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Impedance Model Force Control Using a Neural Network-Based Effective Stiffness Estimator

F. Nagata, T. Mizobuchi
Tokyo University of Science, Yamaguchi
Sanyo-Onoda, Japan

T. Hase, Z. Haga
R&D Center, Meiho Co. Ltd.
Nogata, Japan

K. Watanabe
Okayama University
Okayama, Japan

Maki K. Habib
American University in Cairo
Cairo, Egypt

Abstract

In manufacturing industries of metallic molds, various NC machine tools are used. We have already proposed a desktop NC machine tool with compliance control capability to automatically cope with the finishing process of LED lens molds. The NC machine tool has an ability to control the polishing force acting between an abrasive tool and a workpiece. The force control method is called impedance model force control. The most effective gain is the desired damping of the impedance model. Ideally, the desired damping is calculated from the critical damping condition in consideration of the effective stiffness in force control system. However, there exists a problem that the effective stiffness of the NC machine tool has undesirable nonlinearity. The nonlinearity gives bad influences to the force control stability. In this paper, a fine tuning method of the desired damping is considered by using neural networks. The neural networks acquire the nonlinearity of effective stiffness. The promise is evaluated through an experiment.

1 Introduction

Up to now, many kinds of robot systems for polishing and deburring have been developed in various manufacturing fields. In manufacturing process of small metallic molds such as LED lens molds, 3D CAD/CAM system and NC machining center are used generally and widely, and these have drastically rationalized the design and manufacturing process. However, the finishing process after the machining process has been hardly automated yet, because the target mold has several concave areas to be polished in almost all cases. That means the target mold is not axis-symmetric, so that conventional effective polishing systems, which can deal with only axis-symmetric workpiece, can not be applied. Accordingly, such axis-asymmetric lens molds are polished by skilled workers in related industrial fields.

To automate the finishing process of metallic molds, we have already proposed the polishing robot for PET bottle blow molds [1] and desktop NC machine tool for LED lens molds. The control strategy for these two types of systems is almost common. A ball-end abrasive tool attached to the arm tip is controlled by the CAD/CAM-based position/force controller. The force controller used is called the impedance model force controller, in which the desired damping is tuned to be in critical damping condition. The desired damping is one of the impedance parameters and has a large influence on force control stability. The critical damping condition is calculated with the effective stiffness that includes the characteristics of the robot or NC machine tool itself, force sensor, abrasive tool, jig, floor and so on. However, there exist undesirable nonlinearities in the effective stiffness.

In this paper, an impedance model force control using neural networks is proposed to deal with the nonlinear effective stiffness. In advance, the nonlinearity is examined by a simple static position and force measurement. The effectiveness stiffness is easily obtained by the measurement. The desired damping in impedance model force control law is statically calculated from the critical damping condition of the force control system. The neural networks learn the relation between the contact force and effective stiffness, so that the desired damping can be dynamically generated according to the contact force. The effectiveness and promise are demonstrated through an experiment using the desktop NC machine tool.

2 Desktop NC machine tool

Figure 1 shows the developed desktop NC machine tool consisting of three single-axis robots with position resolution of 1 μm. The size of the robot is 850 $\times$ 645 $\times$ 700 mm. The single-axis robot is a position control device ISPA with high-precision resolution provided by IAI Corp., which is composed of a base, linear guide, ball-screw, AC servo motor. The effective strokes in x-, y- and z-directions are 400, 300 and 100 mm, respectively. The tool axis is designed to be parallel to z-axis. A small wood stick tool is fixed to the tip through a 3-DOF compact force sensor. To regulate the rotation, a servo spindle is located parallel to the tool axis.

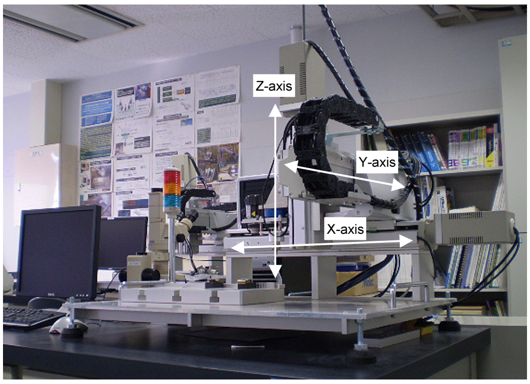

Figure 1: Proposed NC machine tool.

