Development of Nanometer Positioning System Driven by Force Operational Water Hydraulic Actuator with Rigid Slide Guide-way, -Simulation and Experimental Evaluation of Non-Linear Positioning Characteristics-

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1. Introduction

Most of conventional machine tools use slide guide-way system in order to obtain both high positioning rigidity and damping characteristics to suppress reaction force and oscillation due to cutting and/or grinding process. However, the nonlinear friction load of slide guide-way causes stick-slip motion, and as a result decreases motion accuracy as well as stability of the positioning system. A new control system design is required to realize nanometer-positioning system with high rigidity and high damping characteristics. Kanai et al. proposed a new theoretical model which can simulate the nonlinear friction characteristics of the slide guide-way in several hundreds nm displacement region.

The goal of our research is to develop a nanometer positioning system that is applicable to the ductile mode grinding system of next generation. The newly developed simulation system includes the nonlinear friction characteristics model and the elastic model of the saddle structure. In this paper, the new nonlinear simulation method is proposed and its validity is experimentally evaluated.

2. Positioning system

Fig.1 shows the schematic of the experimental positioning system. A force operation type water hydraulic cylinder, which is exempt of unwanted heat source, generates huge force by the differential pressure control operated by a servo-valve (MOOG, E061-007). The saddle is guided by the double-V type slide guide- way that realizes high stiffness and high damping toward the operation axis, and high motion accuracy toward the guide axis (both horizontal and vertical). A digital controller operates the servo-valve with PID position feedback control, where a linear scale is used as the feedback sensor with the resolution of 2.5nm.In this

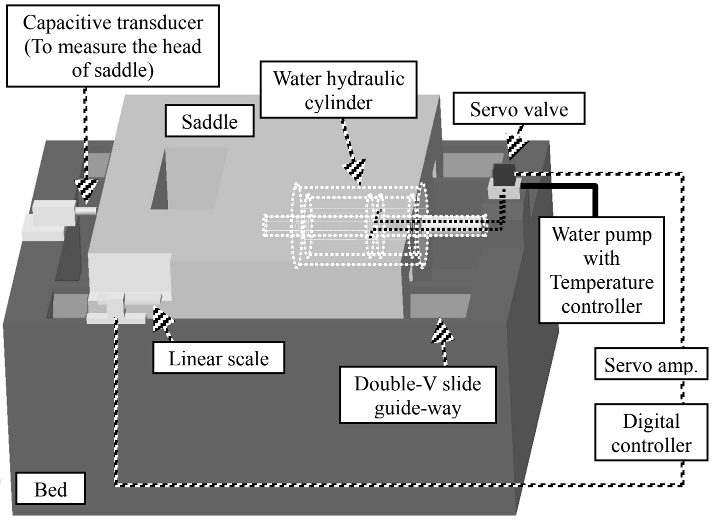

Fig.1 Schematic of the positioning system

positioning mechanism, the frictional load is so huge that the saddle is forced to be deformed. Through the experiment, the static rate of the deformation has turned out to be 0.14nm at operational force of 1N.

3. Simulation model

Fig.2 indicates the simulation model of the whole positioning system. In Fig.2, C_q and C_p are the flow gain and the pressure gain of the servo-valve. ω_n and ζ are the characteristic frequency and the damping ratio of the flapper in the servo-valve. A represents the piston area of the cylinder. V and K_v are the volume and the volume elasticity of water.

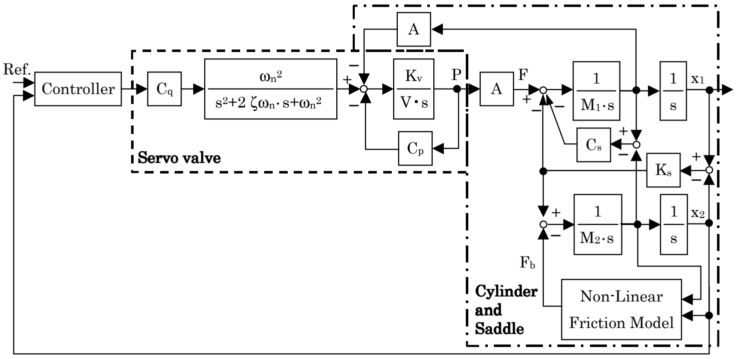

Fig.2 Schematic of simulation model of the positioning system

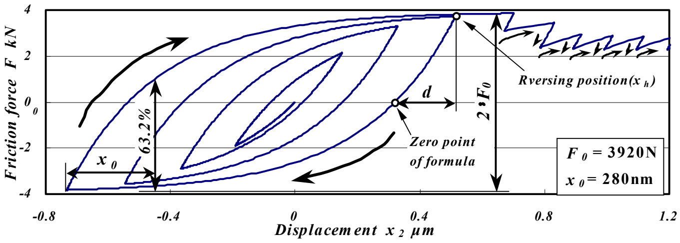

Fig.3 Friction characteristic of slide guide-way (Swaying and stepping motion)

