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Nonlinear robust control of a hydraulic elevator: experiment-based modeling and two-stage Lyapunov redesign

Chang-Sei Kim[a], Keum-Shik Hong[b,*], Moon-Ki Kim[c]

[a]Robot Research and Development Team, Daewoo Shipbuilding and Marine Engineering, Ltd., Geoje-si, Gyeongsangnam-do 656-714, Korea
[b]School of Mechanical Engineering, Pusan National University, San 30, Jangjeon-dong, Gumjung-gu, Busan 609-735, Korea
[c]Department of Mechanical and Industrial Engineering, University of Massachusetts Amherst, Amherst, MA 01003, USA

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Abstract

In this paper, a robust velocity control problem for hydraulic elevators is investigated. The analysis is divided into two parts, mechanical and hydraulic. A detailed mathematical model for the mechanics is established for the purpose of simulation, but the control system design is carried out with a simplified model reduced from the detailed one. The three important characteristics of a hydraulic elevator, including cylinder friction, pump friction, and pump leakage, are modeled through experiments. The leakage property is characterized as a function of temperature and pressure. A two-stage nonlinear robust controller using the Lyapunov redesign method is established for velocity tracking control. At the first stage, a robust controller for the mechanical part is designed to yield the desired cylinder pressure for reference velocity tracking. At the second stage, a robust controller for the hydraulic part is designed to track the reference pressure generated from the first controller. Simulation results validate that the proposed method is robust in the presence of nonlinearities and uncertainties.

Keywords: Hydraulic elevator; Control system design; Lyapunov redesign; Friction; Leakage; Stability; Robustness

1. Introduction

There are two types of elevator systems depending on the actuation mechanism: a roped elevator and a hydraulic elevator. The roped elevator is driven by a rope and an electric motor, while the hydraulic elevator is driven by a cylinder and fluid power. The assembly of the car, rope and pulley of a hydraulic elevator is similar to that of a roped elevator. But, the up and down movement of the car of a hydraulic elevator is achieved by the pushing and pulling of the pulley hooked at the end of a hydraulic jack, whereas that of a roped elevator is achieved by the winding and unwinding of the rope on a drum.

The hydraulic elevator is cost-effective and makes for very clean lines of building exterior due to the elimination of the conventional penthouse-type machine room. Since hydraulic circuits can be inserted anywhere inside a building, possible sun blocking due to building extensions can be avoided. Particularly, to secure pedestrians' space and improve the appearance of a street, the installation of hydraulic elevators at subways, pedestrian crossings, and in low-level buildings is increasing. The use of hydraulic elevators is especially promising in low-level buildings such as airports and low-rise houses. It has been reported that since 1990 the market share of hydraulic elevators has been over 35% (Sedrak, 2000).

The control scheme of a hydraulic elevator consists of three control steps: the load pressure compensation step,

*Corresponding author. Tel.: +82 51 510 2454; fax: +82 51 514 0685.
E-mail addresses: cskim5@dsme.co.kr (C.-S. Kim), kshong@pusan.ac.kr (K.-S. Hong), mkim@titan.me.jhu.edu (M.-K. Kim).

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the velocity tracking control step, and the destination position control step. The load pressure compensation step reduces the jolt at the departure of the car that may produce an uncomfortable ride for passengers. The velocity tracking control makes the car follow a reference velocity profile that helps the passengers feel comfortable during the movement. The destination position control reduces the position error, which may exist after the velocity tracking control, at the target position.

A hydraulic pump connected directly to an electric motor generates fluid power and controls the velocity of the car. A smooth transition of car depends on the smooth movement of the cylinder. However, the following problems occur: (1) The system characteristics change due to the variations of the load and oil temperature; (2) jolts occur due to unequal pressures at the departure and arrival points; (3) an undesirable descent occurs due to oil leakage; and (4) unknown nonlinearities in the friction and continuity equations appear. These problems will eventually degrade the safety and comfort of the passengers (Nakamura, 2000).

