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Study on Sensor Fault Tolerance Control of Machining Center Based on MPC Technology

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***Abstract*—For the sensor gain failure and deviation fault of the machining center, the paper suggests an active fault tolerance control method based on model predictive control (MPC). Firstly, the method senses the fault of the sensor with fault detection and diagnosis (FDD); and then the monitor decision-making unit would adjust the prediction model in each sampling time to adapt to the fault of a sensor according to the fault information to reach the fault tolerance. In the end, the VDL600A machining center is the example in the paper to carry out the active fault tolerance control simulation. The simulation result proves the effectiveness of the methods mentioned above. The method could handle the restriction when adjusting the fault to reduce the complication of a traditional controller.**

Keywords—Fault tolerance control; machining center; fault diagnosis

I. Introduction

Along with the modernization development of sensor[1][2][3], the control system of the machining center has been developed from the mechanical hydraulic controller to be full authority digital electronic one. Since there are vast of electronics, sensors and actuators in a digital electronic control system, there is lower reliance on the control system. Sensor [4][5], as the part of the control system, mainly takes in charge of the information acquisition, delivery and transfer and it would provide evidence for further decision-making. The correctness of information detection, timeliness of information delivery and reliance on running is extremely important, which would directly affect the control quality of digital electronic control system. The control system of the sensor signal, ageing performance, gain reduction and other faults in a harsh environment with high temperature and strong vibration. According to statistics, the faults in the sensor and actuator account for about 70% among all of the faults in the control system. Hence, it is very important to have fault tolerance control in the sensor of a machining center. By far, more and more advanced control concepts and methods have been proposed and applied in the design of fault tolerance control system of the sensor. Among these, model predictive control (MPC) has been greatly focused on the industry for explicit processing of input and output constraints. In 2013, Saluru suggested replacing the traditional PID with MPC and the effectiveness was also proved. MPC is based on a control method of the model and the main idea of control is to match the predicted model and the actual one. The control effect would be better if the matching degree is higher. The feedback correction in classical MPC algorithm could achieve the anti-disturbance, so the feedback correction could be used to realize the fault tolerance to the sensor in a small range. However, there would be a steady-state error, chattering and even divergence in MPC if there is a larger-extent mismatch in the model. As a result, feedback correction could not do the fault tolerance for the faults in the sensor of large scale, and it needs to have online readjustment of controlling rhythm. The principle of traditional FTMPC (Fault-Tolerant Model Predictive Control) is to calculate the controlling rhythm that normal system should be implemented with the online rolling optimization mechanism of MPC, and then there is simple compensation on the controlling rhythm according to the fault information to deduct the fault to the system when there is a fault. The more advanced fault-tolerant control method is to have a correction of these mechanisms according to the fault information with many mechanisms of MPC itself, such as prediction mode, restriction conditions, target functions, etc., so that controller could adapt to the impact of the fault on the system by itself. There are bigger study space and application prospect for the latter one.

By far, there are many more studies in foreign countries to have fault tolerance control of the control system with MPC. The common fault tolerance method is tantamount to combine the prediction model with multiple models [6][7]. For the fault of the control system, S Kan and Saluru proposed a method to combine multi-models with MPC. Each fault is correspondent to one prediction model, so as to build up a fault model base offline. And it is switched to correspondent prediction model according to fault information to revise the controlling rhythm by revising the prediction model. However, the study above has not provided principle or evidence to strengthen the base, but just a framework and a diagram of the simulation result. Qi Sun suggests having fault tolerance with the method of the effective factor. Faults estimated by the observer are embedded into a prediction model to revise the controlling rhythm by correcting the prediction model. Although the multi-model is not adopted in this method, it provides the principle of the fault tolerance control and it could be evidence for the buildup of the faulty base. The studies above are for the faults of actuators and components, and it is not the sensor. In 2015, Bavili applied the fault tolerance control method based on MPC to the sensor. In the study, the two optimal observers are used to estimate the system status, actuators and the loss of effective factors of sensors. In each sampling moment, monitoring unit would adapt to simultaneous faults of partial actuators and sensors with fault models and correction, and it is embedded to the prediction model so that the faults of actuators and sensors could be complemented at the same time. However, the key point of the study is to discuss and verify the fault in actuators, and there is less verification on that of the sensor. Concurrently,

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the feedback correction suggested by the study could only just achieve the fault tolerance to small range instead of that in a large range.

