2002 Japan-USA Symposium
on Flexible Automation
Hiroshima, Japan, July 14-19, 2002

A PRACTICAL SERVO PARAMETER TUNING METHOD FOR HIGH SPEED FEED DRIVES OF NC MACHINE TOOLS

Atsushi Matsubara, Soichi Ibaraki, Yoshiaki Kakino and Kangkyu Lee
Department of Precision Engineering, Graduate School of Engineering
Kyoto University
Address: Yoshida-honmachi Sakyo-ku Kyoto, Japan 606-8317
E-mail: matsubara@ prec.kyoto-u.ac.jp
Yasuhiko Suzuki and Yoshinori Yamaoka
Machining Technology Research Center
Yamazaki Mazak Corporation

ABSTRACT

This paper presents a practical servo tuning method for high speed machine tools to improve the motion accuracies. Vibration in high speed feed drive systems is easy to be inspired by high response in the servo systems. In order to balance the servo and vibration errors, the CNC servo parameters are tuned and a couple of candidates are presented by using a simulation model identified in the experiments. As such off-line tuning can offer the good chance to explore many combinations of servo parameters, a few experimental tests is enough to decide the most adequate combination. A case study of an existing machining center shows that the proper tuning of servo parameters reduces the vibration in the machine tool and improves its motion accuracies.

INTRODUCTION

This paper deals with a practical servo tuning method for high speed and high acceleration feed drives in the latest NC machine tools. General CNC servo systems of machine tool drives consist of current-velocity-position FB (feedback) control, FF (feedforward) control and command generator. Due to the technical progress in hardware and software, a high response servo control can be adopted in commercial feed drives.

One or two axes combination of feed drives has less vibration problems as it drives a table in a horizontal plane. However, when it is built in a complicated structure, vibration problems tend to occur in practical applications. In particular, vibrations at low frequency deteriorate the contouring accuracy. Notch filters cannot compensate such vibrations, because their phase lag often deteriorates the closed-loop servo control performance. Thus we have to find out good combination of parameters in the basic CNC servo system. As the empirical search of such combinations of CNC servo parameters requires a lot of efforts or experiences, quick and accurate tuning methods are necessary.

The total tuning method was proposed by Kakino et al. (1997) to reduce the motion errors. It proposed to tune mechanical parameters such that the natural frequency of the dynamics of each axis agrees with each other, and to tune servo parameters such that the velocity transfer function of each axis agrees with each other. However, since the natural frequency of each axis is designed to match the lowest one among three axes, it may significantly sacrifice servo control performance of other axes.

On the other hand, the method using the fuzzy interference is proposed to identify the parameters of the plant and tune the control system (Iwasaki et al., 1992). But the method has some limitations in application that the plant is not machine tools but only the motor and the rule will be complex if the number of the parameters increases.

More importantly, vibration components outside feed drives are not considered in above-mentioned methods. To find out CNC servo parameters that can offer accurate, smooth and vibration-free trajectory, we propose a simple and systematic tuning method based on the simulation and measurement technology and apply it to a commercial machining center to validate the proposed method.

OVERVIEW OF TUNING METHOD

We propose a simple but effective tuning method as shown in Fig. 1. The procedure starts with motion accuracy tests.

Conventionally, the DBB (Double Ball Bar) device is used to measure a contouring error profile as the machine is traversing along a circular trajectory. The diagnosis methodology of error sources based on the DBB measurement mainly focuses on motion errors due to mechanical structure (Kakino et al., 1993). It contributes to improve its motion accuracies but it is not proper in diagnosing the servo control system because it is restricted to the measurement of motion errors in circular interpolation operations.

From this reason we use KGM method instead of DBB method. The KGM method (Teimel, 1992) uses the principle of diffracted light to measure the two-dimensional position as the scanning head crosses perpendicularly the grating of the interferometer's glass encoder. A test trajectory to measure the machine's motion accuracy is selected as shown in Fig. 2. It consists of straight lines (inclined by 0, 45 and 90 degree from the X axis), a sharp corner and a right angle corner to inspire mechanical vibration, a dull corner and arcs to check smoothness.

