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Development of the Polishing Tool System Based on the Pneumatic Force Servo

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Abstract: The deterministic polishing process is usually used to reduce the roughness and improve the form accuracy for the high precision optical part and mold surfaces. The polishing process is regarded as deterministic if the material removal during the polishing is controllable, thus the control of the polishing force is required essentially for the deterministic polishing. According to the polishing compliance principle, a position-force decoupled polishing system based on a pneumatic force servo is designed and developed. The real-time control platform consists of the data acquisition card, Labview software and Labview Real-time module is configured. With the input of Pseudo Random Binary Sequence (PRBS) signals and output force data, the system model is identified by the least square method. The PID controller is implemented and experimentally tested in the polishing system. The polishing experiments are conducted to verify the effectiveness of the polishing tool.

Key Words: deterministic polishing; polishing force control; pneumatic force servo; system identification

1. INTRODUCTION

With the development of the industry and science, high precision optical part and mold surface components have become a key component of optoelectronic and communications industry [1]. As the last process of surface manufacturing, polishing process plays a vital role in the assurance of its quality and working life [2]. Different from turning, grinding and milling processes, the deterministic polishing needs to control not only speed and position, but also the polishing force which can ensure the deterministic of material removal [3]. How to combine the controlling of the polishing force with the speed, displacement in the traditional CNC machine has been a research focus.

There are two basic force control methods in the automatic polishing field, rigid force control and compliance force control [4].When using rigid force control during the polishing process, the contact force between the polishing tool and workpiece is provided by the drive device of each axis. In this case, polishing force and displacement are coupled; it is called force/position coupled control. The force/position coupled control requires the establishment between the displacement of polishing tool end and contact force. That is adjusting the relationship of force and displacement by adjusting the parameters (spring, damping, stiffness parameters) [5]-[8]. And it is necessary to calculate the components of the displacement and force assigned to each axis to drive the drive device of each axis. The structure of force/position coupled control is simple but the force from drive device to the end of the actuator has a long delay, it has a negative effect to the controlling ability. Using compliance force control method, a separated force source added to the end of the actuator. Drive device only needs to control the displacement. Force and displacement are decoupled in this case, and it is easy to control. The force source of force/position decoupled method has two choices: pneumatic device and electromagnetic force device [11]-[13]. As the compressibility and compliance of the gas, pneumatic device is suitable [10]-[12],[14]-[16].

In this paper, a polishing force control system based on pressure proportional servo valve and guide rod cylinder is developed according to the principle of compliance of polishing process. The transfer function of the polishing force control system is deduced, and the system model is parameterized. Using the PID control to control the polishing force, a good control effect is got.

2. STRUCTURE OF POLISHING TOOL SYSTEM

The mechanical structure of polishing machine and its tool system are shown in Fig.1. The deterministic polishing control system is divided into a motion control system and a polishing force control system. The motion control system consists of the m5i20 motion control card and the X, Y, Z triaxial drive. The polishing tool system consists of a cylinder, an encoder, a DC polishing motor, a force sensor, a mounting plate and a polishing toolhead. The force required for polishing is provided by the tool system. The schematic of polishing force control circuit is shown in Fig.2. The cylinder is the short stroke guide rod cylinder, and the cylinder bore is 16mm. Force sensor is the SENSORIKA 52011 single point dynamometer, with the measuring range 0-200N. The force sensor is mounted between the polishing shaft and the cylinder to measure the

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normal polishing force during the polishing. After the force sensor forced, it will output voltage from 0 to 5mv, then the amplifier from SENSOTEC company is used to amplify the voltage. The data acquisition card is used to collect voltage data. Polishing spindle motor is 3557006CR DC motor from FAULHABER company with maximum speed 5300rpm and the maximum torque 70mNm. The selected encoder is the Agilent HEDS-550 encoder. The driver of the polished spindle is Sprint's 200XLV drive.

