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Research article

Acceleration tracking control combining adaptive control and off-line compensators for six-degree-of-freedom electro-hydraulic shaking tables

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ABSTRACT

An electro-hydraulic shaking table (EHST) is an essential experimental facility to simulate in real-time actual vibration situations. An adaptive controller combined with off-line compensators is proposed to improve the acceleration frequency bandwidth and tracking accuracy of a six-degree-of-freedom (6-DOF) EHST. A servo controller has been employed to implement acceleration closed-loop and coordinate control of the 6-DOF EHST. A recursive extended least-squares algorithm is employed to identify acceleration closed-loop transfer functions and a zero-phase-error tracking controller is used to design off-line inverse model compensators using the identified transfer functions. However, the off-line compensators cannot compensate in real-time varying dynamics of the 6-DOF EHST; so an online adaptive controller with a least-mean-squares (LMS) algorithm based on a delay compensator is employed. The proposed controller combines advantages of the off-line compensators and the online adaptive controller, which guarantees both a fast rate of convergence of the LMS algorithm and high-fidelity acceleration tracking accuracy of the 6-DOF EHST. Some experimental studies have been conducted on a 6-DOF EHST and experimental results show that acceleration tracking control performances, including the rate of convergence of the LMS algorithm and acceleration tracking accuracy, have been improved compared to a conventional three-variable controller and adaptive controllers.

1. Introduction

An electro-hydraulic shaking table (EHST) has been used in many vibration tests to evaluate structural original performances and their potential problems under actual vibrations [1–3]. The EHST generally consists of servo-valves, hydraulic actuators, a motion table, and a measurement and control system [1,4]. The purpose of the EHST is to replicate a variety of desired acceleration waveforms on a tested structure with a reasonable acceleration tracking error between the desired and actual acceleration waveforms. However, control of an EHST of six-degree-of-freedom (6-DOF) with eight hydraulic actuators to accurately track a desired acceleration signal is a challenge [5] because the 6-DOF EHST cannot normally work due to geometric effects [6], different electric parameters, and installation errors of the eight hydraulic actuators, which result in large internal coupling forces in the 6-DOF EHST. Hence, a coordinate controller is used to reduce internal coupling forces in the 6-DOF EHST. In [5,6], a general transformation framework was designed and a complete multi-axis decoupling controller was proposed for a multi-axis servo-hydraulic shaking table. An eight DOF control method was employed to implement coordinate control for a 6-DOF EHST [7]. The 6-DOF EHST can normally work with the coordinate controller and the decoupled EHST system should be excited by high-accuracy vibration drive signals [3] to obtain a high-fidelity acceleration feedback waveform. Linear feedback control, such as proportional-integral-derivative (PID) control [5], three-variables feedback control (TVC-FB) based on a combination of position, velocity, and acceleration feedback signals [8–10], and feedback linearization [11], is widely employed to improve system stability and obtain high-fidelity tracking accuracy of desired reference signals for electro-hydraulic servo systems.

However, some nonlinear and time-varying elements in electro-hydraulic servo systems caused by the dynamics of servo-valves and hydraulic actuators, such as a dead zone, friction between the rod and the bore of cylinders [12–14], and varying

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dynamics of a test specimen, deteriorate acceleration tracking performances of the 6-DOF EHST and result in difficulties to provide accurate acceleration signals to the specimen [1]. A three-variable controller (TVC) [1,3,4] is a basic controller for the EHST to improve the dynamics of servo-valves and hydraulic actuators and it consists of a three-variable feed-forward controller (TVC-FF) and a TVC-FB, which are employed to extend the frequency bandwidth of the acceleration closed-loop system and improve stability of the 6-DOF EHST by increasing natural frequencies and damping ratios of hydraulic systems, respectively. Some off-line compensators, such as the TVC, off-line iterative controllers [10], and off-line inverse model compensators (OIMCs) [3], were widely employed to compensate the dynamics of servo systems. However, the off-line compensators cannot be effectively used in nonlinear cases and this shortcoming may be remedied by using an online adaptive controller for the 6-DOF EHST, in which parameters of varying dynamics, including changes within an existing specimen during testing [5], are simultaneously adapted. Hence, some adaptive and intelligent control methods, such as adaptive inverse control [15,16], minimal control synthesis [17,18], adaptive notch filtering [1], and combined adaptive control [4,19,20], have been sought and they have attractive potentials for varying dynamics.

However, convergence performances of these above-mentioned adaptive and intelligent control algorithms, especially their rates of convergence, significantly limit control performances of these adaptive controllers for electro-hydraulic servo systems that need faster convergence. There have been numerous attempts to improve rates of convergence of these adaptive controllers using some appropriate modification methods. In [21], an approximate feed-forward inverse model controller and an adaptive controller using a velocity minimal control synthesis algorithm were proposed for a multi-axis hydraulic test rig. In [22], a frequency-domain adaptive filter with a filtered-X least-mean-squares (LMS) algorithm was employed for an adaptive inverse controller that needs faster convergence. In [23], a filtered-X LMS algorithm and an H_∞ filter were combined to improve the rate of convergence of the LMS algorithm for an electro-dynamic shaker. In [24], a novel adaptive inverse control framework with an LMS algorithm was employed to yield an accurate acceleration waveform on shaking tables.

