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Real-time electro-hydraulic hybrid system for structural testing subjected to vibration and force loading

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ABSTRACT

Real-time electro-hydraulic hybrid system (REHS) with shaking table and force loading simulator is an essential experimental facility for evaluating structural performance subjected to simultaneously vibration excitation and force loading. The key feature of this paper is combination of a feedforward force controller including modified force inverse model compensator (MFIMC) and velocity feedforward compensator (VFFC) with an internal model control (IMC) to compensate the surplus force disturbance caused by active motion of shaking table and to obtain high fidelity force loading tracking performance. An acceleration tracking controller is also designed with modified acceleration inverse model compensator (MAIMC) to extend the acceleration tracking frequency bandwidth and to improve the acceleration tracking performance. The acceleration/force closed-loop transfer function model and their inverse model are identified and designed by multi-step recursive extended least squares (RELS) algorithm and zero magnitude error tracking controller (ZMETC) technology respectively because the identified transfer function model of the acceleration and force loading closed-loop systems may be a nonminimum-phase (NMP) system and their inverse model are instable. An acceleration and force modeling error compensator (MEC) are utilized in MFIMC and MAIMC to minimize the effect of the inaccuracy of identified model and designed inverse model. Experimental results obtained on a real uniaxial REHS with xPC rapid prototyping technology clearly demonstrate the benefit of the proposed compensation method.

1. Introduction

Real-time electro-hydraulic hybrid system (REHS) with shaking table and force loading simulator is a novel structural testing method for evaluating the structural original performance and for detecting structural potential problems subjected to simultaneously the actual vibration and force loading excitation operation of the structures, and it is extensively utilized in civil engineering structures [1–2], automobile industry [3], seismic testing [4], structure fatigue testing [5] etc. The structure of this REHS is shown in Fig. 1. The REHS consists of a horizontal moving platform that moves on two linear rails, and it is connected by a uniaxial electro-hydraulic vibration exciter for vibration and seismic tests and a single channel force loading hydraulic actuator using four low friction linear spherical hinges. The REHS has advantages in power density, large forces, high accuracy [6–7], combined use of vibration and force loading [1]. The purpose of REHS is to generate simultaneously the desired acceleration and force signal on the tested structure with a reasonable tracking error between the desired acceleration/force reference signals and actual acceleration/force measured signals reproduced by the REHS. In order to achieve a better acceleration/force tracking accuracy, the REHS should be excited with high precise vibration and force loading drive signals. However, the acceleration/force loading tracking precision with traditional methods on the REHS are inaccessible simultaneously because of the REHS inherent nonlinearities and uncertainties, such as servo-valve and hydraulic actuator dynamics, dead zone, friction between rod and bore of cylinders, etc. [8,9]. Besides, vibration and force loading interaction especially surplus force disturbance caused by shaking table's active motion [7] and reaction forces disturbance generated by a specimen deteriorate [10], dynamics of the base support [11] also affects the acceleration/force tracking performance.

How to improve force tracking performance of electro-hydraulic servo system under inherent nonlinearities and parametric uncertainty has been of great interest in industries. Karpenko [12] designed a nonlinear quantitative feedback theory (QFT) controller to address the accurate force tracking issue of an electro-hydraulic load emulator. Robust force control with QFT of electro-hydraulic actuators have been designed with respect to the variations in environment and hydraulic component parameters in the literature [13]. In [14] a novel electro-hydraulic structure was proposed to improve the force

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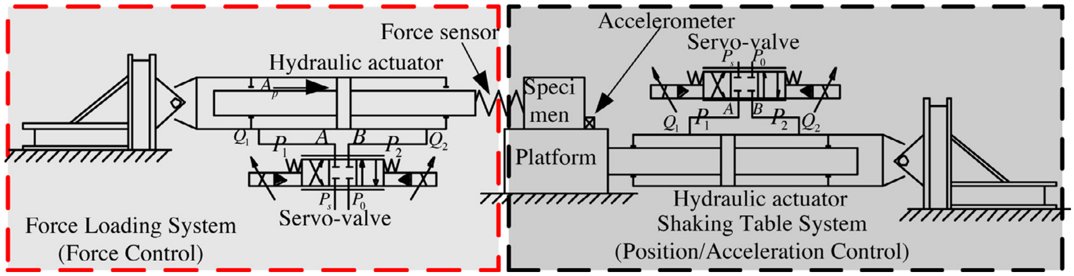

Fig. 1. Schematic diagram of the REHS.

tracking quality and a robust force controller was designed to control the proposed electro-hydraulic structure and model linearization uncertainties were approximated by polytope method. Wang et al. [15] employed a feedback domination controller to compensate finite time force tracking of an electro-hydraulic actuator with actuator friction parameter uncertainties. Nakkarat [16] proposed a backstepping approach to design a nonlinear controller for force control of a single-rod electro-hydraulic actuator and obtained a relatively better tracking performance. Guo [8] proposed extended disturbance observer to compensate electro-hydraulic actuator load pressure in the presence of parameter uncertainties and external disturbances. For further compensating the hydraulic resonance caused by the low damping ratio and resonant frequency inherent nonlinearities in electro-hydraulic shaking table systems, three variable controller (TVC) [17,18] consisting of TVC feedback and feedforward components was employed in electro-hydraulic shaking table. Nakata [19] proposed an acceleration trajectory tracking control to improve the acceleration control performance of earthquake simulators. Wang [20] employed acceleration feedback to improve the stability of a pneumatic actuator systems.

