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Research paper

Iterative learning fault-tolerant control for injection molding processes against actuator faults

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ABSTRACT

The injection molding process is a typical multi-phase batch process. As the filling and packing-holding phases share the same actuator, faults occurring in the actuators may cause serious impact on the performance and running time. Because these two phases are of crucial importance in relation to the final quality of the product, to solve this problem is essentially meaningful. This paper proposes iterative learning fault-tolerant control (ILTFC) in terms of common multi-phase batch processes and then applies it to the injection molding processes. To develop the ILFTC design, the multi-phase batch process is treated as a switched system composed of different dimensional subsystems and then converted to an equivalent two-dimensional (2D) switched fault-tolerant Rosser model. A hybrid fault-tolerant law is then designed based on an average dwell time method. Sufficient conditions and minimum running time guaranteeing the exponential stability under both normal and fault conditions are obtained. Under the proposed control law, the control performance and running time will restore to the previous level before actuator faults occur. The efficiency and merits of the proposed scheme is illustrated by an injection molding process, and results show that it can guarantee the stability and minimum running time whether the process is in normal operation or in case of actuator faults.

1. Introduction

With the progress of science and technology, plastic products have been widely used all over the world due to their excellent plasticity, light texture, good durability and other characteristics, which has become an indispensable part of all industries and daily life. However, although there is a large market for the plastic products in China, the domestic injection molding technology is far behind the international advanced level and sometimes has to rely on foreign advanced technology, which is extremely unfavorable for the long-term development of the plastics processing industry in China. Therefore, the study on injection molding process has become one of the most popular research directions nowadays in our country.

In fact, the injection molding process is a typical case of the so-called batch processes. Furthermore, for the actual production process, research on batch processes is full of generality and universal applicability. In recent years, owing to the rapid development of manufacturing business, batch processing mode have achieved great development since it is a preferred choice for low-volume and high value-added products, such as pharmaceuticals, consumer products and bio-products [1,2], and study on its control has attracted considerable attention.

In practical production processes, the existence of system fault is almost inevitable owing to equipment aging, improper operation and other reasons and it has become one of the realistic problems that have to be faced in the process of production. When the fault occurs, deterioration on system performance and the production efficiency and product quality will be resulted with the accumulation of time if the accurate diagnosis and timely exclusion are not implemented. Seriously, it may even pose a threat to the personal safety of the production personnel. Therefore, research on the system fault has become one of the hottest directions in the field of control.

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Common fault types mainly include the actuator fault, the sensor fault and the system internal fault. Taking the injection molding process as the background, this paper will put actuator fault existed in production process into study. As the actuator of the injection molding process, the valve opening is to control the input of raw material. Under normal circumstances, the valve opening can be adjusted freely to meet the required dosage of raw materials according to the different needs of practical production. Once the actuator fault occurs, namely the valve opening loses its ability to adjust freely, it will cause too fast or too slow injection velocity in the filling phase, not enough dosage of raw materials to be supplied, and uneven change of cavity pressure in the packing-holding phase. Finally, the quality of products will be affected, which even result in wasted products.

Therefore, in the presence of faults, fault-tolerant control (FTC) is significant and necessary for maintaining closed-loop control performance when admissible faults occur. After years of development, the design of FTC for continuous processes has been widely investigated and achieved relative maturity [3–8]. In order to solve this problem, some scholars proposed their own thoughts. To maintain the closed-loop stable system and good control performance, the reliable control has been a popular FTC method [9–12]. Exploiting the 2D and repetitive nature of batch processes [13–16], 2D ILC for batch processes has developed increasingly in recent years. With the support of this technology, a 2D iterative learning reliable control (ILRC) was first proposed by representing the batch process with a 2D Fornasini–Marchsini (2D-FM) model within the 2D system framework [17]. In this paper, the 2D ILRC theory was proposed by integrating ILC with reliable control and has demonstrated to be effective through simulation. Considering the sensor failures, a reliable control scheme was designed in [18]. Assume that the process delay is within a pre-described range, a robust ILRC using state space model was proposed [19]. Exploiting the predictive control scheme, some results about the predictive fault-tolerant control were proposed for batch processes [20,21]. It can be seen that many researchers have contributed to the design of FTC for batch processes [22–26].

In fact, the injection molding process is a multi-phase batch process [27], which is composed of the following five phases: mold close, filling, packing-holding, cooling and mold open. Among the phases, the filling and packing-holding are the most important phases affecting the product quality and they share the same actuator. When the actuator fault occurs, the irregular variation of injection velocity in the filling phase at the current batch will result in uneven cavity pressure in the packing-holding phase; then in turn, the latter variation will affect the injection velocity in the filling phase in the next batch. In other words, these two phases have an impact on each other. In the existing literatures, however, what has been discussed mostly is the single-phase (filling or packing-holding phase) fault-tolerant control problem, while it is rare to find research for the multi-phase situations. So, there is extremely practical significance for research on multi-phase fault-tolerant control issues in injection modeling.

On the other hand, the actuator fault will have an enormous effect on the running time and the control performance. As a vital factor affecting the productive efficiency, the running time has not received enough attention and there are only few results about it. In most production processes, the acquisition of running time is through actual experience rather than accurate calculation, which will extend the running time of the subsystems to a certain degree and then reduce the efficiency in the whole process. Fortunately, the average dwell time method [28,29] can satisfy the pursuit for minimum running time of subsystems. In 2016, an iterative learning control strategy based on the average dwell time method for multi-phase batch processes was proposed [30]. In this paper, using the average dwell time method, the minimum running time of subsystems under stable running was figured out accurately. Since the actuator faults are unable to change the system switching sequence, the average dwell time method is still feasible for batch processes with actuator faults.

Based on the above analysis, this paper explores the injection molding with actuator faults focusing the following characteristics,

(1) Repetitiveness, that is, a large number of products are acquired batch by batch through repeating a fixed manufacturing procedure during the injection modeling;
(2) 2D, namely the system dynamics change along both time and batch directions simultaneously;
(3) Different dimensions, which means that the dimensions of system state in different phases may be different;
(4) Limited running time, in other words, each batch should be completed within a finite time.

The issues of control strategy and running time are studied under the circumstances that this process can still run smoothly within the tolerance range of faults. To solve the above problems, the fault-tolerant control for multi-phase batch processes with actuator faults is studied first and then applied to injection molding in this paper. The specific idea is given as follows. Utilizing the relevant theory on switched system, the established faulty state space model with different dimensions is converted into an equivalent hybrid 2D Rosser model firstly, which is a switched system with actuator faults. The corresponding switching sequence and state-transition matrix are constructed through the relationship between adjacent phases, and the switching signal related to the states is designed. Next, the iterative learning reliable control strategy combined with feedback control is designed. On the basis of the average dwell time method, sufficient conditions ensuring exponential stability and the design of reliable control law are given by Riccati equations, and simultaneously, the sufficient condition for the lower bound of running time under the stable running is achieved. Finally, the proposed method is applied to the injection molding and its effectiveness will be shown in the results of case analysis. Under the case of a given α integrated with the related switching conditions and the average dwell time method, the corresponding gains of the updating law and the minimum running time in each phase can be obtained. To demonstrate adequately the effectiveness and feasibility of the proposed control law in this paper, the related comparisons are carried out in the section of case analysis.

This paper is organized as follows. Section 2 shows the problem formulation. The main strategy of the proposed method is detailed in Section 3, where the batch process is first converted to a 2D fault model and a corresponding ILRC is designed using the average dwell time method. In Section 4, the effectiveness and merits of the proposed method is shown through the case of injection molding. Conclusion is in Section 5.