The dynamics of the saddle is modeled as the two masses (M_1, M_2) linked by a spring with the spring constant of K_s, and associated with a damper with damping ratio of C_s. The cylinder is connected to M_1, and M_2 is placed on the slide guide-way. x_1 and x_2 ,which are the displacement of the masses M_1 and M_2, express the displacement of the head and that of the side of the saddle. In order to prevent an unwanted momentum from arising, it is better to align the axis of the cutting/grinding with that of operation. However the aligned position of two axis puts the restriction on the freedom of the placement of the sensor.

The block named "Non-linear friction model" is the one of the displacement for the frictional load characteristics in the sub μm range, which is expressed by the formula (1)1) and which depends on both the history and the direction of saddle motion. Fig.3 is the typical fluctuation of the characteristics.

$$F(x)=\pm F_0\cdot\left(1-2\cdot\exp\left(\mp\frac{x}{x_0}\right)\right)\ \ldots(1)$$

$F(x)$: frictional load
F_0 : stationary frictional load
x : displacement after reversing feed direction
x_0 : displacement constant

With regard to the positioning system of this development, stationary frictional load (F_0) is 3920N, displacement constant (x_0) is 290nm.

4. Experimental and simulation result

The characteristic behavior of the positioning system in this development appears at the motion including some "start-and-stop" actions like step feed, because the non-linearity of the huge frictional load affects on the response. Fig.4 displays the experimental result of the displacement and operational force fluctuation at 50nm step feed. Similarly, Fig.5 shows the simulation result. Fig.6 represents the results of both the experiment and simulation. And also plotted in Fig.6 is the behavior of formula (1). To be note is that the operation force is plotted against the displacement of the side of the saddle. On these figures, first 20 steps are directed to the positive, and the after, 20 steps are directed to the negative. In both experiment and simulation, before turning to the positive stepping, the saddle moves several micrometers, which are much larger than the transient domain, by the positive continuous feed to saturate the frictional load.

In Fig.4 showing the fluctuation of the motion, the side of the saddle, which is closely controlled, among the motion direct to the positive follows well the commanded position without the significant over-shoot larger than 10nm. The head of the saddle follows the commanded position with the deviation less than several ten nanometers and over-shoot larger than 50nm. Then if the fluctuation of the operational force is observed, it increases about 0.5kN and decreases almost same in one step, and its shape of the fluctuation remains almost equal at each step.

The observed fluctuations are explained as follows. First, the side of the saddle keeps well up with the commanded step motion with a little over-shoot. With the displacement of the step motion, the frictional load increases according to the formula (1), therefore the operation force also increases according to the formula (1). Next, the side of the saddle is controlled to compensate the over-shoot, therefore both the frictional load and the operation force decrease in line with the formula (1). The saturation of the frictional load makes the shape of the each response similar to one another. And the fluctuation of the operation force (about 0.5kN) and the elasticity of the saddle (0.14nm/N) cause the large over-shoot (70nm) at the head of the saddle.

After the step direction is reversed, if the operation force is observed, it decreases without increasing toward the positive until the 3rd step. From the 4th step, the increase starts and becomes larger and larger. And as steps progress, the increase becomes almost equal to the decrease. The fluctuation of the operation force toward the negative seems to show the behavior typical to the step response curve of first order delay with a time constant. If the displacement in the zoomed view of Fig.5 is observed, the side of