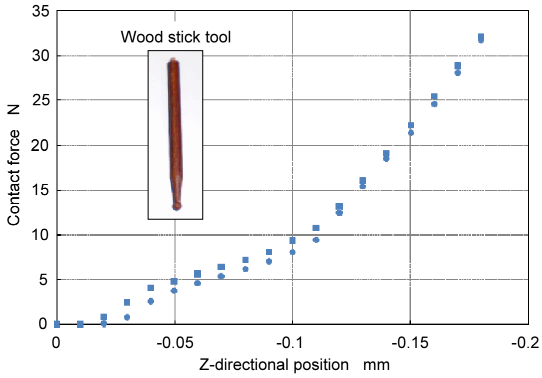

Figure 2: Static relation between position and force.

2.1 Measurement of effective stiffness

In this subsection, effective stiffness, valid position resolution of Cartesian-based servo system and resultant force resolution are evaluated through a simple static position/force measurement. The effective stiffness means the total stiffness including the characteristics composed of the single axis robot, force sensor, attachment, wood stick tool, workpiece, jig and floor.

Figure 2 shows the relation obtained by a simple contact experiment. The quantity of the position is the z-directional component at the tip of a wood stick tool. The quantity of force is yielded by contacting the tool tip with a workpiece and measured by the force sensor. The graph drawn with squares in Fig. 2 shows the relation the position and contact force in press motion. After the press motion, the tool tip was away from the workpiece once, and returned to the position again where 32 N had been obtained. After that, the tool tip was unpressed every 0.01 mm. The graph drawn in circles in Fig. 2 shows the relation of the position and contact force of this case. It is observed that small backlash exists. Also, the force is about 32 N when the position of the tool tip is -0.18 mm, so that the effective stiffness within the range can be estimated with 177.7 N/mm.

2.2 Learning of effective stiffness

The force control method used is called the impedance model force control. When the force controller is applied, the desired damping should be suitably tuned according to the effective stiffness. Since unstable phenomena such as overshoot and non-

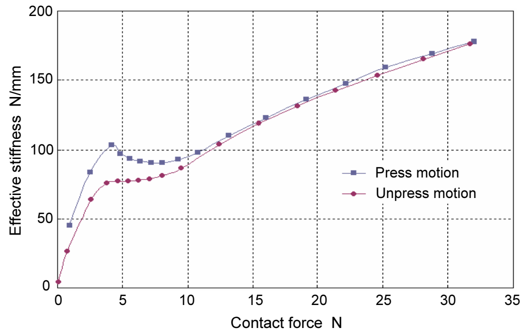

Figure 3: Effective stiffness of the NC machine tool.

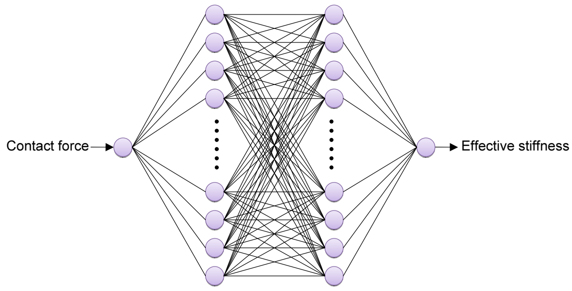

Figure 4: Neural network for acquiring nonlinearities.

contact state tend to appear in force control system with the increase of the effective stiffness, the desired damping has to be given larger values. A systematic tuning method for the desired damping was already proposed in consideration of the critical damping condition in force control system. The calculation of the critical damping condition requires the effective stiffness of force control system. Figure 3 shows the nonlinear variations of effective stiffness in press and unpress motions obtained from Fig. 2.

In this subsection, in order to consider the nonlinearity, a neural network is employed as shown in Fig. 4. Hereafter, the neural network is called NN. Two NNs are learned for the press and unpress motions, respectively. The NN consists of an input layer, two hidden layers and an output layer. Each layer has one, thirty and one units, respectively. Note that the output layer does not have an activated function, i.e., sigmoid function. Therefore, the NN directly yields an estimated effective stiffness from the calculation of weighted sum. The NN acquires the relation between the contact force and the effective stiffness shown in Fig. 3 by the back propagation algorithm. Teaching patterns are given in the order from left to right on horizontal axis in Fig. 3.

Figures 5 and 6 show the learning results of the press and unpress motion, respectively. It is recognized that the learnings are successfully conducted with the increase of the trial times. The learned NNs are called NN-based effective stiffness estimator.