The first trial test is conducted on the machine with the aggressive setting of servo parameters. By using the results of trial tests, mechanical parameters, which cause the vibration problem, are identified. By using the simulation on the identified model, servo tuning is conducted to select the candidates of best combination of CNC servo parameters. Each candidate is tested on the machine to decide the most adequate combination.

TUNING MODEL, SIMULATION PARAMETERS

For our tuning purpose, we need a model of the entire servo control system for feed drives, which consists of command generator, FF control, FB control and a mechanical vibration model. As for CNC servo system, the following simplification and generalization are made to meet our requirements.

(1) The command generator is modeled to have the same function as the actual CNC has, such as corner velocity restriction and smoothing function. Acceleration and deceleration profile is an S curve, which has the first and second time constants. A step-type velocity command profile may cause the vibration due to the impact to the machine base. To prevent it, CNC command is converted from step-type into trapezoidal type through the acceleration filter. There are two methods to distribute a velocity command to each axis: the pre-interpolation acceleration control and the post-interpolation acceleration control. In post-interpolation acceleration control, a velocity command is distributed to each axis, and then is filtered for the smoothing independently in each axis. In pre-interpolation acceleration control, a velocity command is first filtered for the smoothing and then is distributed to each axis. Post-interpolation acceleration control deteriorates the motion accuracy particularly at corners because the overlapping of the deceleration and acceleration. Pre-interpolation acceleration control improves the motion accuracy but the cycle time gets longer because there is no overlapping time. In this paper, we choose the pre-interpolation acceleration control to improve the motion accuracy but we can control the overlapping time by setting of the corner speed.

(2) FF controller is 1st order. The FB controllers in the current loop, the velocity loop and the position loop must be tuned such that the machine tracks the command as fast as possible, but there are some limitation to secure the stability of the closed-loop system. To address these problems, the velocity FF controller is inserted between the command generator and the velocity FB controller.

(3) In the simulation model, the transfer function of the velocity and current control loops is regarded as ideal (=1) and only the position loop is considered. In many commercial CNC systems, a high-order position control

