, and the computer can accurately control the loading force by PID algorithm. When the load task finishes, a voltage signal is sent to the controller by the computer and the spool is moved to the opposite position. Thus, the force is released, and the cylinder stops. The controller automatically makes the valve working in the mid position when the electrical source is turned off.

## 3. Modelling of pneumatic digital servo valve

Some supposition is made to simplify the analysis of the pneumatic servo loading system for the complexity of the flowing gas. These suppositions are showed as follows:

- Working fluid is ideal gas;
- Leakage is ignored;
- Pressure field and temperature are symmetrical in the same container;
- The course of flowing is isentropic flow.

The principle of loading system is showed in figure 5. Chamber A and B are connected to the top one of the cylinder and the bottom chamber of the cylinder respectively, and the system works in the loading state.

### 3.1. Equations of valve port flux.

There are two equations, which are the valve port flux between chamber A and high-pressure chamber ( $Q_{mA}$ ) and valve port flux between chamber B and low-pressure chamber ( $Q_{mB}$ ) [3].

$$Q_{mA} = \begin{cases} \frac{C_c A_1 p}{\sqrt{RT_1}} \sqrt{\frac{2k}{k-1} \left[ \left( \frac{p_A}{p} \right)^{\frac{2}{k}} - \left( \frac{p_A}{p} \right)^{\frac{1+k}{k}} \right]} & \left( 0.528 \leq \frac{p_A}{p} \leq 1 \right) \\ \frac{C_c A_1 p}{\sqrt{RT_1}} \sqrt{\frac{2k}{k+1} \left( \frac{2}{k+1} \right)^{\frac{1}{k-1}}} & \left( 0 \leq \frac{p_A}{p} \leq 0.528 \right) \end{cases} \quad (1)$$

$$Q_{mB} = \begin{cases} \frac{C_c A_2 p_B}{\sqrt{RT_2}} \sqrt{\frac{2k}{k-1} \left[ \left( \frac{p_0}{p_B} \right)^{\frac{2}{k}} - \left( \frac{p_0}{p_B} \right)^{\frac{1+k}{k}} \right]} & \left( 0.528 \leq \frac{p_0}{p_B} \leq 1 \right) \\ \frac{C_c A_2 p_B}{\sqrt{RT_2}} \sqrt{\frac{2k}{k+1} \left( \frac{2}{k+1} \right)^{\frac{1}{k-1}}} & \left( 0 \leq \frac{p_0}{p_B} \leq 0.528 \right) \end{cases} \quad (2)$$

3.2. Flow quantity equilibrium equations.

There are also two equations, which respectively show flowing equilibrium of the two chamber in cylinder. Flow quantity equilibrium equations are expressed as

$$Q_{mA} = \rho_A A_{p1} \frac{dx_p}{dt} + \frac{\rho_A V_A}{E_a} \frac{dp_A}{dt} \tag{3}$$

$$Q_{mB} = \rho_B A_{p2} \frac{dx_p}{dt} + \frac{\rho_B V_B}{E_a} \frac{dp_B}{dt} \tag{4}$$

3.3. Force equilibrium equations.

According to Newtonian Secondly Law, Force equilibrium equations are established as

$$p_A A_{p1} - p_B A_{p2} = m \frac{d^2 x_p}{dt^2} + \beta_a \frac{dx_p}{dt} + K x_p \tag{5}$$

At last, Laplace transformation is used, and the systematic block diagram showed in figure 6 is obtained.

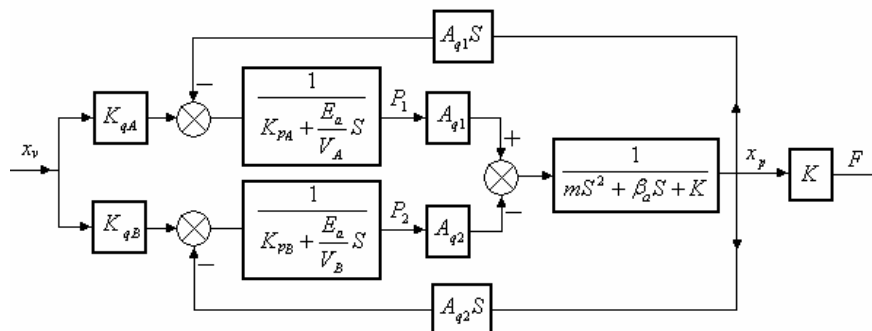


Figure 6. systematic block diagram of pneumatic servo loading system.