II. Fault analysis of sensor

The discrete state-space equation of engine steady point can be concluded by the linearization with small deviation [8][9][10], and it is stated with a unified formula (1)

$$\begin{cases} x(k+1) = Ax(k) + Bn(k) \\ y(k) = C(x(k) + Dn(k) \end{cases} \quad (1)$$

In the formula, X is a state quantity and y is the output quantity; n is control quantity. A, B, C and D represent for state matrix, control matrix, measurement matrix and transfer matrix representative. The common faults in machining center include the fault in actuator, sensor and components. There are multiple fault classification methods for sensors, including the method based on the method and the one based on time-varying characteristics of faults. The study is based on an effective factor, so it is adopted with fault classification based on the model. Ordinary faults are gain fault and deviation fault.

The sensor fault could be performed as follow:

$$y_z(k) = (W + y_z)y(k) + y_{z0}(k) \quad (2)$$

$y_z = diag(y_{z1}, y_{z2}, y_{z3}, y_{sq})$, W stands for the unit matrix.

TABLE I. Chart 1 Chart of sensor fault classification

	$y_{zi}=0$	$y_{zi}\neq 0$
$y_{zi}=0$	Normal	Deviation fault
$-1 < y_{zi} < 0$	Gain fault	Mixed fault of gain and deviation
$y_{zi} = -1$	Invalid	Jam

III. Principle of active fault tolerant control method for sensor

The target of the fault tolerance control: No matter whether there is a fault in the sensor of the machining center, the output low voltage spindle motor (Nf) could trace the expectation value normally. Meanwhile, all variables are within the restriction range, including master box (Wf) and main bearing (Nf, Nh). The active fault tolerance control system in the paper includes the three parts, fault optimal estimator, monitor decision-making unit and MPC controller. The fault optimal estimator is used for estimation of the effective factor of the sensor. The paper illustrates the faulty degree of the sensor with an effective factor. The monitor decision-making unit is used to pass the fault information of the sensor to the prediction mode in the MPC control. MPC controller would adjust the prediction model according to the fault information to achieve the fault tolerance control.

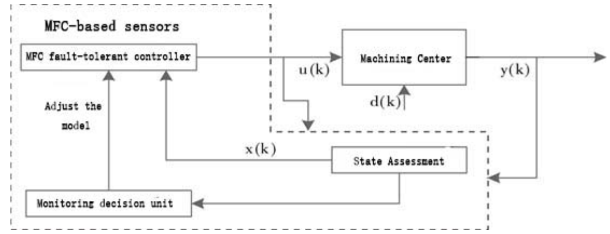

Figure 1 Sensor active fault-tolerant control method framework

A. Estimation of effective factor of sensor

When there is a fault in the sensor, the state space equation is changed with the combination of formula (1) and formula:

$$\begin{cases} x(k+1) = Ax(k) + Bn(k) \\ y_f(k) = (i+y)x(k)) + Dn(k) \end{cases} \quad (3)$$

For the convenience of estimation, the multiplicative terms with effective factors need to transfer to be the known items, and it needs to handle the output formula:

$$\begin{cases} x(k+1) = Ax(k) + Bn(k) \\ y(k) = C(x(k) + F(k)rs(k) \end{cases} \quad (4)$$

Based on the optimal estimation of the measurement deviation, the effective factor γ is estimated as a deviation, and the specific effect is shown as follows:

The non-deviation estimation of state quantity:

$$\begin{cases} T_{k+1|k} = FT_w \\ T_{k+1|k+1} = T_{k+1|k} - W_{x+1}^{x} \\ P_{x+1|w+1}^{x*} = P_{k+1|k+1}^{x} \end{cases} \quad (5)$$

B. Monitor decision-making unit

Monitor decision-making unit could gain the fault and state estimation value, so as to achieve fault tolerance to controlled by adjusting the internal model.

