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Active chatter suppression in turning by band-limited force control

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ABSTRACT

The suppression of chatter vibration is required to enhance the machined surface quality and to increase tool life. In this study, a new, conceptually active approach for chatter suppression in machining is proposed. The hybrid control method developed by applying sensorless force control with a disturbance observer enables the simultaneous and independent control of the position trajectory and band-limited forces. The proposed method is introduced to the carriage of a prototype desktop-sized turning machine, and the ability to suppress chatter is evaluated by end-face cutting tests. The results demonstrate that actively controlling a band-limited force leads to the avoidance of chatter.

1. Introduction

The suppression of chatter vibration is one of the most important issues in machining processes. The model-based chatter vibration theory based on a continuous cutting process such as turning and an intermittent process such as end milling has been developed with considerable accuracy by a series of studies conducted by CIRP. Smith and Tlusty created a time-domain simulation model for chatter vibration in milling [1], whereas Minis and Yanushevsky [2] as well as Altintas and Budak [3] developed analytical models to analyze the chatter stability in cylindrical end mills. Further, Shamoto developed an analytical method to predict chatter stability in ball end milling with tool inclination [4].

However, the vibration models must be altered depending on the cutting conditions, machine tools, tools, and workpieces. Thus, it is very difficult to identify the parameters of a vibration model. Another way of suppressing chatter is to implement adaptive control in accordance with chatter detection. In many studies regarding the detection of chatter vibration in cutting, the use of external sensors such as accelerometers and dynamometers is considered necessary. However, adding external sensors increases the cost of the machine tools, and the maintenance interval becomes shorter to maintain the normal performance of the sensors without failure. Thus far, the reliability of these methods is insufficient in practical use.

In order to solve the problem of monitoring, a sensorless chatter detection method with a disturbance observer (DOB) [5] was developed [6]. In this study, a new approach with band-limited force control is proposed to suppress chatter. The band-limited force control system is developed by applying sensorless force control with a DOB and enables simultaneous and independent control of the position trajectory and band-limited forces.

This paper first describes the design of the band-limited force control system without a force sensor. Next, the basic performance is evaluated by a frequency-response test, and finally, the effects of band-limited force control on chatter suppression are investigated experimentally via end-face turning tests.

2. Integration of position control and force control

2.1. Acceleration control unit using disturbance observer

Because acceleration is a dominant factor for the determination of the position and force, an acceleration-based control system should be designed to control both the position and force effectively. A disturbance cancelation technique using a DOB is applicable to the construction of an acceleration-based control system. The DOB can estimate a pre-defined disturbance including the sum of the external load and the parameter-fluctuated forces from the current reference I_a^{ref} and position/angle information, which correspond to the input and output information of the servo motor, respectively. Owing to disturbance cancelation, an ideal motor whose performance complies with a nominal parameter is created by feeding the compensating current I_a^{com}, which is equivalent to the disturbance, back to the motor current. The design of an acceleration-based control system is realized by applying the created ideal motor. Fig. 1 shows the acceleration

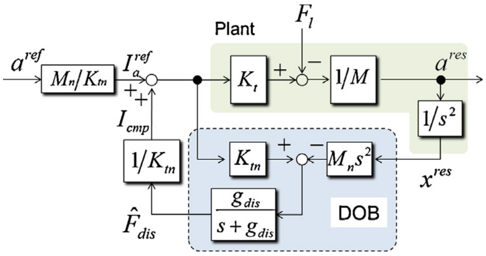

Fig. 1. Block diagram of the acceleration control unit.

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control unit for the linear motor. F_l [N] is the sum of the external load forces; K_t [N/A] is the thrust force coefficient; M [kg] is the mass of the movable part; F_{dis} [N] is the disturbance force; a [m/s^2] and x [m] are acceleration and position of the movable part, respectively; and n, ref, and res denote the nominal value, reference value, and response value, respectively.

The placement of the adjustment block M_n/K_{tn} before the motor causes the transfer function from the acceleration reference to the response to become one within the cut-off frequency of the DOB g_{dis}. This acceleration control unit is fundamentally important for both position control and force control in this study.

2.2. Position/force control system based on acceleration control

The position control system is designed according to the following guidelines.

- The transfer function regarding the position is designed using a second-order delay model because the acceleration is a second-order differential of the position.
- The critical damping condition is applied to achieve highly responsive positioning without over-shoot.
- The gain is maintained, and the phase delay is suppressed within the bandwidth of acceleration control unit.

