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Experimental study on a hybrid-driven servo press using iterative learning control

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Abstract

Servo presses provide flexible punch motions, which satisfy different production needs. To achieve this merit, the control system must maintain the punch motion accurately despite versatile desired trajectories or varied loadings. Against this backdrop, the current paper proposes an iterative learning control (ILC) scheme for a hybrid-driven servo press. A proportional derivative (PD) type ILC controller that contains a closed-loop feedback controller is adopted. The sensitivity Jacobian is introduced into the controlling algorithm as the proportional gain in order to smoothen and increase the error convergence rate. The proposed ILC controller is then developed and verified on a servo press prototype. Experimental validations of a cup-shaped drawing are also carried out. The results show that the proposed ILC scheme effectively made the punch position root-mean-square (RMS) errors converge to less than 0.2 mm within five iterations. The precision was also improved to less than 50 μm that was equivalent to 35–40% of the original level without the ILC.

Keywords: Servo press; Hybrid driven; Iterative learning control

1. Introduction

The servo press provides flexible punch motions, which can provide an optimal stamping action that is programmed for production needs. For example, a forming result can be improved by utilizing the most suitable punch speed and dwelling duration; faults such as cracks, wrinkles, and spring-backs can thus be improved or even avoided. The tool life may also be extended by slowing down the punch speed to lessen the impact, along with the reduction of stamping noise. For a servo press, the punch stroke becomes adjustable, and this enhances productivity. This means that the user could set a very short stroke so as to not waste time and energy. In summary, high productivity, formability, low noise, long tool life, and energy saving can be achieved by applying the servo press on stamping operations [1].

Nowadays, most servo presses in the market are directly driven by a servomotor(s), and they do not use a flywheel for energy accumulation. This implies that the servomotor(s) need to offer all of the force and energy required for stamping. Sometimes, this creates a limitation on the tonnage and energy capability of the servo press. The solution to this problem may be to use high-power servomotors, but this incurs additional financial expenses that may not be feasible.

For this reason, the novel concept of hybrid-driven servo press [2,3], which utilizes two degree of freedom (2-DOF) mechanism with two inputs, is studied. The flywheel can be used on such a press for energy storing, and thus the power demand of servomotor can be reduced. A more detailed introduction on the hybrid-driven servo press is given in Section 2.

While the servo press is stamping, different loadings would always affect the punch motion significantly; this would cause the errors of punch position and velocity. Therefore, the control system of the servo press plays an important role in the machine. In a previous study done by the authors of this paper, Tso et al. [3] divided a complete

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punch stroke into numbers of discrete segments and successfully used point-to-point feedback control to implement different punch motions on the hybrid-driven servo press. The tracking error due to the stamping load was corrected with a pre-compensator. Guo et al. [4] studied the trajectory planning and optimization for the variable-speed servomotor-driven crank, and the different punch motions are realized on the hybrid-driven servo press with the use of feedback control. However, based on these control schemes, the tracking performance of each punch stroke is independent. One cannot therefore guarantee that any two strokes will have identical performance in terms of accuracy. Moreover, for such a hybrid-driven servo press, since the punch position is determined by two inputs, the machine's precision depends not only on the quality of the mechanical elements but is also significantly influenced by the following errors of the control variables. Thus, the two inputs must be regulated carefully. Furthermore, the instantaneous large stamping force is bound to cause the punch motion error, which is unable to be predicted and corrected by the feedback control strategy. To overcome these problems, the authors intend to apply an ILC on the hybrid-driven servo press.

The basic idea of ILC is to use information from the previous execution of a trial in order to improve performance from trial to trial. Uchiyama [5] first introduced the concept of iterative learning for generating the optimal input to a system. The purpose of this was to improve the performance of robot motion. Then Arimoto et al. [6] developed the idea rigorously and coined the term "iterative learning control"(ILC). ILC is an approach that may deal with the control problems of repetitive motions. In ILC, the next input command is computed by a learning controller based on the error signal of the previous output. Therefore, the ILC is closed loop in the iteration number direction, that is, in the repetition domain. This is because the updates are performed for the next repetition using the feedback measurements of the previous repetition. Therefore, the significant advantage of ILC is that when a detailed model of the system is not available as a machine, actuator dynamics, and friction, the ILC can still work. Many ILC applications are associated with robotic manipulators. In relation to this, Gopinath et al. [7] combined a linear feedback law and feed-forward control law in the ILC scheme to deal with a 2-DOF robotic manipulator. He introduced the dynamic models of the manipulator and actuator into the ILC scheme, and the simulation results showed that his ILC algorithm could effectively take care of the actuator dynamics and system friction. It is believed that the ILC would work better as more information about system dynamics becomes available, and there is much potential in using this to improve the performance of the ILC controller. For the application of ILC on stamping machine tools, Nakagava et al. [8] applied a learning control strategy on a linear motor drive CNC press. The results obtained indicated that using the learning control could maintain the punch position at a high accuracy despite the sudden load changes and long-term environmental condition changes that could occur.

In this paper, a PD-type ILC strategy is adopted for the motion control of the hybrid-driven servo press. In doing so, some difficulties are inevitable. First, for generating the desired punch motion, the specified relation between two inputs must be fulfilled. The correct synchronization that keeps the inputs regulated in the desired correlation is a control problem to be overcome. Accordingly, a synchronous controller is embedded with a closed-loop feedback control in the ILC control scheme; this part is for commanding the servo press to execute a tracking task, which has been studied in previous work [3]. Second, the servo press is expected to do various stamping operations, but the precision of the punch motion should be maintained despite diverse trajectories and varying loadings. Therefore, the servo press should be capable of adapting to versatile stamping operations. This paper thus proposes an ILC scheme including an inner feedback loop for tracking control, and an outer ILC loop is for correcting input commands in repetitive manner. Thus, the motion error should be convergent stroke by stroke.

Although ILC is a simple concept, the controller performance is highly related to the magnitude of ILC gains. Several techniques have been developed for choosing the ILC gains, such as the steepest-descent, Gauss-Newton, and Newton-Raphson methods [9]. These gains are either constant or time varying and are evaluated fully-mathematically but irrelevant to any knowledge of the machine. As mentioned earlier, the ILC would perform better with more information about system dynamics, and this can be done by attempting to introduce sensitivity analysis into the control system. In Ting's research [10], the sensitivity Jacobian, the Rayleigh quotient of the sensitivity Jacobian, and the sensitivity index are used to describe the relationship between performance quality and the dimensional tolerances, and to identify the least vulnerable to dimensional tolerances. Different aspects of the sensitivity Jacobian are considered in this paper, which will employ it as the proportional gain value in the ILC updating law in order to deal with the non-linear kinematics of the hybrid-driven servo press mechanism.

The ILC controller has been established and experimentally validated on a 30 kN hybrid-driven servo press prototype. A practical drawing process has been carried out. The results show that the proposed ILC scheme was effective in reducing the punch motion errors of the servo press under stamping operations. The accuracy and precision of the punch motion were both enhanced.

This paper is organized as follows. A detailed introduction on the hybrid-driven servo press is given in Section 2. Section 3 proposes the ILC control scheme and the updating algorithm. In Section 4, experimental validations of a cup-shaped drawing are accomplished on a 30 kN servo press prototype. The experimental results of the three examples are presented. Sections 5 and 6 then present the discussions and conclusions.