1) Gain fault

The $y(k)$ is replaced with $y_f(k)$ when there is gain fault in the sensor.

2) Deviation fault

When there is deviation fault of sensor, $y_z(k) = (W + y_z)y(k) + y_{z0}(k)$. For the deviation in a small range, MPC could achieve fault tolerance through feedback correction; but there should be transferred from deviation one to gain one for the deviation of the large range.

3) Mixed fault

When there is a mixed fault in sensor, the output formula is changed to be $y_z(k) = (W + y_z)y(k) + y_{z0}(k)$ with the combination of formula (1) and (3).

In conclusion, no matter what type of fault of the sensor, the inner model could be adjusted with CPnew to reach better fault tolerance.

C. Simulation experiment of machining center

Simulation verification is undertaken in MATLAB/Simulink platform to build up fault tolerance control system. The VDL600A model of Dalian Machining Center is used as a simulator of the machining center. The state quantity is mechanical rotational speed and high-pressure rotational speed, and the control quantity is engine rotational speed. The output quantity is side shaft rotational speed. The reference value is planned to be 1000r/min. At the same time, the control quantity Wf and rotational speed of output quantity shall not exceed the limit. Stimulation in the paper has been compared with the simulation result of non-fault tolerance, fault tolerance to gain fault, fault tolerance to deviation fault, and mixed fault tolerance. The parameters setting is shown as: ny=3 and nu=2 in MPC controller.

The linear matrix is as follows:

$$A = \begin{cases} -3.156, & 1.426 \\ 0.469, & -4.751 \end{cases}$$

$$B = \begin{cases} 240.312 \\ 652.126 \end{cases}$$

$$C = \{1,0$$

$$D = \{0$$

Build the MPC controller on the Matlab/simulink platform to process the center The linear model is used as an engine simulator, and the simulation diagram is shown in Figure 2.

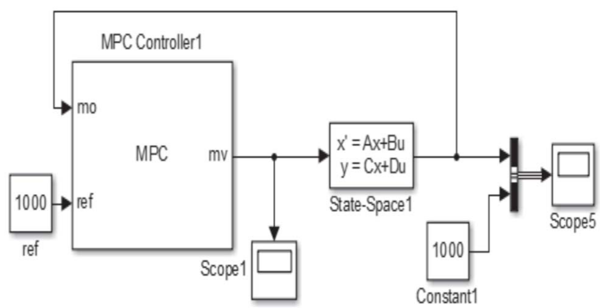

Figure 2 MPC frame

In the first scenario, the sensor has not failed and the system is in normalstatus. It can be seen from Figure 3 and Figure 4 that the input and output are within the constraint range, and the output can track the expected value, indicating that the MPC algorithm designed in this paper can Good enough to handle input and output constraints.

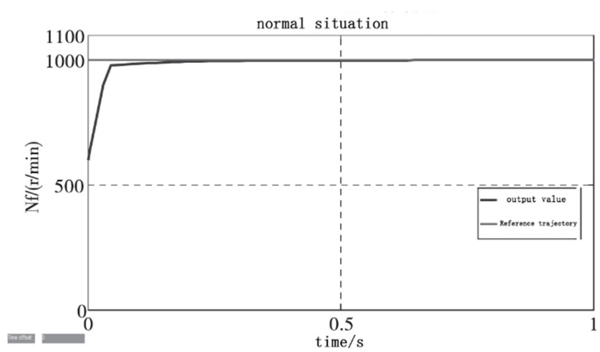

Figure 3 Normal MFC simulation diagram

Assuming that the sensor has a gain failure, where rs = -0.5, first use the method in section 3.1 to estimate the effective factor value of the sensor, as shown in Figure 4. From the simulation result graph of Figure 5, it can be seen that the two proposed The staged Kalman filter method can effectively estimate the effective factor of the sensor. Due to uncertain factors, small deviations occur and need to be corrected. This is not specifically introduced in this study.

