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Robust force control with a feed-forward inverse model controller for electro-hydraulic control loading systems of flight simulators

Jinsong Zhao [a,b], Gang Shen [c,*], Weidong Zhu [d], Chifu Yang [e], Jing Yao [a,b]

[a] Hebei Provincial Key Laboratory of Heavy Machinery Fluid Power Transmission and Control, Yanshan University, Qinhuangdao, 066004, China
[b] Key Laboratory of Advanced Forging & Stamping Technology and Science (Yanshan University), Ministry of Education of China, Qinhuangdao, 066004, China
[c] School of Mechatronic Engineering, China University of Mining and Technology, Xuzhou, 221116, China
[d] Department of Mechanical Engineering, University of Maryland, Baltimore County, Baltimore, MD, 21250, USA
[e] State Key Laboratory of Robotics and System of China, Harbin Institute of Technology, 150001, China

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A B S T R A C T

A hybrid control strategy for an electro-hydraulic control loading system (EHCLS) of a flight simulator in the presence of a control mechanism kinetic parameter perturbation is proposed to improve the force tracking accuracy and guarantee robust stability of the EHCLS system. A double-loop model of the EHCLS, including the control mechanism and the hydraulic mechanism, is established and analyzed from the force-displacement impedance perspective. A force closed-loop parameter model of the EHCLS is identified by a recursive-least-squares (RLS) algorithm and its inverse model is designed using a zero phase error compensation technology to expand the frequency bandwidth of the force closed-loop system of the EHCLS. A μ theory of robust control is employed to design a stable controller for enhancing robust stability of the EHCLS in the presence of uncertainties of the inner loop, the control mechanism and the high frequency disturbance force. Simulation and experimental results show that the proposed hybrid control approach can greatly improve the control performance of the EHCLS by expanding the frequency bandwidth of the force closed-loop system and enhancing stability of the EHCLS, which can decrease displacement output response error of the EHCLS from 10.34% to 3.1%.

1. Introduction

A flight simulator is employed to provide student pilots with a scientific and practical training facility, and an electro-hydraulic control loading system (EHCLS) is one of important human-feeling components in the flight simulator [1] to provide flight force feel for trained pilots [2]. The force feel simulation control structure of the EHCLS includes position, velocity and force closed-loops [3]. The inner loop of the EHCLS is a typical electro-hydraulic force servo system, and evaluation of force tracking performance includes replicating a command signal and reducing a disturbance force generated by the hydraulic actuator motion of the EHCLS. Some researchers focus on force tracking control by reducing the disturbance force [4–8]. This paper focuses on how to improve ability of replicating the force feel command signal on the electro-hydraulic force servo system.

The linear feedback control with features of a simple structure and easy adjustment is widely employed to improve system stability and replicate a command signal of an electro-hydraulic servo system, such as the proportional-integral-derivative (PID) controller [9], the three variables feedback controller based on the position, velocity and acceleration [10] and feedback linearization [11]. However, some nonlinear and time-varying elements **exist** in the electro-hydraulic force servo system, which are caused by throttling characteristics of an electro-hydraulic servo-valve, position changes of the hydraulic piston and changes of oil temperature, and so on. To solve the nonlinear and time-varying problem, some adaptive control and intelligent control methods were used, such as simple adaptive control [12], nonlinear adaptive robust control [13,14] and adaline neural network-based adaptive inverse control [15].

However, convergence performance, especially response time, of some adaptive control methods can degrade tracking control performance of a system that needs short response time, such as the EHCLS. To solve this problem, some robust controllers, such as quantitative feedback theory [16–20], hybrid control strategy [21] and H_∞ control theory [22], were used to improve replicating ability of a command signal of a control system with uncertainties and nonlinearities. However, a feedback controller based

* Corresponding author.
E-mail address: shenganghit@163.com (G. Shen).

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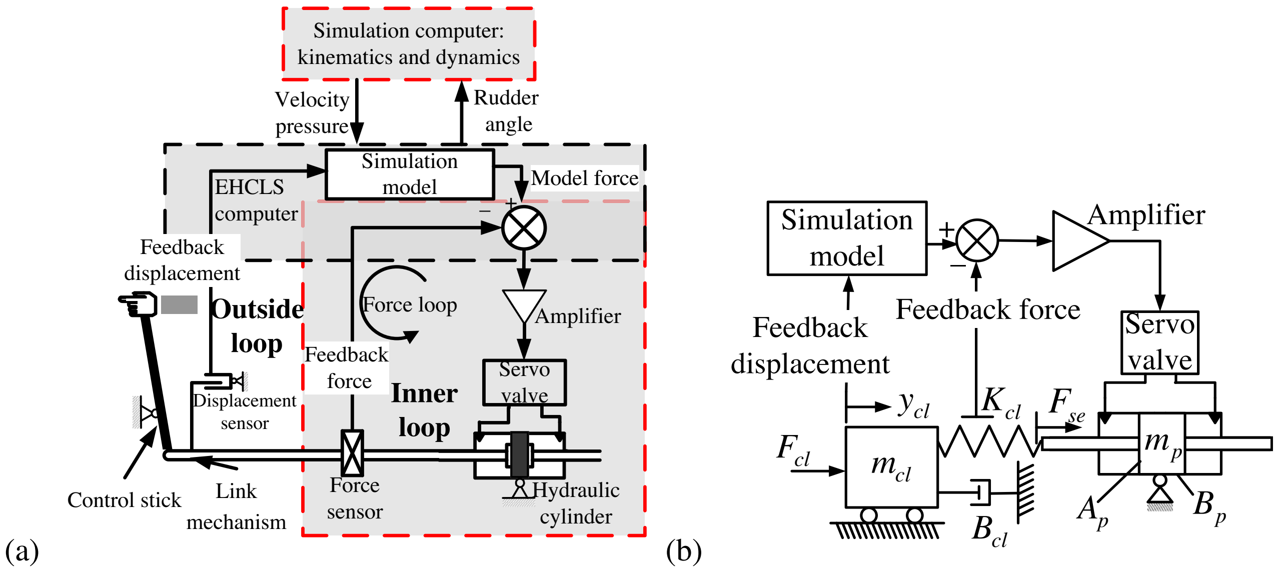

