Expert Systems with Applications 38 (2011) 12262–12269

Contents lists available at ScienceDirect

Expert Systems with Applications

journal homepage: www.elsevier.com/locate/eswa

Adaptive cascade control of a hydraulic actuator with an adaptive dead-zone compensation and optimization based on evolutionary algorithms

Leandro dos Santos Coelho [a,*], Mauro André Barbosa Cunha [b]

[a] Industrial and Systems Engineering Graduate Program, LAS/PPGEPS, Pontifical Catholic University of Paraná, PUCPR, Imaculada Conceição, 1155, 80215-901 Curitiba, PR, Brazil
[b] Automation and Control Research Group, Sul-rio-grandense Federal Institute for Education, Science, and Technology, Praça Vinte de Setembro, 455, 96015-360 Pelotas, RS, Brazil

ARTICLE INFO

Keywords:
Hydraulic actuator
Adaptive control
Adaptive dead-zone compensation
Trajectory tracking
Evolutionary algorithm

ABSTRACT

This work presents an adaptive cascade controller tuned by using evolutionary algorithms for the trajectory tracking control of a hydraulic actuator with an overlapped proportional valve. The hydraulic actuator mathematical model includes the dead-zone nonlinearity due to the use of the overlapped valve. By considering the hydraulic actuator as a mechanical subsystem driven by a hydraulic one, a cascade strategy is proposed. Such cascade strategy is based on the order reduction and allows one to propose different control laws for each subsystem. Adaptive algorithms are used to compensate the parametric uncertainties in the hydraulic and mechanical subsystems including an adaptive compensation for the valve dead-zone. In the sequence, evolutionary algorithms are used to tune the proposed controller for performance optimization. Simulation results illustrate the main characteristics of the proposed controller and the performance of the evolutionary algorithm called differential evolution in tuning of proposed controller.

1. Introduction

The increase of automation in the modern industry is a well know fact. The precision of mechanical positioning systems represent an important role in automation process. Such positioning systems are driven by actuators: electrical, hydraulic or pneumatic. Hydraulic actuators are very attractive for applications that require a high force/size ratio. However, hydraulic actuators present some undesirables characteristics (nonlinearities, parametric uncertainties, and lightly damped dynamics) that limit their use in high precision applications with simple controllers in the closed loop. Due to the development in the signal processing technology, more elaborated control laws could be proposed to overcome the limitations imposed by the hydraulic actuators. It has taken a research effort in the development of controllers that can overcome the hydraulic actuator limitations for high performance applications by using different control techniques (Bu & Yao, 2000; Cheong & Cho, 1997; Kasprzyczak & Macha, 2008; Ramon, De Baerdemaeker, & Van Brussel, 1996; Selemic & Lewis, 2000; Sirouspour & Salcudean, 2000; Tsai & Huang, 2008; Virvalo, 2002).

This work's authors have developed controllers in a cascade strategy that is based on the reduction order proposed by Utkin (1987). In a gradual manner, from the work of Guenther and De Pieri (1997), many cascade controllers have been proposed in order to overcome different limitations of the hydraulic actuators. Here, one outlines some of them: parametric uncertainties in the mechanical subsystem (Cunha, Guenther, & De Pieri, 1998), parametric uncertainties in the mechanical and hydraulic subsystems (Guenther, Cunha, & De Pieri, 1998; Guenther, Cunha, De Pieri, & De Negri, 2000), inclusion of the valve dynamic (Cunha, Guenther, De Pieri, & De Negri, 2000), and design methodology (Cunha, Guenther, De Pieri, & De Negri, 2002). More details about such developments can be found in Cunha (2001).

In Cunha, Guenther, and De Pieri (2004), a fixed cascade controller NFCC (Cunha, 2001) was combined with an adaptive dead-zone compensation. However, the parameters of the mechanical and hydraulic subsystems were considered known. In Cunha (2005), considering the valve dynamic, a cascade controller with adaptive algorithms for the mechanical and hydraulic subsystems was proposed. In Cunha and Guenther (2005, 2006), in order to deal with parametric uncertainties in both subsystems and with the valve dead-zone nonlinearity, one proposed a controller that combined FACC (Cunha, 2005) together with an adaptive dead-zone compensation scheme (Cunha et al., 2004). This controller was referred to as FACCADZC (Cunha & Guenther, 2005, 2006). The adaptive dead-zone algorithm is based on Tao and Kokotovit (1996).

Although there was improvement obtained by using the controller proposed in Cunha and Guenther (2005, 2006) in the closed-loop, the controller gains were tuned by using visual observation and the practical experience of that work's authors.

* Corresponding author.
E-mail addresses: leandro.coelho@pucpr.br (L. d. S. Coelho), mauro@pelotas.ifsul.edu.br (M.A.B. Cunha).

0957-4174/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.eswa.2011.04.004

Here, aiming to optimize the controller performance, the gains are tuned with evolutionary algorithms.

Evolutionary algorithms have been investigated by many authors in optimization problems in engineering systems (Alfaro-Cid, McGookin, & Murray-Smith, 2009; Chen & Chang, 2009; Coelho, Pessôa, Sumar, & Coelho, 2010; Fleming & Purshouse, 2002; Iruthayarajan & Baskar, 2009; Kim & Lee, 2006; Lee, Sun, Tahk, & Lee, 2001; McGookin, Murray-Smith, Li, & Fossen, 2000; Oh, Jung, & Pedrycz, 2009; Onnen et al., 1997; Poursamad & Montazeri, 2008; Vlachos, Williams, & Gomm, 2002).