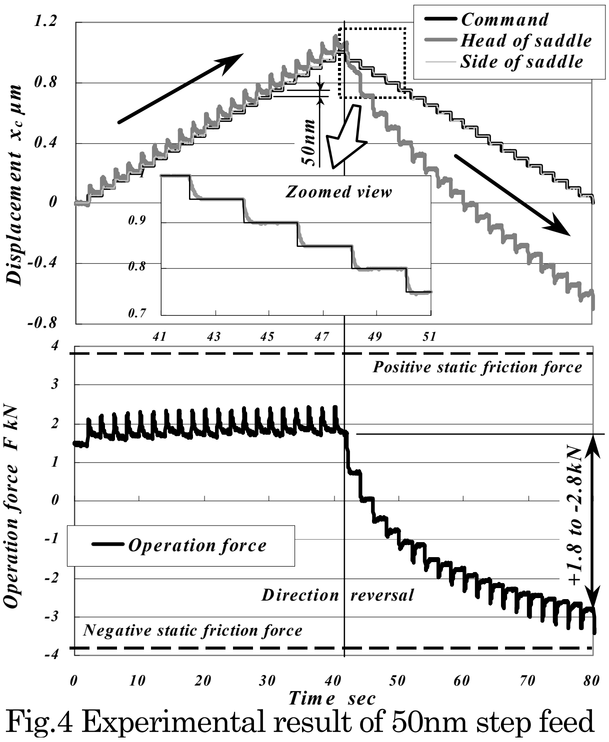

Fig.4 Experimental result of 50nm step feed

the saddle follows well the commanded position, changing the response at each step. The head of the saddle moves about two times as much distance as the command. It also changes the response at each step.

In Fig.6, the operation force considerably fluctuates to the negative along with the curve of the formula (1). After over-shoot starts, the fluctuation gradually deviates because the reversing position shifts. The equivalent spring stiffness according to the frictional load in the formula (1) changes so significantly for the positioning system dynamics that the response of the saddle changes depending on the shift of the frictional load. When the frictional load becomes close to the stationary frictional load, the equivalent spring stiffness becomes so soft that the over-shoot happens easily. But if the over-shoot is very large, the decrease of the frictional load on the compensation motion becomes large and the equivalent spring stiffness increases. Therefore at the step feed which travels over the transient domain, the frictional load is saturated near the stationary frictional load.

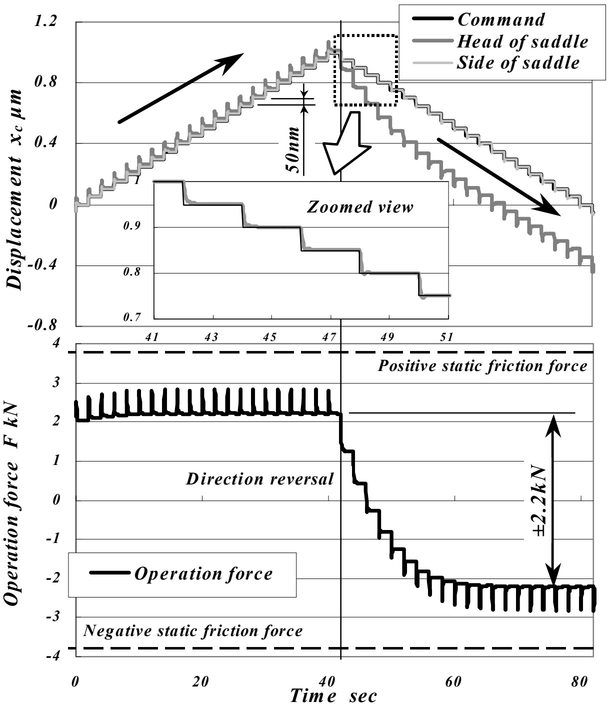

Fig.5 Simulation result of 50nm step feed

If the fluctuation of the operation force and saddle motions in Fig.5 and 6 are observed, there is a good agreement between the experiment and simulation results. It can be thought that the errors of the two results are caused by the characteristics that are not included in this simulator, which is the non-linearity of the servo-valve, the viscosity of the lubricating oil and the distribution of the frictional load along the slide guide.

5. Conclusions

By comparing the simulated positioning characteristics with the experimental one, it has been shown that both results describes good agreement each other, although the associate phenomena include the non-linearity in the positioning that depends on the direction of stepwise motion, the step height, and the history of motion.

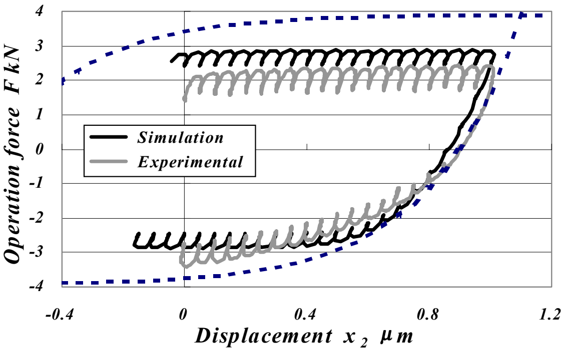

Fig.6 Simulation and experimental result of 50nm step feed

6. References

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