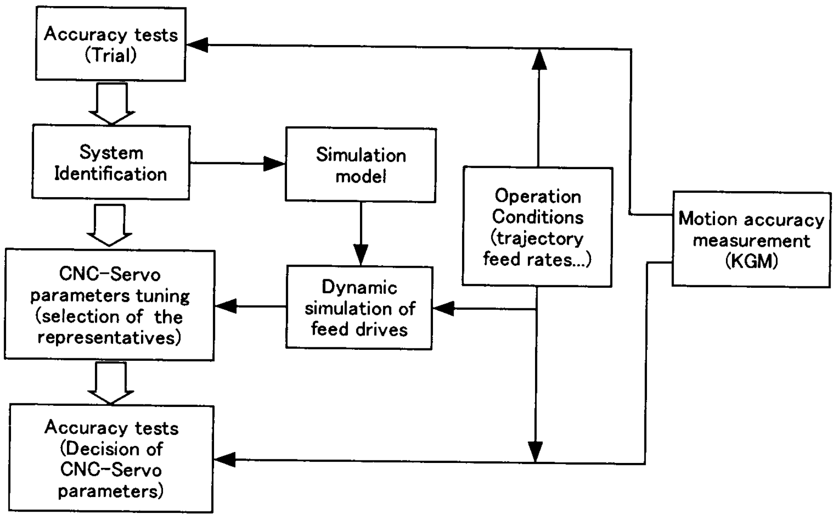


Fig. 1 Tuning procedure

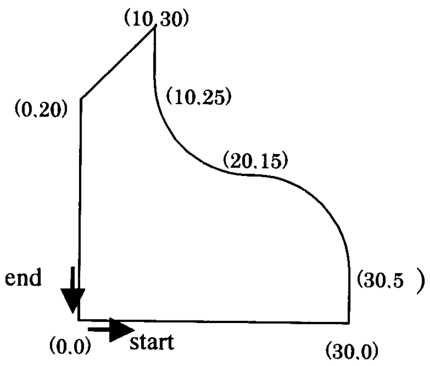


Fig. 2 Test trajectory

block is implemented within the position FB loop to improve the response of the system (Takeshita et al., 1997). By using a high order position FB controller, the radius reduction in circular interpolations is declined due to the improvement of the control performance. Furthermore, a more stable response can be expected particularly at corners due to the decrease of the impact. The mechanical vibration dynamics can be modeled as a second-order linear model. Base vibration model and table vibration model are considered. The base vibration is mainly introduced by the vibration of the column, which is inflicted by the reaction force against the table motion. The table position is given as the relative position to the base vibration.

Fig. 3 shows the block diagram of the model considering the above assumptions. In the figure, K_f : Feedforward gain [%], HPC: High order position controller (Takeshita et al., 1997), K_p: Position loop gain [1/s], h_{pc1}(=8/3) and h_{pc2}(=6): HPC gain coefficient, K_l: longitudinal stiffness of the ball screw and the support bearing [N/m], M_t: mass of the table [kg], C_t: damping coefficient of the guideways [N·s/m], M_b: mass of the base [kg], C_b: damping coefficient of the base [N·s/m], K_b: stiffness of the base [N/m].

Tuning parameters are the acceleration time (first-order time constant), the time constant of the smoothing filter (second-order time constant), FF gain, position loop gain and corner speed. The acceleration time is the for the command feedrate to reach the given level. The smoothing filter is a moving average filter that converts the trapezoidal velocity reference trajectory into the S curve. Clearly, the acceleration time and the time constant of the filter are among the most critical factors affecting the mechanical vibration. The corner deceleration also causes a trade-off between the motion accuracy and the productivity. If the machine is decelerated to zero speed at each corner, then the minimum contouring error can be expected, although it obviously lengthens the cycle time. On the other hand, if the machine moves fast at a corner, it may cause a large contouring error and a structural vibration. The above parameters are included in command generator. The ripple occurs by the period of calculation and resolution because the FF controller needs differential of the command. Therefore, when the FF gain becomes higher, the mechanical vibration takes place. But it is desirable to set FF gain as closed to 1 as possible to avoid the vibration. High gain of position loop can reduce the influence of the friction and the disturbance but the value is limited to insure the system stable.

CASE STUDY

The tuning method is applied to a commercial gantry type machining center. The stroke of X, Y and Z axes are 1020 [mm], 510 [mm] and 490 [mm] respectively. The maximum feedrate is 50 [m/min]. Table 1 shows the experimental condition.

Fig. 4 (a) shows the KGM measurement result of motion accuracy at first trial test in XY-plane. As this combination of each parameter is aggressive enough to induce the mechanical vibration, about 30Hz mechanical vibration can be observed in X axis direction at each corner. The main cause of this vibration is the lack of damping in the column structure of the gantry.

By analyzing the vibration components at each corner, the mechanical parameters are identified and set in the simulation model. Fig. 4 (b) shows the simulated profile and has a good agreement with Fig. 4 (a). Based on this model, manual servo tuning is conducted by using dynamic simulation. Several candidates of parameter combinations are selected so as not to