Moreover, in this work, an evolutionary algorithm called differential evolution (DE) (Storn & Price, 1995, 1997) is evaluated to tune the proposed FACCADZC. DE algorithm is a recently proposed population-based evolutionary method for global optimization. Storn and Price (1995) first introduced the DE algorithm a few years ago. DE uses a rather greedy and less stochastic approach to problem solving compared to evolutionary algorithms. It has been proven to be a powerful tool for solving the global optimization problems, especially with a nonsmooth objective function because the DE algorithm does not need the derivative information about the objective function. The potentialities of DE are its simple structure, easy use, convergence property, quality of solution and robustness. Due to these good features, the effectiveness and efficiency of DE algorithm has been successfully demonstrated in a variety of continuous optimization problems in different knowledge fields (Coelho & Mariani, 2007; Mayer, Kinghorn, & Archer, 2005; Price, Storn, & Lampinen, 2005; Wang & Zhang, 2007).

The rest of paper is organized as follows. Section 2 presents the mathematical model of a hydraulic actuator with a valve that presents a dead-zone. In Section 3, a combination of the FACC with an adaptive dead-zone compensation algorithm is presented (FACCADZC). Section 4 presents a brief description of DE evaluated to tune the FACCADZC. Section 5 presents the simulation results and, in Section 6, the conclusions and perspective are outlined.

2. Hydraulic actuator

2.1. Mathematical model

The hydraulic actuator considered in this work is shown in Fig. 1 (Cunha et al., 2004), where M represents the system total mass, B is the viscous friction coefficient, p_s is the supply pressure, p_0 is the return pressure, p_1 and p_2 are the pressure in lines 1 and 2, v_1 and v_2 are the volume in lines 1 and 2, A is the cylinder piston cross sectional area, Q_1 is the flowrate from the valve to chamber 1, Q_2 is the flowrate from chamber 2 to the valve and u is the electrical voltage applied to the electronic card.

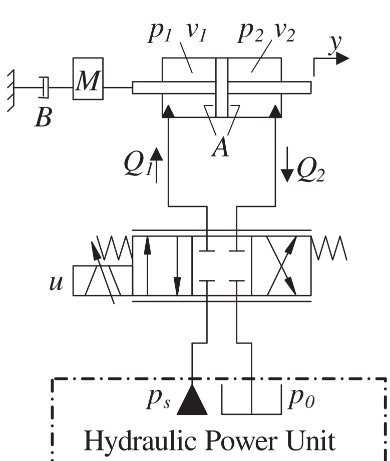

Fig. 1. Hydraulic actuator.

An overlapped proportional valve is built with the lands of the spool greater than the annular parts of the valve body, causing a dead-zone in the relationship between the valve spool displacement and the flowrate. Valves with dead-zones require less precision in the fabrication and are less expensive than those with a null overlap.

The hydraulic actuator mathematical model can be written as (Cunha et al., 2004)

$$M\ddot{y} + B\dot{y} = Ap_{\Delta} \tag{1}$$

$$\dot{p}_{\Delta} = -fA\dot{y} + fK_h g x_v \tag{2}$$

$$x_v = DZ_1(x_{vb}) \tag{3}$$

$$\dot{x}_{vb} = -\omega_v x_{vb} + K_{em}\omega_v u \tag{4}$$

$$x_v = DZ_1(x_{vb}) = \begin{cases} x_{vb} - b_r, & x_{vb} > b_r \\ 0, & b_l \le x_{vb} \le b_r \\ x_{vb} - b_l, & x_{vb} < b_l \end{cases} \tag{5}$$

where $f = f(y) = \frac{\beta v}{(0.5v)^2 - (Ay)^2}$, x_v is the valve spool position, $p_{\Delta} = p_1 - p_2$ is the cylinder chambers pressure difference, β is the bulk modulus, $v = v_1 + v_2$, K_h is the hydraulic constant, $g = g(p_{\Delta}, x_v) = \sqrt{p_S - sgn(x_v)p_{\Delta}}$, K_{em} is the valve constant, ω_v is the valve bandwidth, x_{vb} is the valve spool position before the dead-zone, b_r is the right breakpoint and b_l is the left breakpoint. Fig. 2 shows a block diagram of the relation between the control input u and the spool position (x_v). The signal x_{vb} is the signal that is measured by an internal transducer in the valve and is available in the electronic card.

2.2. Parametric uncertainties

The bulk modulus (β) is difficult to be measured and its value depends on the air inside the cylinder, the oil temperature, and the pressure. The parameter K_h can be calculated by using some data from the valve manufacturer, but it also depends on some variables, in such a way that the calculated value is only an approximation. The mass (M) is obtained by adding the fluid mass and the load mass. The fluid mass can be considered constant. However, in positioning systems, the mass load normally varies during the operation, like in pick and place tasks in a robot manipulator. The viscous friction coefficient (B) is a linearization of the friction force and, therefore, its value depends on the operation point. The area (A) and the volume (v) can usually be determined with a good precision (Cunha & Guenther, 2005, 2006).

2.3. Nonlinearities

The hydraulic actuator presents many nonlinearities. The flowrate depends on the square root of the pressures and it involves the signum function of the spool position. Furthermore, the square of position appears in the denominator of function (f).

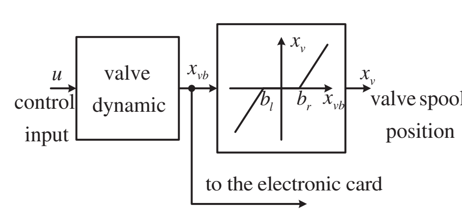

Fig. 2. Block diagram of a valve with dead-zone.