On the basis of the these guidelines, the transfer function is given by

$$\frac{x^{res}}{x^{cmd}} = \frac{s^2 + As + B}{s^2 + As + B} = 1 \qquad (1)$$

where A and B are real variables, and s is the Laplace operator. Therefore, the acceleration reference is given by

$$a^{ref} = A\left\{\frac{B}{A}(x^{cmd} - x^{res}) + (\dot{x}^{cmd} - \dot{x}^{res})\right\} + a^{cmd} \qquad (2)$$

According to Eq. (2), when B/A and A are represented as the position gain K_p and the velocity gain K_v, the position controller is represented as shown in Fig. 2. In addition, assuming the damping ratio equals 1.0, the following relationship between K_p and K_v holds: $K_v = 4\,K_p$.

On the other hand, the controller for sensorless force control system should be designed according to the following guidelines.

- A reaction force observer needs to be employed to feed the estimated reaction force back to the force controller.
- A proportional controller is sufficient as the force controller because of Newton's second law.

A force control system with an acceleration control unit is shown in Fig. 3. From the above guidelines, a position and force control system can be designed with a common acceleration control unit.

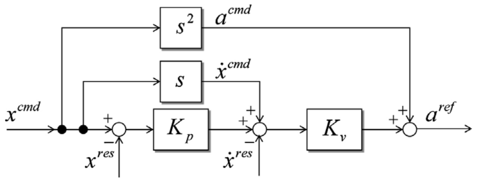
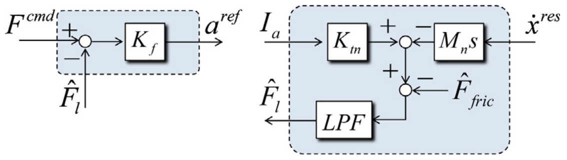


Fig. 2. Position controller.



(a) Force controller (b) Reaction force observer

Fig. 3. Elements for the sensorless force control system.

2.3. Integration of position control and force control by frequency separation

In order to suppress chatter vibration, which is one of the main issues for machining processes, we propose a position–force simultaneous control method to implement band-limited force control on a position-control-system basis. Generally, it is impossible for a control system to account for the position and force at the same time, as there is mutual interference according to Hooke's law. Furthermore, a position control system and a force control system require different control systems in terms of both hardware and software, i.e., position control is on a velocity-control basis, and force control is on a thrust-force-control basis of the servo driver. On the other hand, the acceleration control unit has a major advantage in that both the position control system and the force control system can be constructed on an acceleration-control basis. Further, it is considered that this control system has the possibility of controlling both position and force by frequency separation. The proposed integration control system for position and force is represented in Fig. 4. From the DC component up to the cut-off frequency of filter 1 that uses a low-pass filter (LPF), position control should be adopted so that the steady-state positioning error can be eliminated. Above the cut-off frequency, the application of force control would be effective for actively suppressing vibration caused by a machining process. For example, it is technically possible to apply force control to a certain limited frequency range or to multiple different frequency bandwidths by properly designing the filters.

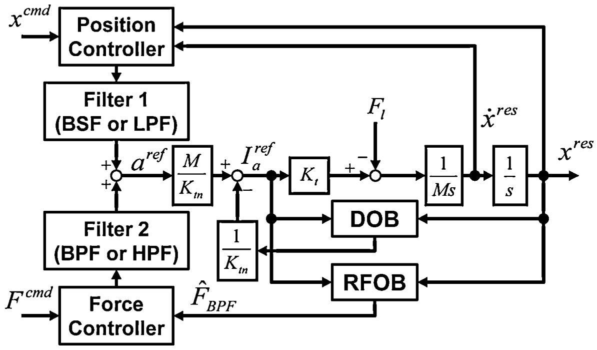


Fig. 4. Block diagram of band-limited force control.

3. Experimental setup

3.1. Prototype turning machine and system configuration

Fig. 5 shows the prototype desktop-sized precision turning machine that consists of the work spindle supported by an aerostatic bearing and the linear motor driving carriage. Because the work spindle employs a non-contact mechanism, its friction force is almost zero, which enhances the accuracy of the cutting

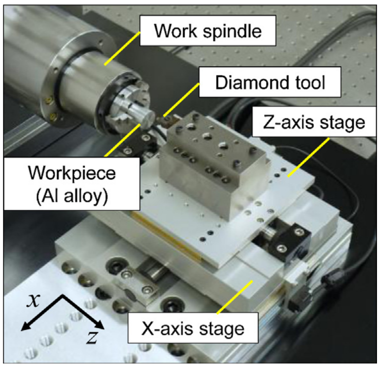


Fig. 5. Prototype precise turning machine.