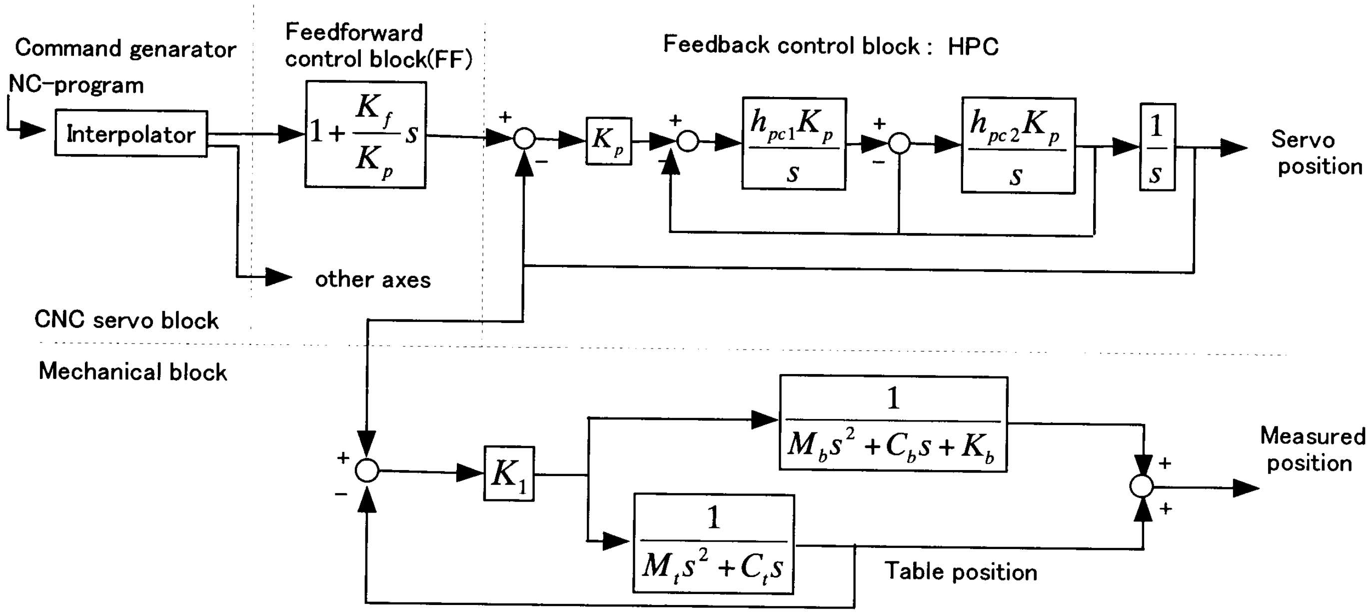
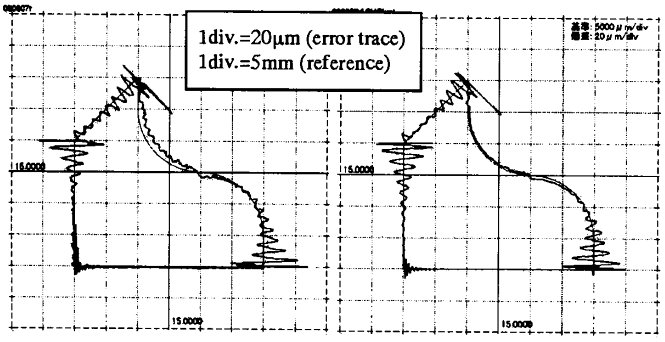
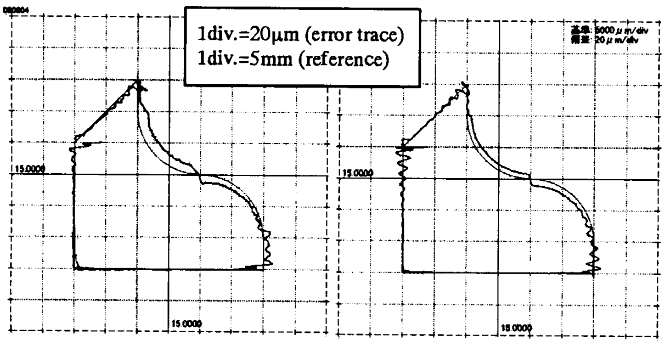