As shown in Fig.2, the air compressor will produce a certain pressure of air sent to the separator for oil/water separation and drying. In order to ensure the accurancy of the control of polishing pressure, the working medium has a high demand, a secondary treatment is needed for the compressed air. Thus, a filter regulator is set in the circuit. At the same time, compressed air through the filter regulator can keep pressure stably. The compressed air enter the upper chamber and lower chamber of the cylinder through the two proportional servo valves. During the polishing, a constant voltage signal is given to the proportional servo valve for the lower chamber,which makes the pressure of the compressed air into the lower chamber stable. The control voltage signal of upper chamber pressure proportional valve is calculated based on the measured actual force signal and the required polishing force. When the polishing process ends, the control voltage of pressure proportional valve connected to upper chamber will decrease to 0V slowly. Polishing shaft will leave the workpiece and moving upward under the pressure of lower chamber.

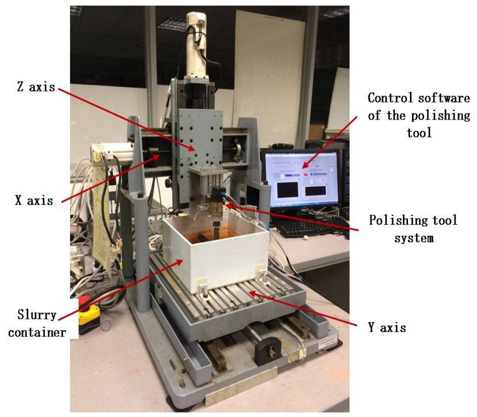


Fig.1 The structure of polishing tool system

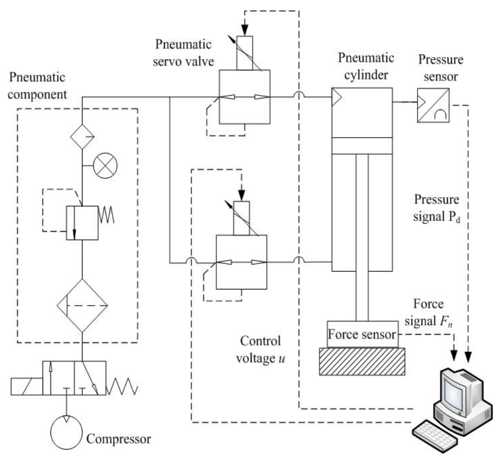


Fig.2 Polishing force control circuit

3. CONTROL SYSTEM ARCHITECTURE

With the development of computer technology and software technology, the virtual instrument development platform Labview combined with multi-function data acquisition card has been applied to test and control field, with the advantages of simple structure and flexible application. However, the ordinary Labview program is usually built on the Windows system, because of the non-real-time of the Windows system, it can only be applied to simple data collection tasks, and can not be applied to control system which has relatively high requirement of real-time communication.

In this paper, a real-time polishing force control system based NI PCIe6321 data acquisition card, Labview and its real-time module was developed. The architecture of the real-time polishing force control system is shown in Fig.3. The Windows operating system is set as Host PC, and the Labview software develops the human-computer interaction interface. The Host PC communicates with the real-time machine with the Real Time module via the TCP/IP protocol. Real-time module installed in the real time machine so that the real time machine can realize the real-time control and transport the collected parameters to the Host PC. At the same time, Host PC accepts and displays the process parameters of the control system in order to monitor the control system, meanwhile the parameters need to change of the command transport to the real-time machine via the Ethernet.

The schematic of polishing tool control is shown in Fig.4. Data acquisition card outputs the voltage signals to drive the pressure proportional servo valve and motor driver. In addition, it also collect the force signal of force sensor and the rotating speed signal of the encoder. According to the feedback signal, controller in the real time machine adjust the output to realize the control of polishing force and rotating speed.