3 Design of controller

3.1 CAD/CAM-based controller

Figure 7 shows the block diagram of the CAD/CAM-based control system used in the NC machine tool. The tip of abrasive tool is controlled the

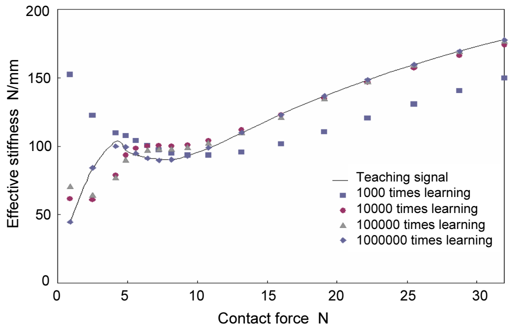

Figure 5: Learning result in press motion.

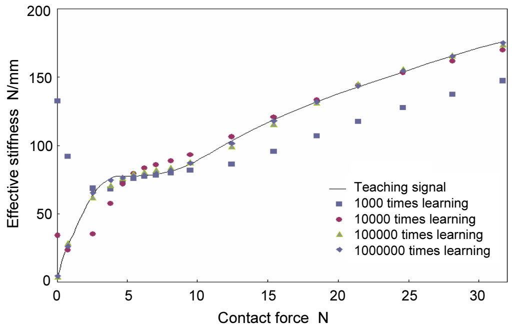

Figure 6: Learning result in unpress motion.

translational velocity ${}^{W}\boldsymbol{v}(k) \in \Re^{3\times 1}$ given by

$$ {}^{W}\boldsymbol{v}(k) = {}^{W}\boldsymbol{v}_t(k) + {}^{W}\boldsymbol{v}_n(k) + {}^{W}\boldsymbol{v}_p(k) \tag{1} $$

where k denotes the discrete time and ^{W} means a work coordinate system. First of all, ${}^{W}\boldsymbol{v}_t(k)$ is the manipulated variable generated from the feedforward control law based on cutter location data called CL data. ${}^{W}\boldsymbol{v}_t(k)$ is the tangential velocity along curved surface and written by

$$ {}^{W}\boldsymbol{v}_t(k) = v_{tangent}(k)\frac{{}^{W}\boldsymbol{t}(k)}{\|{}^{W}\boldsymbol{t}(k)\|} \tag{2} $$

where $v_{tangent}(k)$ is a velocity scalar generated from the fuzzy feed rate generator. The fuzzy feed rate generator yields suitable feed rate norms according to surface curvatures. ${}^{W}\boldsymbol{t}(k)$ is the tangential vector obtained by analyzing the CL data [1].

${}^{W}\boldsymbol{v}_n(k)$ is the manipulated variable generated from the force feedback control law. ${}^{W}\boldsymbol{v}_n(k)$ is the normal velocity at the contact point and written by

$$ {}^{W}\boldsymbol{v}_n(k) = v_{normal}(k)\,{}^{W}\boldsymbol{o}_d(k) \tag{3} $$

where ${}^{W}\boldsymbol{o}_d(k)$ is the normalized normal vector calculated using the direction components of CL data. The scalar $v_{normal}(k)$ representing the norm of the normal velocity is the output of the impedance model force control law, which is calculated by

$$ v_{normal}(k) = v_{normal}(k-1)\; e^{-\frac{B_d}{M_d}\Delta t} + \left(e^{-\frac{B_d}{M_d}\Delta t} - 1\right)\frac{K_f}{B_d}E_f(k) \tag{4} $$

where K_f is the force feedback gain, impedance parameters M_d and B_d are the desired inertia and damping coefficients, respectively. Δt is the sampling time.

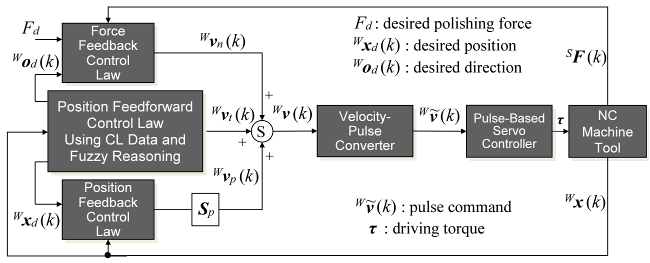

Figure 7: Block diagram of control system.