Fig. 3 Block diagram of the simulation model



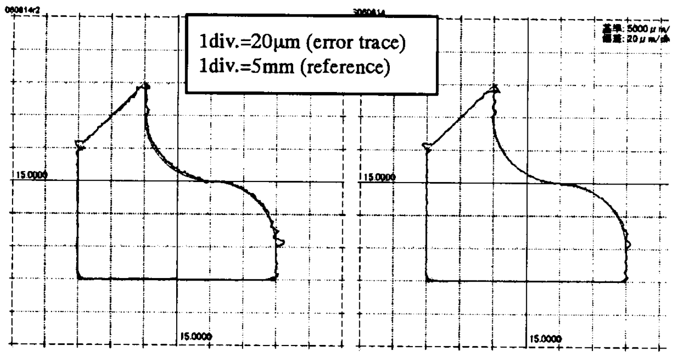
(a) KGM Measurement (b) Simulation

Fig. 4 Motion error traces before tuning



(a) KGM Measurement (b) Simulation

Fig. 5 Motion error traces in first trial



(a) KGM Measurement (b) Simulation

Fig. 6 Motion error traces in the final selection

induce the mechanical vibration and not to make the cycle time longer.

In the first trial of simulation, the acceleration time constant is increased from 140 [ms] to 300 [ms]. The position gain is reduced from 100 [1/s] to 60 [1/s] and the corner speed from 1300 [mm/min] to 690 [mm/min]. Fig. 5 shows that the amplitude of the vibration gets smaller but still it remains at each corner and the servo error is increased a little in the arc due to the decrease of the position gain. The cycle time was 2.56 [s].

Finally, we find parameters as follows and the obtained motion error traces are shown in Fig. 6. The acceleration time is increased from 300 [ms] to 600 [ms] and the corner speed is

Table 1 The experimental conditions

Parameter	Before tuning	First trial	Final selection
Acceleration time ms	140	300	600
Time constant of the smoothing filter ms	56.8	56.8	28.4
FF gain K_f %	40	40	56
Position loop gain K_p 1/s	100	60	80
Corner speed mm/min	1300	690	110
Feedrate mm/min	3000		

decreased from 690 [mm/min] to 110 [mm/min] in order to soften the mechanical shock at the corner. Instead of this, the time constant of the filter is reduced from 56.8 [ms] to 28.4 [ms] to prevent the increasing of the cycle time. The FF gain is raised from 40 [%] to 56 [%] and the position gain is raised from 60 [1/s] to 80 [1/s] to compensate the error on the arc. As a result, the cycle time was 2.59[s], which was not so longer than the aggressive fist trial (2.50[s]).

CONCLUSIONS

A practical tuning method for high speed machines is proposed. As this method utilizes the simulation model identified by simple but practical measurements of contouring error tests, it is quite practical to find out the best combination of CNC servo parameters. By using this method, a commercial machining center is tuned to have good motion accuracy while keeping enough speed.

REFERENCES

Kakino, Y., Ihara, Y., Shinohara, A., 1993, "Accuracy Inspection of NC Machine Tools by Double Ball Bar Method", Hanser Publisher, Munichi

Kakino, Y., Matsubara, A., Ibaraki, S., Nakagawa, H., Takeshita, T., Maruyama, H., 1997, "A Study on Total Tuning of Feed Drive Systems in NC Machine Tools (4th Report), *Journal of Japan Society for Precision Engineering*, Vol. 63, No. 3, pp. 368-372.

Iwasaki, T., Morita, A., Maruyama, H., 1992, "Plant Identification with Fuzzy Interference and Its Application to Auto-Tuning", *Journal of Japan Society for Precision Engineering*, Vol. 58, No. 10, pp. 2997-3002.

Teimel A., 1992, "Technology and Application of Grating Interferometers in High Precision Measurement", *Precision Engineering*, Vol. 14, No. 3, pp. 147-154.

Takeshita, T., Kazama, T., Kachi, M., 1997, "A Study on the Improvement of Servo Performance of CNC Machine Tools", *Journal of Japan Society of Mechanical Engineering-C*, Vol. 63, No. 11, pp. 3870-3875.