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Development of machine tool spindle with active spindle center position control

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Abstract

In recent years, the proliferation of electric vehicles and the need to reduce CO_2 emissions have led to a demand for more efficient internal combustion engines that require the machining of non-axisymmetric and non-circular holes within a few tens of microns. However, there is currently no machine tool that can achieve this machining. In a previous study, a spindle driven by a bearingless motor with the function of simultaneously controlling rotation and radial force and using a disturbance observer for positioning control was developed. In this study, an Extended Kalman Filter (EKF) was added to the control model of this spindle. By measuring the rotational spindle motion state are rotational angle position and its velocity, damping coefficients and spring constants are also estimated in this study. These two elements constantly change depending on the cutting conditions and the environment. Therefore, to improve the accuracy of the model, it is necessary to adjust these values to the current machining conditions. The new control model was tested and the differences with and without the EKF were evaluated. The test results confirm that the noise component can be suppressed by adding the EKF to the control model including the disturbance observer.

Position control, Kalman filter, Non-Axisymmetric machining, Bearingless motor

1. Introduction

Currently, to reduce CO_2 emissions, which cause global warming, are a problem, as a countermeasure, there is a need to improve the efficiency of internal combustion engines. For this purpose, it is important to optimize the cylinder shape considering thermal deformation during operation. Therefore, machining of noncircular inner cylinders with radial diameter change of several tens of micrometers is desired. In a previous study, a machine tool spindle equipped with a motor that can simultaneously control radial force and rotational torque was developed. To improve the control performance of this spindle, the equivalent mass, damping coefficient, and spring constant were identified experimentally, and the estimation performance of the disturbance caused by cutting resistance was evaluated using a disturbance observer. As a result, although the effectiveness of the observer was confirmed, profile errors still remained in the workpiece geometry. In this paper, an Extended Kalman Filter (EKF) is implemented to the spindle control model to estimate the modal parameters of the spindle to achieve precise machining closer to the target geometry. The control model in this study, by measuring radial displacement and, damping coefficient and spring constant are identified by EKF. The effectiveness of EKF will be evaluated by implementing this model on an actual machine and conducting experiments.

2. Principles of spindle

Figure 1 shows the spindle developed in the previous study[1]. This spindle equips a bearingless motor, which has a magnetic bearing function and rotational servomotor. Therefore, two types of coils in the motor generate rotational torque and radial force, respectively, which can be controlled to control the tool tip position at the certain rotational spindle position.

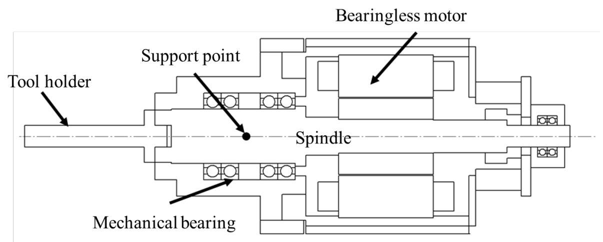

Figure 1. Schematic diagram of developed spindle

This enables the spindle to simultaneously control the rotational torque and radial force, and to control the tool tip position, thereby enabling machining to the desired shape.

3. Parameter estimation with EKF

The control system parameters estimated by EKF are damping coefficient, and spring constant. Radial displacement and angular velocity are frequently obtained in spindle motion [2]. In this study, in addition to these parameters, the damping coefficient and spring constant are also estimated. Since these two parameters constantly change depending on cutting conditions and the surrounding environment, it is necessary to adapt these values used for the inverse transfer function to the machining conditions in order to improve the accuracy of the model. Therefore, by substituting the damping coefficient and spring constant estimated by EKF to the inverse transfer function, the parameters are constantly updated to their most suitable values. The equation of motion for the spindle of a bearingless motor which position is changed by an electromagnetic force u is expressed in two-dimensional coordinates in the X-Axis direction by the following equation (1), where the disturbance d is applied to the spindle as a spring-mass-damper system.

$$m\ddot{x} + c\dot{x} + kx = u \qquad (1)$$

x: position [m] m: mass [kg] c: damping coefficient [Ns/m]

k: spring constant [N/m] u: electromagnetic force [N]

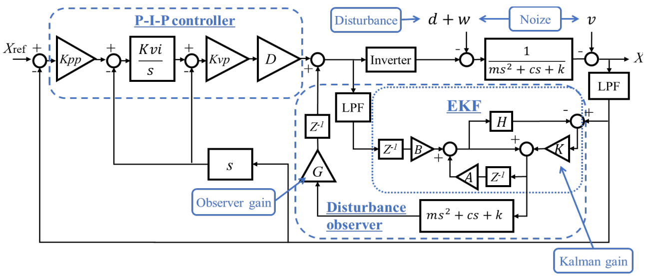

Figure 2. Block diagram of implemented EKF

When the state vector of this system is $\boldsymbol{x} = [x\ \dot{x}\ c\ k]^T$, the following equations (2), (3) represent the system in a state-space model.

$$\boldsymbol{x}_n = \boldsymbol{A}\boldsymbol{x}_{n-1} + \boldsymbol{B}\boldsymbol{u}_n + w \quad (2)$$

$$z_n = \boldsymbol{H}\boldsymbol{x}_n + v \quad (3)$$

$$\boldsymbol{A} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ -\frac{k}{m} & -\frac{c}{m} & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}, \quad \boldsymbol{B} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & \frac{1}{m} & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

$$\boldsymbol{H} = [1 \quad 0 \quad 0 \quad 0]$$

$w \sim N(0, \boldsymbol{Q})$: system noise $v \sim N(0, R)$: observation noise

This model is discretized at sampling time and the state is estimated by repeating the prediction and update steps.