Also, $E_f(k)$ is the force error between the desired polishing force F_d and norm of force ${}^{S}\boldsymbol{F}(k) \in \Re^3$ measured by the force sensor, which is given by

$$ E_f(k) = F_d - \|{}^{S}\boldsymbol{F}(k)\| \tag{5} $$

where superscript ^{S} represents the sensor coordinate system. Further, we consider another velocity ${}^{W}\boldsymbol{v}_p(k)$ for regular position control in spiral direction. ${}^{W}\boldsymbol{v}_p(k)$ is the manipulated variable yielded by a position feedback control law represented by

$$ {}^{W}\boldsymbol{v}_p(k) = \boldsymbol{S}_p\Big\{\boldsymbol{K}_p\boldsymbol{E}_p(k) + \boldsymbol{K}_i\sum_{n=1}^{k}\boldsymbol{E}_p(n)\Big\} \tag{6} $$

where $\boldsymbol{E}_p(k) = {}^{W}\boldsymbol{x}_d(k) - {}^{W}\boldsymbol{x}(k)$ is the position error. The desired position ${}^{W}\boldsymbol{x}_d(k)$ is calculated using CL data. $\boldsymbol{K}_p = \mathrm{diag}(K_{px}, K_{py}, K_{pz})$ and $\boldsymbol{K}_i = \mathrm{diag}(K_{ix}, K_{iy}, K_{iz})$ are proportional and integral gains for position feedback control. Switch matrix $\boldsymbol{S}_p = \mathrm{diag}(S_x, S_y, S_z)$ makes the weak coupling control to the direction of force control active or inactive. If an element of $\boldsymbol{S}_p$ is set to 1, then the weak coupling control in the corresponding direction becomes active. Due to the weak coupling control, it is simultaneously realized that stable polishing force control and regular profiling control along a spiral path.

${}^{W}\boldsymbol{v}_n(k)$, ${}^{W}\boldsymbol{v}_t(k)$ and ${}^{W}\boldsymbol{v}_p(k)$ comprise ${}^{W}\boldsymbol{v}(k)$. Further, the velocity pulse converter transforms the fine manipulated value in velocity into the pulse command given by an integer, which can be outputted to the pulse-based servo controller. The velocity pulse converter for the pulse-based servo controller is located after the position/force controller as shown in Fig. 7.

3.2 NN-based effective stiffness estimator

Figure 8 shows the detailed block diagram of the force feedback control law illustrated in Fig. 7. Figure 9 also shows the detailed block diagram of the NN-based effective stiffness estimator illustrated in Fig. 8. The two NNs in Fig. 9 are switched by the sign of

$$ \Delta\|{}^{S}\boldsymbol{F}(k)\| = \|{}^{S}\boldsymbol{F}(k)\| - \|{}^{S}\boldsymbol{F}(k-1)\| \tag{7} $$

If $\Delta\|{}^{S}\boldsymbol{F}(k)\| > 0$, then NN learned with the teaching patterns in press motion is selected. Also, if $\Delta\|{}^{S}\boldsymbol{F}(k)\| < 0$, then NN learned with the teaching patterns in unpress motion is used. For example, when the desired polishing force F_d is set to 10 N, the points

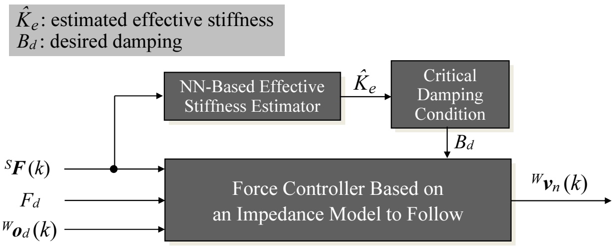

Figure 8: Feedback control law shown in Fig. 7.

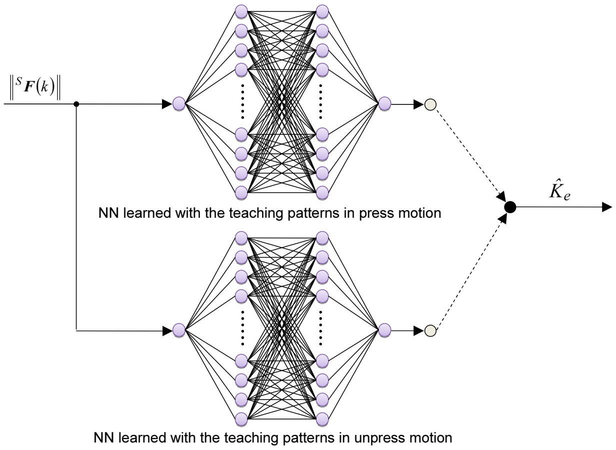

Figure 9: NN-based effective stiffness estimator.

of 10 N in Figs. 5 and 6 become the operating points. The NN-based effective stiffness estimator generates time-varying effective stiffness $\hat{K}_e$ around the operating points. In the next subsection, critical damping condition in force control system generates the desired damping for stable force control.