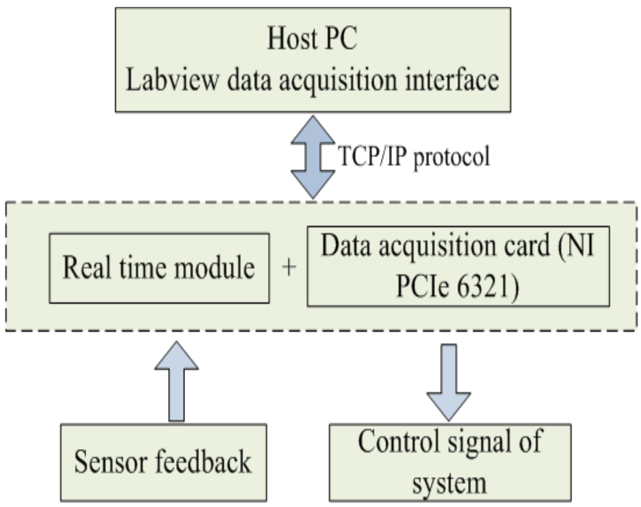


Fig.3 The architecture of real-time control system

4. SYSTEM TESTING AND IDENTIFICATI-ON

After the text edit has been completed, the paper is ready for the template. Duplicate the template file by using the Save As command, and use the naming convention prescribed by your conference for the name of your paper. In this newly created file, highlight all of the contents and import your prepared text file. You are now ready to style your paper; use the scroll down window on the left of the MS Word Formatting toolbar.

4.1 Frequency response and cut-off frequency

You will have the greatest control over the appearance of your figures if you are able to prepare electronic image files. It is a very important engineering method to analyze the relevant characteristics of the system by measuring the frequency characteristics of the system, and it can have a more intuitive understanding of the basic characteristics of the system and the influence of each parameter on the overall performance of the system. The traditional measurement method of system frequency characteristics (amplitude-frequency characteristics and phase-frequency characteristics) is inputting different frequency sinusoidal wave to the system and measuring its output. By changing the frequency of the input signal, output signal with different frequency is acquired. The amplitude ratio and phase difference of the input and output signals are calculated to obtain the amplitude and frequency characteristics and phase frequency characteristics of the system. This method is complicated and time-consuming. Based on virtual instrument technology, inputting sweep sinusoidal signals to the system, and collect the response value of system. Comparing the input excitation and output response, amplitude ratio and phase difference can be obtained.

The frequency of sweep sinusoidal signals increases with the increase of the time. The signal can be expressed as:

$$x = A\sin\left(\frac{a_f i^2}{2} + b_f i\right) \tag{1}$$

A is the amplitude of the signal, i is a integer greater than 1, a_f and b_f can be expressed as

$$a_f = \frac{2\pi(f_2 - f_1)}{n}, \quad b_f = 2\pi f_1 \tag{2}$$

In (2), n is the number sampling sites, f_2 and f_1 are final frequency and starting frequency after standardization, respectively.

$$f_{1,2} = \frac{F_{1,2}}{d} \tag{3}$$

F_1 and F_2 are final frequency and starting frequency of sweep function respectively, d is sampling frequency. F_1 =0 Hz, F_2=4Hz, d=500Hz, n=6×104. Input signal and output force signal are shown in Fig.5a and Fig.5b respectively.

As shown in Fig.5, when the frequency of the input signal is low, the amplitude of the output is large. With the increase of the frequency of input signal, the amplitude of the output signal gets smaller. When the frequency of the input signal reaches the cut-off frequency of the system, the amplitude of the output signal nears zero. Processing the signals in Fig.5, the frequency response of the system can be obtained and it shows in Fig.6. Since the measured output force signal is unavoidable with noise signals, the calculated frequency

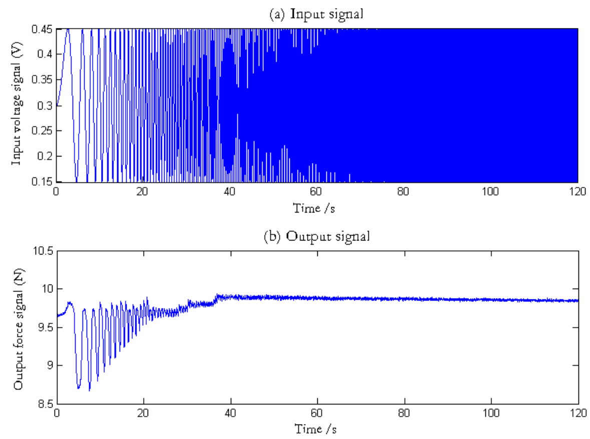


Fig.5 Measuring the input signal of voltage and output signal of force by frequency response

