Available online at www.sciencedirect.com
SCIENCE DIRECT®
International Journal of Machine Tools & Manufacture 45 (2005) 923–931
INTERNATIONAL JOURNAL OF MACHINE TOOLS & MANUFACTURE DESIGN, RESEARCH AND APPLICATION
www.elsevier.com/locate/ijmactool

Iterative learning control of electro-hydraulic proportional feeding system in slotting machine for metal bar cropping

Shengdun Zhao[a,*], Ji Wang[a], Lihong Wang[b], Chunjian Hua[a], Yupeng He[a]

[a]School of Mechanical Engineering, Xi'an Jiaotong University, Xi'an 710049, People's Republic of China
[b]Xinxing Ductile Iron Pipes Co., Ltd, Handan 056017, People' Republic of China

Received 28 October 2003; accepted 22 October 2004
Available online 7 January 2005

Abstract

A non-linear method, iterative learning control (ILC), is proposed to control the electro-hydraulic feeding process of a new slotting machine. The method attempts to acquire high precision of feeding length and trapezoid feedrate, whereas the complexity of iterative learning control algorithm does not increase much more than that of industrial PID controller. After an analysis of the two-way proportional feeding system, a non-linear dynamical mathematic model with system delay, saturation and dead-zone is developed. The computer flowrate control and the ILC controller are investigated in detail. PID controller, ILC of displacement and ILC of feedrate are compared with the dynamical model under the same desired trajectory. It is experimentally found that the proposed control scheme is more effective to improve the tracking accuracy of hydraulic feeding system of the slotting machine than that of fuzzy PID controller.

Keywords: Slotting machine; Hydraulic system; Iterative learning control; PID; Feedrate; PLC

1. Introduction

Precision baiting for metal bar is widely used in industrial production, such as micro-motor shaft, pin and bearing. It is well known that high speed cropping, radial holding differential cropping and blanking under high axis load are effective and economical processes of bar cutting [1–3]. Unlike these common shear methods, where a cropping die is used so as to cause huge shearing force and defective fracture surface, a new method was proposed where the metal fatigue vibration was considered as a factor to improve breakability and surface finish and decrease cutting force and tool wear of metal bar cropping [4]. In the fatigue baiting process, 'V' shape grooves were cut at specific length intervals in the metal bar to engender stress concentration at the bottom of the grooves. Then the slotted bar was fed to crop under low-cycle vibration and would rupture after certain fatigue periods. It is obvious that the degree of stress concentration at the bottom of the 'V' shape groove primarily determines the surface quality of rupture section and vibrating time. Although there are several different types of slotting machines commercially available on the principle of turning or milling for metal bar or tube, they are scarcely applied to fabricate the 'V' shape groove. One reason is that these slotting devices with only one cutting machine tool are unable to keep large local stress at these grooves for mass production for a long period. Moreover, a feeding device is necessary if many metal bars of several meters long are slotted continually at constant intervals, but most slotting machines do not possess the device. A slotting machine with PLC control has been developed to cut sharp grooves with specific intervals in metal bars shown in Fig. 1 [5], where two tools are used for slotting bar or tube in turn.

In the slotting machine, a hydraulic position control system was adopted to clamp and feed the metal bar during the cropping process for its large torque and high response. Many researchers have paid attention to non-linear dynamic behaviors of hydraulic position servo (HPS) [6], which is widely applied to position control or track for its excellent

* Corresponding author. Fax: +86 029 82669103.
E-mail addresses: sdzhao@mail.xjtu.edu.cn (S.D.Zhao), wherb@263.net (L.H.Wang).

0890-6955/$ - see front matter © 2004 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijmachtools.2004.10.013

Nomenclature

A_1, A_2	piston areas in the non-rod chamber and the rod chamber
B_t	viscous friction coefficient of feeding parts
C_d, C_{ip}, C_{ep}	coefficients of volume flowrate, internal leak and external leak
$e(n)$, $e_i(n)$	system error of the nth sample
f_r	the Coulomb friction force
K_D	derivational coefficient
K_I	integral coefficient
K_P	proportional coefficient
K_t	elastic coefficient
K_u	coefficient of voltage displacement
M_n	control variable of the nth sample
M_t	mass of the feeding parts
MX	integral item before the nth sample.
P_1	pressure in the non-rod chamber of the feeding cylinder
P_2	pressure in the rod chamber of the feeding cylinder
P_B	supply pressure of hydraulic system
P_O	return pressure of hydraulic system
Q_1, Q_2	nominal volume flowrate
t_d	time delay of feeding system
u	input voltage of amplifier of proportional valve
u_{min}, u_{max}	dead zone and saturation critical voltages of proportional valve
V_{10}, V_{20}	initial volumes of two chambers in the feeding cylinder
w_b	width of the rectangular valve window of proportional flowrate valve
x_v, x_t	displacements of the valve spool from neural and the piston

performance and generally consists of an oil cylinder and an electro-hydraulic servo valve. The transfer function of HPS is generally linearized at the operating point and treated as a second-order or third-order system. Several researchers have reported the fuzzy logic and neural network based methods [7,8]. Much work has been focused on variable structure control [6,9] and adaptive control [10]. Recently, an optimal-tuning PID control has also been devoted to a proportional control system including a 4/3-way proportional valve and a differential cylinder with computer data acquisition system [11]. However, these methods are relatively more complex compared with the widely used PID control and are very difficult to be realized in common industrial PLC with PID function. Moreover, a hydraulic servo also requires high investment on accurate electro-hydraulic servo valve and sensors [12].

In this paper a PID-type iterative learning control (ILC) was adopted for the hydraulic feeding system of the slotting machine and attempted to improve the performance of PID instruction in industrial PLC. An electro-hydraulic two-way flowrate proportional regulating valve and a 4/3-way electromagnetic valve were also adopted to replace the function of electro-hydraulic servo valve partially. Because the 4/3-way electromagnetic valve keeps permanent flow direction in one feeding operation, the direction of feeding displacement essentially cannot be regulated reversely. This operation is completely different from general electro-hydraulic servo. In fact, a pair of stiff-stoppers were used to ensure feeding length with continual oil supply in the feeding cylinder. However, due to the inertia of feeding parts including piston, connect rod, holding cylinder and metal bar, there was serious impact among stoppers and feeding parts which influences the position accuracy of stoppers. The impact noise generated also seriously influenced the worker health during the feeding process. The purpose of this paper was to investigate whether the proposed iterative learning controller would improve the precision of feeding length and diminish impact noise.

2. Model of hydraulic feeding system

2.1. Experimental apparatus station

The hydraulic feeding system of the slotting machine was retrofitted as a research platform to establish PID-type iterative learning control system. The schematic diagram of hydraulic feeding system is shown in Fig. 2, which included a 4/3-way direction valve, an electro-hydraulic two-way flowrate proportional regulating valve DYBQ-G 16, a feeding cylinder and a holding cylinder. A linear variable displacement transducer (LVDT) with 0.1 mm was also

Fig. 1. The automatic slotting machine.