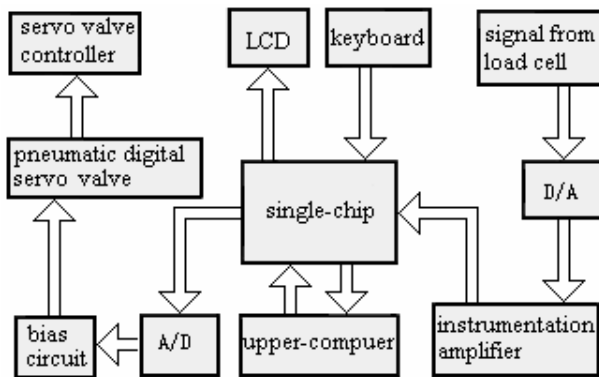


Figure 7. schematic diagram of servo loading system.

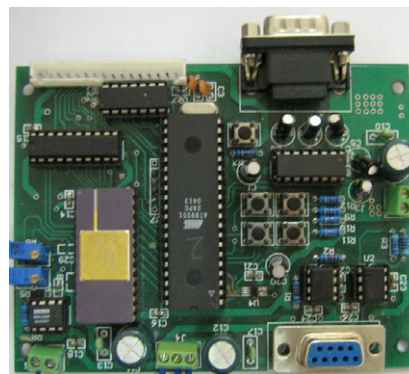


Figure 8. signal collection and control board.

4. Hardware of the pneumatic servo loading system

The schematic diagram of pneumatic servo loading system is showed in figure 7. And the hardware of the pneumatic servo loading system can be divided in two parts, servo valve controller and signal collection and control board. Among them, servo valve controller is mainly control the stepper motor. To sustain both high speed of response and good quantitative accuracy, a special algorithm that is smooth tracking control algorithm has been designed to control the stepper motor to produce a continuous rotary displacement. By adopting the algorithm, the contradiction between the stepper error and response speed of the digital valve is solved. And the signal collection and control board has many sub systems, such as signal transmitter, A/D, D/A, LCD and communication with super-computer. The signal collection and control board is showed in figure 8.

## 5. Experiment and results

Upper-computer controls the servo loading system by sending signals to the nether machine through serial interface, and many functions can be realized such as startup, stop, setting loading force and modifying PID parameter. During the experiment, the signal from the load cell is tracked by oscillograph, which can reflect the change of force. While the system works, the overshooting cannot be too large in order to protect the workpiece, the value of PI is setting comparatively small. The voltage-time curves are saved by oscillograph, and there is some linearity relationship between voltage and force. So the force-time curves can be obtained by multiplying a coefficient. And a force-time curve, which reflects the load force jumping from 40 kgf to 60 kgf, is showed in figure 9. The response time of the pneumatic system is comparatively long, which can also be found in the figure 9, and the loading force becomes steady in about 8 seconds. As double-sided polishing process is slow in nature, the loading force should be precisely controlled and there is no need of high response time. So the pneumatic servo loading system can satisfied the request of double-sided polishing machine. Through the experiment, it is demonstrated that the error rate of load is less than 5% and a super-smooth surface of silicon wafer with roughness Ra 0.401 nm can be obtained. (Figure 10)

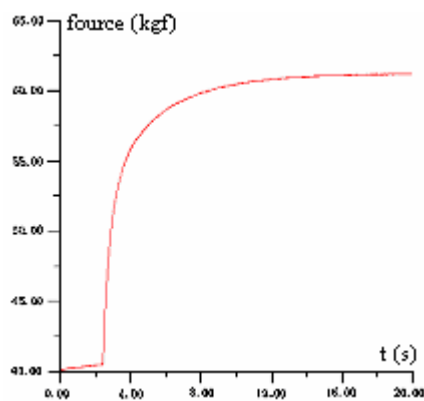


Figure 9. force-time curves of the servo loading system.

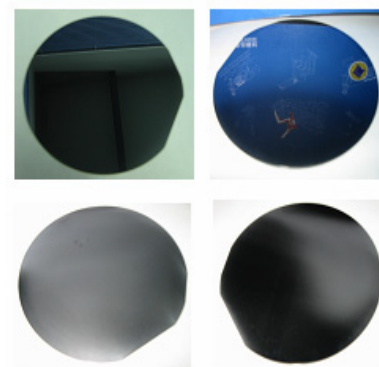


Figure 10. silicon after polishing process.

## 6. Conclusion

The structure of the new designed pneumatic digital servo valve is optimized comparing with traditional digital valve. The contradiction between the stepper error and response speed of the digital valve is solved by using the smooth tracking control algorithm. This pneumatic servo loading system can satisfy the needs of double-sided polishing machine, which can successfully produce the ultra-smooth and flat surface on both sides of silicon.

## Acknowledgements

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