Fig. 1. (a) Structure and (b) the simplified physical model of the EHCLS.

on robust control theory is limited by stability of the control system. Feed-forward inverse model (FFIM) control is widely used to expand the frequency bandwidth of the control system without changing its stability [23–25]. Control performance of the FFIM is limited by precision of the identified model and its designed inverse model. There are several closed-loop model identification methods, such as the H1 estimator [26], the recursive-least-squares (RLS) algorithm [27], the modal parameter-based structural identification [28] and the state-space model [29]. However, the identified model always contains non-minimum-phase (NMP) zeros and its direct inverse model is unstable and cannot be used as an inverse model controller. To overcome this problem, a stable approximate inverse model is designed for NMP systems in the literature [30]. The FFIM can effectively expand frequency bandwidth of the local control loop without affecting its stability, but modeling error can degrade stability of the outside loop in the EHCLS.

The main contribution of this paper is to develop and evaluate a hybrid control strategy that combines the FFIM of the inner loop and robust control using a μ control theory for the EHCLS. The control structure presented can expand the frequency bandwidth of the inner loop using the FFIM and enhance robust stability of the EHCLS affected by the inverse modeling error and model uncertainties of the system using the μ controller.

A mathematical model of a double-loop structure of the EHCLS based on the force closed-loop is established in Section 2. Section 3 discusses the proposed hybrid controller including a disturbance force compensator, model identification and its FFIM, and system stability analysis. Some simulation results and performance analysis are shown in Section 4. An experimental setup of the EHCLS used is shown in Section 5 and a series of experiments are conducted on the EHCLS to demonstrate effectiveness of the proposed method. Section 6 concludes main points and contributions of this study.

2. Mathematical model of the EHCLS

The structure of the EHCLS based on the force closed-loop is depicted in Fig. 1(a), where the control mechanism includes the control stick and the link mechanism. With consideration of flexibility between the hydraulic piston and the control mechanism, a simplified physical model of the EHCLS is shown in Fig. 1(b), where A_p, m_p and B_p are the effective actuator area, and the mass and the viscous damping coefficient of the piston, respectively, F_{cl} and y_{cl} are the control force and the equivalent control displacement, respectively, and m_{cl}, K_{cl} and B_{cl} are the equivalent mass, the stiffness and the viscous damping coefficient of the control mechanism, respectively.

The driven system of the EHCLS is the electro-hydraulic servo system, and it is composed of a servo valve and a symmetrical hydraulic cylinder. The transfer function of the servo valve is

$$G_{sv}(s) = x_v/i_A = K_{sv}/\left(s^2/\omega_{sv}^2 + 2\xi_{sv}s/\omega_{sv} + 1\right) \quad (1)$$

where K_{sv} is the ratio between the spool valve position and its command current, i_A is the coil current of the servo valve, and ω_{sv} and ξ_{sv} are the natural frequency and the damping ratio of the servo valve, respectively. The linearized flow equation of the servo valve is given by

$$Q_L = K_q x_v - K_c P_L \quad (2)$$

where Q_L is the load flow, P_L is the load pressure, x_v is the spool displacement, K_q is the linearized flow gain coefficient, and K_c is the flow-pressure coefficient. By applying the law of continuity to the hydraulic actuator chamber, the load flow rate continuity is given by [31]

$$Q_L = A_p\dot{y}_p + C_{tc}P_L + \dot{P}_L V_t/(4\beta_e) \quad (3)$$

where y_p is the piston displacement, K_q is the total leakage coefficient of the hydraulic actuator, V_t is the total volume of two chambers of the hydraulic cylinder, and β_e is the effective bulk modulus of the liquid in the hydraulic cylinder. The force equilibrium equation of the piston is given by

$$F_{se} + P_L A_p = m_p\ddot{y}_p + B_p\dot{y}_p \quad (4)$$

where F_{se} is the force measured by a force sensor, and m_p and B_p are the mass of the piston and the viscous damping coefficient between the piston and the cylinder, respectively. Referring to Fig. 1(b), the force equilibrium equation of the control mechanism of the EHCLS is given by

$$F_{cl} - F_{se} = m_{cl}\ddot{y}_{cl} + B_{cl}\dot{y}_{cl} \quad (5)$$

$$F_{se} = K_{cl}(y_p - y_{cl}) \quad (6)$$

Combing Eqs. (1)–(6), one can obtain the block diagram of the EHCLS that is shown in Fig. 2(a), where a double-loop system takes