1) prediction step:

$$\widehat{\boldsymbol{x}}_{n+1} = \boldsymbol{A}_{d_n}\boldsymbol{x}_n + \boldsymbol{B}_{d_n}\boldsymbol{u}_n, \quad \boldsymbol{P}_{n+1} = \boldsymbol{A}_{d_n}\boldsymbol{P}_n\boldsymbol{A}_{d_n}^T + \boldsymbol{Q}$$

2) update step:

$$\boldsymbol{K}_n = \boldsymbol{P}_{n-1}\boldsymbol{H}^T(\boldsymbol{H}\boldsymbol{P}_{n-1}\boldsymbol{H}^T + R)^{-1}$$

$$\widehat{\boldsymbol{x}}_n = \widehat{\boldsymbol{x}}_{n-1} + \boldsymbol{K}_n(z_n - \boldsymbol{H}\widehat{\boldsymbol{x}}_{n-1}), \quad \boldsymbol{P}_n = (\boldsymbol{I} - \boldsymbol{K}_n\boldsymbol{H})\boldsymbol{P}_{n-1}$$

$\widehat{\boldsymbol{x}}_n$: estimated value $\boldsymbol{P}_n$: error covariance $\boldsymbol{K}_n$: Kalman gain

4. Control system for spindle tool tip position with EKF

Figure 2 shows the new model with EKF added to the position control model developed in the previous study. The given position command value is converted into a force using the P-I-P controller and current-to-force conversion coefficients, and after passing through the inverter of the main spindle, the radial displacement is output from the transfer function of the main spindle. Simultaneously with that, state estimation is performed by EKF using the support control input and the output displacement. The estimated displacement, damping coefficient, and spring constant are substituted to the inverse transfer function of the disturbance observer to estimate the disturbance and execute feedback. This enables machining using optimized parameters and improves machining accuracy compared to a disturbance observer with the fixed parameters.

5. Effects of EKF on actual equipment

The new control model developed was implemented on the actual machine, and the effectiveness of the EKF was verified by running the spindle dry at 500 rpm. I acquired the data at a sampling frequency of 12.5 kHz. The rotation trajectory was as shown in Figure 3. Figure 4 shows the estimated disturbance for the conventional disturbance observer alone and in combination with the EKF and the position commands at each rotation angle. In both the X-axis and Y-axis directions, the noise are smaller in magnitude when combined with the EKF than when using the observer alone. In addition, the disturbance was estimated to a greater extent in the X-axis direction than in the Y-axis direction. The error between the spindle tool tip position and the command value by compensating for the estimated disturbance is shown in Figure 5. Although the error from the command value was not significantly reduced, the noise was suppressed. The values of the damping coefficient and spring

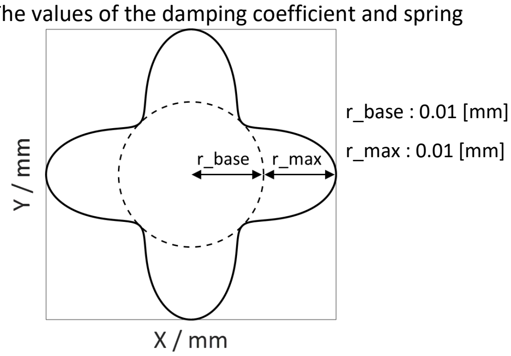

Figure 3. Petal trajectory

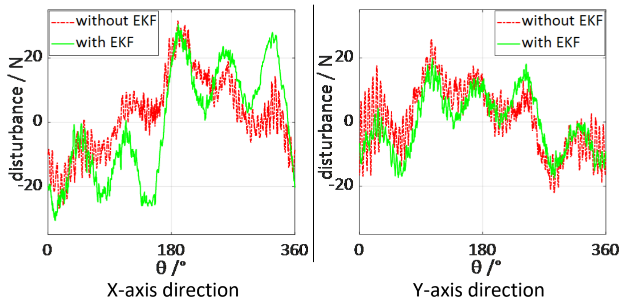

Figure 4. Estimated disturbance

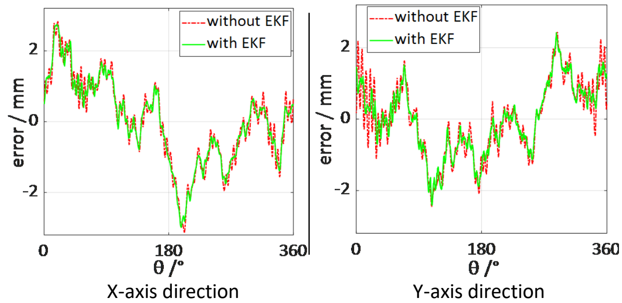

Figure 5. Displacement error

constant didn't fluctuate because of the dry run in this test. These results indicate that the addition of EKF can be effective in reducing noise components.

6. Conclusions

In this study, a new control system for machine tool spindle was developed using a special motor capable of synchronous control of radial force and rotational torque. The results obtained are as follows:

1) The control system was developed by adding EKF to the control model of the spindle, which enables more accurate estimation of the spindle motion.
2) The developed control system was implemented on an actual special spindle.
3) It was confirmed that the addition of EKF suppresses noise components.

Further developments are planned to machine the inner boring by installing this spindle into the machining center.

References

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