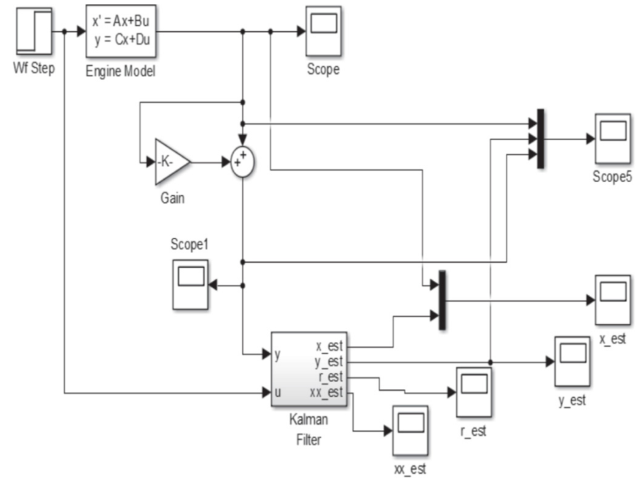

Figure 4 Block diagram of the two-stage Kalman method

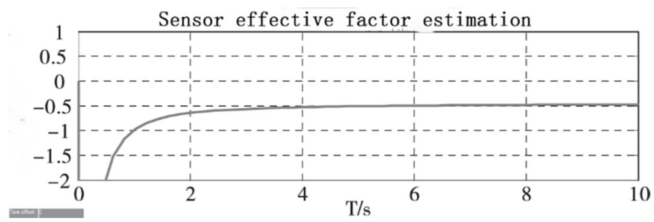

Figure 5 Effective factor estimates

For other degrees of gain failure, this method also has good fault tolerance.

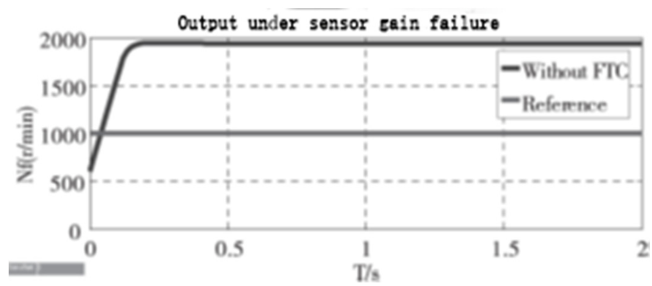

Figure 6 Output under gain failure

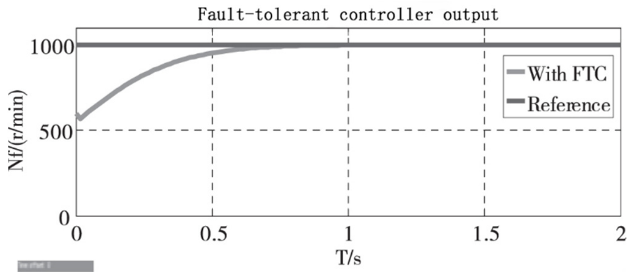

Figure 7 Error tolerance of gain failure

From the figure above, it can be seen that the non-fault-tolerant output traces 2000 r/minLeft and right, after the fault-tolerant output tracking the expected value, indicating the fault tolerance for mixed faultsThe effect is better.

Under normal control, there is no fault in the sensor, and the system is in a normal state. The input and output are within the restriction range, and the output could trace the expectation value. So it is said that the MPC algorithm designed by the paper could handle the restriction limitation of input and output well. It supposes that there is gain fault in the sensor. Firstly, the method mentioned in 3.1 could estimate the effective factor value of the sensor, so that the effective factor could be delivered to monitor the decision-making mechanism. Seen from the concluded simulation result of fault tolerance controller, the output of non-fault tolerance is far more than the expected value, 1000r/min, so as to trace the expectation value of the output of fault tolerance. It means that there is a good effect of fault tolerance to gain fault.

IV. Conclusion

In short, the fault tolerance controller of machining center sensor based on MPC could combine the FDI process and fault tolerance controller, and it would improve the real-time and rapidity of fault tolerance control performance. The controller designed with MPC could achieve the input and output restrictions and sensor fault tolerance control, and it also overcomes the shortage of complicated design of traditionally limited protection. For the limitation of words, the paper only proposes the simulation result as a method, but the fault tolerance could be achieved for sensor faults at different extent.

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