The phase delay of the controlled closed-loop system is one of very important factors impacting on the rate of convergence of the LMS algorithm [4,25] because there is an inevitable delay in response to reference signals due to inherent dynamics of electro-hydraulic servo systems, which results in some adverse effects on the rate of convergence of the adaptive controller [26]. To solve the problem, many phase delay compensators have been presented. A feed-forward inverse model was widely employed to improve the phase delay of the controlled closed-loop system without changing its stability [4,27]. In [28], some non-minimum-phase inversion model design methods, including accurate inversion schemes and stable approximate non-minimum-phase inverse techniques, were investigated. In [29], a derivative feed-forward method was proposed for time delay compensation. In [30], an equivalent discrete transfer function was employed to analyze time delay compensation of a hydraulic actuator. In [31,32], an actuator delay compensator was designed to reduce an inevitable actuator response delay in a real-time hybrid experimental system. In [33], an adaptive controller with consideration of bounded time delays was designed for a class of multi-input multi-output nonlinear systems. An uncertain transport delay time in the transmission of an electro-hydraulic servo-valve control system was presented and a delay time variation can be effectively predicted and unconditionally removed [34].

The goal of this study is to design a combined controller to improve acceleration tracking performances of the 6-DOF EHST in the presence of varying dynamics, plant uncertainties, and modeling errors between the estimated model and the actual controlled plant. The proposed controller combines an OIMC, an improved internal model controller, and an online adaptive controller based on the LMS algorithm and a delay compensator. To develop the idea, the OIMC is employed to extend the frequency bandwidth of the acceleration closed-loop system and yield a desired measured acceleration waveform on the 6-DOF EHST, and the OIMC is designed by a zero-phase-error tracking controller using the identified acceleration closed-loop transfer function that is identified by a recursive extended least-squares (RELS) algorithm. An internal model controller is employed to minimize the effect of modeling error, and the LMS algorithm is further employed to adaptively adjust the time-domain drive signal and yield a high-fidelity acceleration response waveform on the 6-DOF EHST. A delay compensator using a linear acceleration extrapolation is designed to minimize the delay effect of hydraulic actuators and accelerate the rate of convergence of the online adaptive controller. Finally, effectiveness of the proposed controller is examined by some experiments on a 6-DOF EHST and the proposed controller yields a reasonable acceleration tracking performance.

An experimental setup of the 6-DOF EHST and a dynamic model of one hydraulic actuator are established in Section 2. Section 3 discusses the proposed controller including the coordinate controller, the TVC, the OIMC, and the internal model controller of the acceleration closed-loop system, and the delay compensator, the optimal solution, and the convergence performance of the LMS algorithm. Some simulation results and performance analysis are shown in Section 4. A series of experimental results are verified on a 6-DOF EHST to demonstrate effectiveness of the proposed controller in Section 5. Section 6 concludes main points and contributions of this study.

2. Experimental 6-DOF EHST and its dynamic model

2.1. Experimental setup

In this section, an experimental 6-DOF EHST system that is controlled by six degrees-of-freedom (six DOFs) using eight hydraulic actuators is carried out to verify effectiveness of the proposed controller in a real system. Fig. 1(a) and (b) show the experimental setup and its structural scheme, respectively, which consist of eight double-ended hydraulic actuators with a 70 mm bore and a 50 mm rod, eight flow-controlled servo-valves manufactured by Moog, Inc (G761-3004B, 38 L/min with 7 MPa pressure), sixteen spherical hinges and some relative sensors including eight linear variable differential transformers (LVDTs), eight accelerometers, and sixteen pressure transducers. The eight LVDTs are attached on the eight cylinders to measure displacements in real time; the eight accelerometers manufactured by PCB, Inc (G3711, max acceleration 2 g) are mounted on the drive rod of the eight cylinders to measure accelerations in real time, and the sixteen pressure transducers are employed to measure two chamber pressures of the eight cylinders. Main parameters of the experimental EHST system are listed in Table 1.

A block schematic of the experimental 6-DOF EHST control system is shown in Fig. 2, where a host computer serves as the user interface and enables the user to compile programs of these designed controllers and modify the control scheme and adjust parameters. A target computer serves as a real-time processing unit in which a real-time operating system (RTOS) is employed and performs real-time execution of the controller and real-time communication with A/D and D/A boards. Implementation of the digital controller and data acquisition are processed on a MATLAB/xPC target system on the target computer. Control signals are converted to analog signals by two 12-bit D/A ACL-6126 boards