In this paper, the velocity control problem of hydraulic elevators is investigated (Jianmin, 2000; Kang & Kim, 2000; Li, 2001; Sha, Bajic, & Yang, 2002; Teramoto & Nakamura, 1997). Sha et al. (2002) has introduced a new approximated linear model for a hydraulic elevator and investigated a sliding mode control for velocity tracking in the discrete domain. Teramoto and Nakamura (1997) has introduced a third-order linearized model with fixed parameters, for which their open-loop experiments showed that the effects of nonlinearities and uncertainties were too large to describe the system behavior sufficiently.

To solve these problems, the hydraulic elevator system was divided into two facets: a mechanical facet that includes the car, rope, and pulleys, and a hydraulic facet that includes the cylinder, logic valve, hydraulic power unit, and pipes. Then, the dynamic equations for each facet are derived. The mathematical model of the mechanics is a 14th-order linear equation including all the pulleys and rope dynamics, whereas the mathematical model of the hydraulics is expressed as a set of nonlinear equations with uncertainties, that is, flow equations and continuity equations. Kim (2000) revealed that the open-loop simulation results of the mathematical models reported in the literature were inconsistent with open-loop experimental results. Thus, a series of experiments have been performed to obtain more accurate mathematical models for the frictions in the hydraulic cylinder and pump (Armstrong-Helouvry, Dupont, & Wit, 1994; Bo & Pavelescu, 1982; Karnopp, 1985). In addition, the leakage coefficient has been modeled as a function of temperature and pressure in the hydraulic equation.

Recently, many nonlinear robust control methods have been proposed: sliding mode control (Bouri & Thomasset, 2001; Wheeler, Su, & Stepanenko, 1998), the back-stepping method (Krstic, Kanellakopulos, & Kokotovic, 1995), and the Lyapunov redesign method (Kim, Lee, & Cho, 2002; Qu, 1998). Also, numerous applications of the robust control methods for nonlinear systems with uncertainty have been reported (Alleyne, 1996; Sohl & Bobrow, 1999; Yanada & Shimahara, 1997; Yao, Fanping, Reedy, & Chiu, 2000; Corless & Leitmann, 1997; Venkatesh, Cho, & Kim, 2002; Michino, Mizumoto, Iwai, & Kumon, 2003; Kwon, Han, & Ahn, 2004). Alleyne (1996) proposed a variant of the backstepping method and improved the force tracking performance of an electro-hydraulic actuator. To compensate for the parameter uncertainty of a nonlinear cement mill model, Grognard, Jadot, Magni, Bastin, Sepulehre, and Wertz (2001) designeda Lyapunov-function-based controller. Yao et al. (2000) suggested a discontinuous projection-based adaptive robust controller for a single-rod hydraulic cylinder with constant unknown inertia load. Sha et al. (2002) used a discrete adaptive sliding mode control for a hydraulic elevator velocity tracking system.

To improve the efficiency of the elevator system, we propose a two-stage nonlinear robust controller, using the Lyapunov redesign method, for the velocity control of the hydraulic elevator system. At the first stage, a robust controller for the mechanics is synthesized to control the velocity of the car. The control input to the mechanics is used as a reference to the subsequent pressure tracking control. At the second stage, another robust controller for the hydraulics is designed for the purpose of tracking the reference pressure generated from the first controller. The proposed method showed good control performance in the presence of uncertainties.

The paper is structured as follows. In Section 2, the derived mathematical models of the mechanical and hydraulic facets of the hydraulic elevator system considered are presented. In Section 3, a cylinder friction model, a hydraulic pump friction model, and the leakage characteristics of the pump, constructed through a series of experiments, are explained. The controller design, using a two-stage Lyapunov redesign method, is presented in Section 4. In Section 5, the simulation results of the velocity control using the proposed models are shown. Conclusions are given in Section 6.

2. System modeling: dynamics

The equations of motion of the mechanics and hydraulics presented in this section are, respectively, derived from classical Newtonian dynamics, the continuity equation, and the flow equation.

2.1. Mechanics

The mechanics consist of a passenger car (cabin) in which the passengers ride, a hydraulic cylinder, ropes,