As one of the most useful compensation methods, the feedforward inverse model has been employed for tracking control of the electro-hydraulic servo system. Lee [21] designed an inverse transfer function of the real-time hybrid shaking table testing system to improve the acceleration tracking performance. Gang [22] designed an acceleration closed-loop inverse model to improve the acceleration tracking accuracy of electro-hydraulic shaking table. Chen [23] proposed a dual compensation scheme to overcome the inaccurately estimated actuator delay and to improve the performance of the inverse compensation method. However, the estimated discrete-time transfer function model may be a nonminimum phase (NMP) system and modeling error between the estimated model and actual closed-loop system need to be taken into account for the fidelity tracking accuracy. Rigney et al. [24] relied on an RLS parameter estimation algorithm to identified the closed-loop dynamics of the hard disk drive system, and a zero-order Taylor series approximate inverse technique was employed to synthesize an feedforward inverse model in order to obtain high performance settle time. Yao [9] proposed a combined control strategy based on adaptive control and robust control to reduce modeling errors including parametric uncertainties and uncertain nonlinearities of electro-hydraulic servo system. Gang [22] employed a modeling error compensator to improve the acceleration tracking dynamic characteristics of an electro-hydraulic shaking table. To design the acceleration/force feedforward inverse model of the REHS, the transfer function model need to be identified. Márton [25] proposed an iterative algorithm to identify the friction model parameters of the hydraulic actuators. Ziaei [26] identified the position closed-loop model of electro-hydraulic servos system using least squares estimator. Qian [27] employed genetic algorithm to identify the critical parameters in a linearized servo-hydraulic actuator model. Mohanty [28] identified the accurate parameters of hydraulic manipulators using gradient law. An force closed-loop system parameter model of the electro-hydraulic flight simulator has been identified by RLS algorithm in [29].

However, the tracking performance of the acceleration/force closed-loop system is limited by the strongly vibration and force loading interaction disturbance behavior including surplus force and reaction forces of the REHS. To achieve the rejection of the disturbance, various suppressed external disturbance compensation control strategies have been proposed to improve the high fidelity tracking performance of vibration and force loading. A grey prediction model combined with a fuzzy PID controller was proposed by Quang Truong [30] for eliminating the disturbance of force loading system to improve the control quality. In [7], Wang developed a high performance nonlinear adaptive control method to compensate nonlinear characteristics and parametric uncertainties of the electro-hydraulic load simulator and its motion disturbance. A compound control strategy consists of velocity compensator and active disturbance rejection controller was proposed by Gao [31] for external disturbance suppression to improve the positioning accuracy of the electro-hydraulic servo system. A robust force control system with nonlinear QFT was proposed by Karpenko [12] to improve the force tracking performance of electro-hydraulic load emulator because the load dynamic influence the force transfer function. Seki [10] presented an adaptive notch filter to compensate the reaction forces generated by a specimen deteriorate the shaking table motion. Song [32] designed a low order robust stabilizer based on the IMC for the disturbance rejection and was applied to an electro-hydraulic system. A sliding mode control with discontinuous projection-based adaptation laws is proposed in [33] to reject the load external disturbance for hydraulic parallel robot manipulator.

A multi-step recursive extended least square algorithm and a zero magnitude error tracking control algorithm are utilized to develop a stable feedforward inverse model of the acceleration/force closed-loop to improve the acceleration and force loading tracking performance of REHS. To achieve the rejection of the surplus force disturbance, a combined control strategy based on feedforward inverse model , VFFC and IMC has been proposed to improve the high fidelity tracking performance of force loading system. The proposed combined controller utilizes a force loading closed-loop inverse model as a feedforward controller to extend the frequency bandwidth of the loading system, and a modeling error compensator is employed to minimize the effect of the modeling error, VFFC and IMC are employed to suppress surplus force disturbance. The proposed method is implemented in the uniaxial REHS at China University of Mining and Technology, and some experimental investigations, including acceleration/force tracking performance, and the rejection of the surplus force disturbance, are conducted.

The contributions are organized as follows. The vibration and force loading coupling model is firstly described in Section 2. Next, Section 3 discusses the proposed controller including TVC, MAIMC/MFIMC ,VFFC and IMC in detail. The experimental setup of the adopted REHS including uniaxial shaking table and force loading system and a series of experimental results are then conducted on