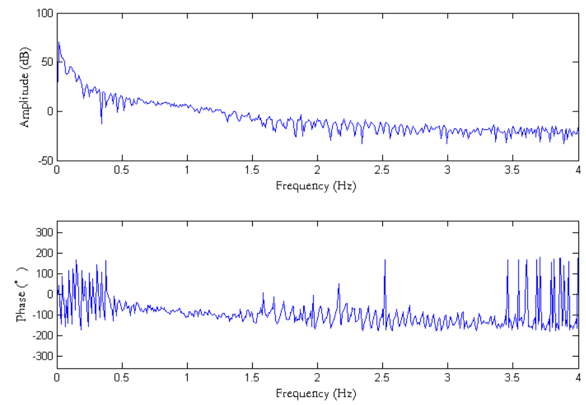


Fig.6 Frequency response of the system

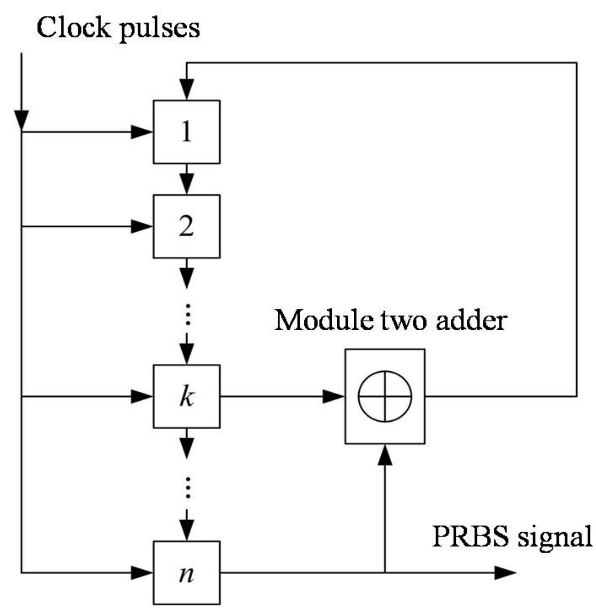


Fig.7 Generation of thePRBS signal

4.2 System model identification based on PRBS signal

4.2.1 PRBS signal

On the basis of frequency response test, PRBS signal and least squares system identification method are utilized to identify the model of the system. As a commonly used system testing signal, PRBS signal has a wide frequency band which makes the energy evenly cover the system spectrum and the system is fully motivated.

The principle of generating the binary PRBS signal is shown in Fig.7. Including a n level shift register with a feedback channel and a model two adder. The status of k level and n level are added in the mode two adder, the output value is the input of the level first. When there is a shift pulse input, the status of level i-1 is transferred to level i. The status of level n is regarded as the output of PRBS signal. Each register has two status 0 and 1. So there are 2n kinds of combination in a n level shift register. Removing the status that all shift registers are status 0, the sequence length of the PRBS signal is $N_p=2^n-1$. If the interval between the two adjacent pulse signals is the clock interval Δt, the period of a PRBS signal T_p can be expressed as:

$$T_p = N_p \Delta t = (2^n - 1)\Delta t \tag{4}$$

Requirements are needed when using PRBS signal to identify the system.

(1) The period of the signal T_p. The selection of the signal period T_P should be greater than the time of the impulse response of the system. It means that the response function of identification object should completely attenuated in the T_P time, it makes the influence of PRBS perturbation signal on the system tested more accurately.

(2) Clock period Δt. The effective bandwidth of the PRBS should cover the main operating spectrum of the identified object, so the clock period should be less than the reciprocal of the cut-off frequency of the identification system, usually taking $\Delta t \leqslant 0.33/C_k$. In addition, the clock period Δt is set to an integer multiple of the sampling time in the actual measurement. $\Delta t=p\Delta ts$. Δts is the sampling time of the system, p=1,2,3….

(3) The amplitude of signal A_p. The signal amplitude of the PRBS should be as small as possible, but must be greater than the amplitude of the system noise. If the signal to noise ratio is too small, the test time must be increased to get better test results. If the amplitude setting is too large, it may stimulate a part of the system non-linear features and adverse the identification process instead. The amplitude of the general setting signal is 3% -5% of the rated value.

According to Fig.6, the cut-off frequency of force control system is 1.25Hz. Choosing Δt=0.05s, it is satisfied

$$\Delta t = 0.05s < \frac{1}{3C_k} = 0.264s \tag{5}$$

The sampling interval time of the system Δt_s is equal to the clock period Δt . As shown in Fig.8. Inputting a step signal at 2s, it costs 0.5s for the system reaching the stable status. In order to make the period of the PRBS signal greater than the system transition time, take n=7, and $N_p=2^7-1=127$.

$$T_p = N_p \Delta t > 0.5 \tag{6}$$

4.2.2 Identification of the system model

When the pneumatic control system is running, friction and non-linear factors have great influence on the system, because of the noise problem, the output signal of force sensor has great fluctuation. So the amplitude of input signal is 10% of the rated amplitude. When the system is input a voltage signal with rated amplitude of 0.5V which is shown in Fig.9a, the output force of the system is shown in Fig.9b.