3.3 Tuning of desired damping

When the polishing force is controlled, the characteristics of force control system can be varied according to the combination of impedance parameters such as desired mass and damping. In order to increase the force control stability the desired damping, which has much influence on force control stability, should be tuned suitably. Here, a tuning method of desired damping is proposed by using the effective stiffness of the NC machine tool. Eq. (4) is derived from the following impedance model.

$$M_d(\ddot{x} - \ddot{x}_d) + B_d(\dot{x} - \dot{x}_d) = K_f(F - F_d) \tag{8}$$

where $\ddot{x}$, $\dot{x}$ and F are the acceleration, velocity and force scalars in the direction of force control, respectively. $\ddot{x}_d$, $\dot{x}_d$ and F_d are the desired acceleration, velocity and force, respectively. When the force control is active, $\ddot{x}_d$ and $\dot{x}_d$ are set to zero. It is assumed that F is the external force given by an environment and is model as

$$F = -B_m\dot{x} - K_m x \tag{9}$$

where B_m and K_m are the viscosity and stiffness coefficients of the environment, respectively. Eqs. (8) and (9) lead to the following characteristics equation.

$$s^2 + \frac{B_d + K_f B_m}{M_d}s + \frac{K_f K_m}{M_d} = 0 \tag{10}$$

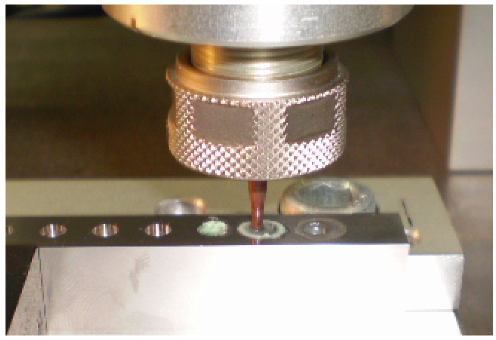

Figure 10: Finishing scene by using the wood stick tool and diamond lapping paste.

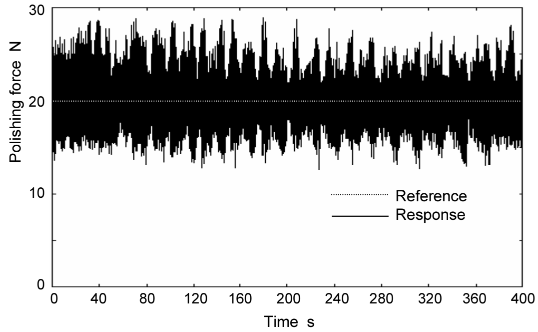

Figure 11: Control result of polishing force $\|{}^S\boldsymbol{F}(k)\|$.

By solving Eq. (10) with the critical damping condition, the desired damping can be given by

$$B_d = 2\sqrt{M_d K_f K_m} - K_f B_m \tag{11}$$

4 Experiment

In this section, the proposed system is applied to the finishing of an LED lens mold. The small ball-end tool lathed from a wood stick is used, whose tip diameter is 1 mm. A spiral path for finishing is generated along the small curved surface by using a CAD/CAM. Figure 10 shows the finishing scene, where a special oil including the diamond lapping paste is poured. In this case, the polishing force was successfully controlled around 20 N as shown in Fig. 11 in spite of oscillations caused by tool rotation of 400 rpm.

5 Conclusions

An impedance model force control using neural networks has been proposed to deal with the nonlinear effective stiffness of a desktop NC machine tool. The neural networks learned the nonlinear relation between the contact force and effective stiffness, so that the desired damping could be dynamically generated according to the contact force. The effectiveness and promise of the proposed method were demonstrated by a finishing experiment of an LED lens mold.

References

[1] F. Nagata, T. Hase, Z. Haga, M. Omoto and K. Watanabe, "CAD/CAM-based position/force controller for a mold polishing robot," *Mechatronics*, vol. 17, no. 4–5, pp. 207–216, 2007.