In fact the control of the polishing tool system is a discrete control process, the input and output of the control system can be expressed in discrete form.

$$A(q^{-1})y(k) = B(q^{-1})u(k) + w(k) \tag{7}$$

In (7), $A(q^{-1})$ and $B(q^{-1})$ are polynominal.

$$\begin{cases} A(q^{-1}) = a_0 + a_1 q^{-1} + a_2 q^{-2} + \cdots + a_{n_a} q^{-n_a} \\ B(q^{-1}) = b_0 + b_1 q^{-1} + b_2 q^{-2} + \cdots + b_{n_b} q^{-n_b} \end{cases} \tag{8}$$

The discrete form of the system transfer function can be expressed as:

$$G(q^{-1}) = \frac{q^{-d}(b_0 + b_1 q^{-1} + b_2 q^{-2} + \cdots + b_{n_b} q^{-n_b})}{a_0 + a_1 q^{-1} + a_2 q^{-2} + \cdots + a_{n_a} q^{-n_a}} \tag{9}$$

The results in Fig.9 are considered as the input and output of the system. The IDENT tool box in Matlab and the least squares method are used to identify the parameters of the model. Set $n_a=n_b+1=n$, n=3 and system delay parameter d=1. The model parameters after identified are shown in Table 1.

5. CONTROLLER DESIGN AND POLISHING EXPERIMENTS

5.1. Polishing force control experiments

PID controller is simple and robust. In industrial application, more than half of the controller are using PID controller. The PID controller is expressed as:

$$G(s) = K_p(1 + \frac{1}{T_i s} + T_d s) \tag{10}$$

In (10), K_p is the proportion gain, T_i is the integration constant, T_d is the derivative constant. In the polishing force control system of this paper, the data acquisition card collects the polishing force F_n of the current time by force sensor then comparing it with the theoretical value and make the difference of the two value ΔF_n. Sending the ΔF_n to the controller and calculate the control voltage. The error will be corrected.

The Z-N rules are used to adjust the PID controller. If using PI control, K_p=0.54 , T_i=0.33. If using PID control, K_p=0.72 , T_i=0.2 , T_d=0.05. The sampling time of the experiments is 2ms. Fig.10a is the curve of PID controller response to the step signal. The output force increased from 6.5N to 14N, the adjust time is 1.5s and the overshoot is

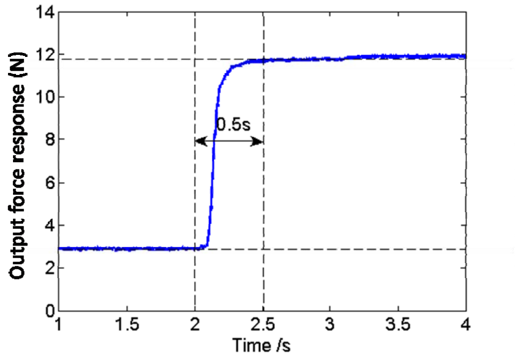


Fig.8 Test of pulse response time

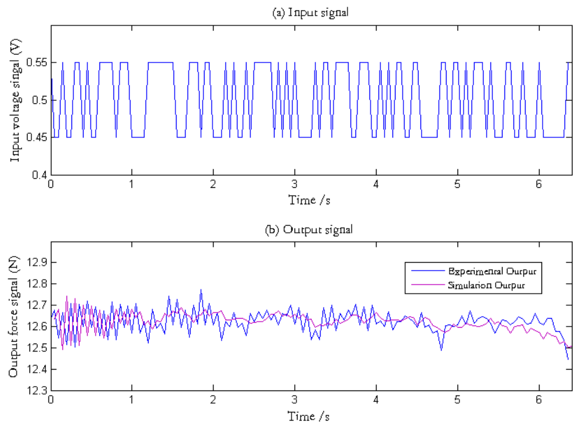


Fig.9 Identification of system open- loop transfer function

Table 1. Parameters of the force control system open-loop transfer function (d=1, n=3)

$G(q^{-1})=q^{-d}B(q^{-1})/A(q^{-1})$	q^0	q^{-1}	q^{-2}	q^{-3}
$B(q^{-1})$	0.2477	0.2712	-0.01567	0
$A(q^{-1})$	1	-0.154	-0.897	0.071

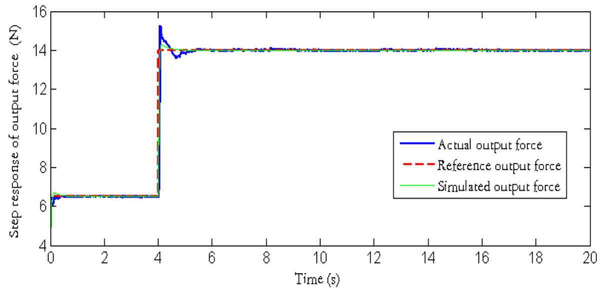
10%. Fig.10b is the curve of PI controller response to the step signal. The adjust time is 2.5s, no overshoot exist.

In polishing experiment, constant polishing force is needed. To avoid the generation of surface damage during the load of polishing force, big overshoot is not allowed. According to Fig.10, using PID controller can avoid big overshoot and keep constant polishing force.

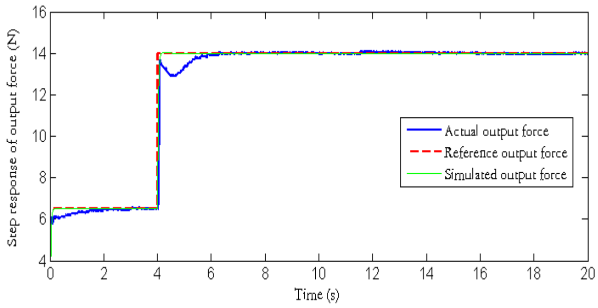
In Fig.10, the rotating speed is not considered. If the rotating speed is considered, it is equivalent to adding a perturbation at the output of the polishing force. It will cause fluctuation of the polishing force. Fig.11 shows the output of polishing force at different rotating speed. The rotating speed increases from 500rpm to 2000rpm, the average value of polishing force is stable(8N), but the amplitude of fluctuation increases.

6. CONCLUSIONS

A polishing tool system with force control which consists of the proportional servo valves and guide rod cylinder is introduced in this paper. The control system is based on NI PCIe6321 data acquisition card, Labview and its real-time module.



(a) K_p =0.72， T_i =0.2， T_d =0.05



(b) K_p =0.54， T_i =0.33

Fig.10 The response curve of PID contro

According to the frequency response of the system, the cut-off frequency of force control system is 1.25Hz. By inputting PRBS signal, the least squares method is used to identify the system model.

According to the experimental results, the PID controller can adjust the system faster, prevent the system from big overshoot and keep a constant polishing force. The rotating speed of the polishing spindle has influence on output polishing force. A higher rotating speed will leads to a greater fluctuation amplitude of the polishing force.

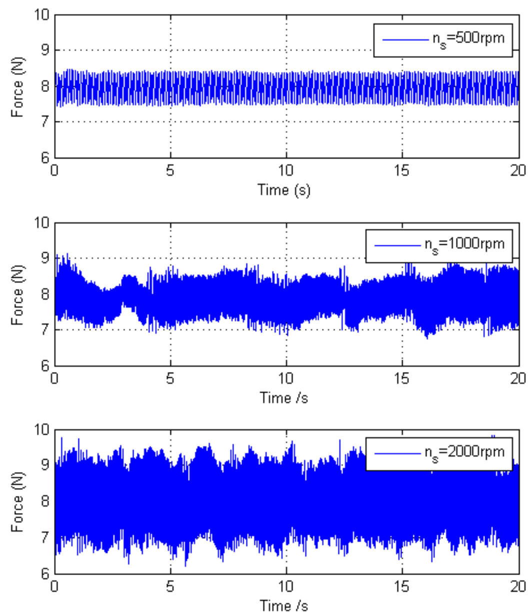


Fig.11 Polishing force in different rotating speed

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