Mechatronics 24 (2014) 1132–1143

Contents lists available at ScienceDirect

Mechatronics

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

Development of hydraulically driven shaking table for damping experiments on shock absorbers

Shou-kun Wang *, Jun-zheng Wang, Wen Xie, Jiang-bo Zhao

Key Laboratory of Intelligent Control and Decision for Complex System, Beijing Institute of Technology, Beijing 100081, PR China

ARTICLE INFO

Article history:
Received 15 May 2013
Accepted 4 September 2014
Available online 22 October 2014

Keywords:
Hydraulic control
Shaking table
Shock absorber
Iterative learning control
Open-closed-loop
Damping characteristic

ABSTRACT

The hydraulically driven shaking table has been developed for damping characteristic experiments on shock absorbers in this paper. The damping characteristics and corresponding experiments on the double-tube hydraulic absorber are analyzed firstly, and its damping force model is also built. Then the working principle is introduced, and the structure and components of the physical shaking table are described, especially the hydraulic actuator, composed of servo valve controlled asymmetric cylinder with damping load, is analyzed. Considering parameter uncertainty, nonlinearity, asymmetry and time-variation of such hydraulic system, as well as repeatability of desired trajectory, an open-closed-loop ILC scheme is designed to solve the challenging control issue. The simulation and experiments are developed to verify the feasibility of working principle and the superiority of proposed control method. The hydraulically driven shaking table developed by discussed electro-hydraulic control technology has been applied in actual damping characteristic experiments for a serial of shock absorbers, and achieved satisfactory testing performance.

1. Introduction

As an important device used in suspension systems of modern vehicles, the shock absorber is mounted between auto bridge and frame for damping the vibration caused by uneven road to moderate impulsive load [1]. Therefore, the damping performance of the shock absorber is of importance to running smoothness, operating steadiness and through capacity of vehicles. With demanding requirements for safety and comfort of driving vehicle, research on the shock absorber have gained more and more attention, including its high frequency performance, experiments for damping characteristic, temperature control, noise issue, etc. [2]. In this paper, based on electro-hydraulic control technology, experiments on damping characteristic of the shock absorbers are researched.

The shaking table, as an important experimental device, has been widely used in design, manufacturing and inspection stages of the shock absorbers, to simulate the vibration condition and test the damping characteristic of absorbers. Regarding the shaking table for shock absorbers, Dutch KONI Co. is in the leading position, whose products have been widely applied by many vehicle manufactures [3], while American MTS Co. and German SCHECK Co. also have developed advanced shaking table products for the shock absorbers [4].

The shaking table for the shock absorbers is normally driven by hydraulic cylinder or electric-motor to generate vibrations [5]. The electric shaking table, driven by electric-motor (as shown in Fig. 1), uses crank and connecting rod mechanism to turn rotation into simple harmonic vibration, although having advantages of simple structure and easy control, as well as low cost, such kind of shaking table also has some notable disadvantages, such as poor control precision, limited vibration bandwidth and inconvenient adjustment for vibration parameters. Hydraulically driven shaking table drives tested absorber to vibrate by means of cylinder's movement directly, then it could regulate the vibration parameters flexibly and achieve ideal control performance, due to advantages of hydraulic control system, such as high power–mass ratio and stiffness, fast response, high control precision, compactness and high payload capability [6]. Therefore, a hydraulically driven shaking table is designed and developed in this paper.

The hydraulic actuator, servo valve controlled asymmetric cylinder, employed in most hydraulically driven shaking tables, is subjected to friction, dead zone, fluid compressibility, internal leakage and hysteresis [7], and the dynamic performance of servo valve is often influenced by supply pressure, fluid and ambient temperature, etc [8], furthermore, the asymmetric structure of single-rod cylinder brings great asymmetry and time-variation. Apart

* Corresponding author. Tel.: +86 013810022292; fax: +86 01068912465 210.
E-mail address: bitwsk@bit.edu.cn (S.-k. Wang).

http://dx.doi.org/10.1016/j.mechatronics.2014.09.001
0957-4158/

from such nonlinear nature of hydraulic dynamics, the electro-hydraulic servo system also has a large extent of model uncertainties, which cannot be modeled exactly, and the nonlinear functions that describe them accurately are difficult to get known [9]. Therefore, control for hydraulically driven shaking table is always a challenging issue.

Traditional proportional–integral–derivative (PID) control method has been widely applied in many electro-hydraulic control systems due to its simplicity, clear functionality and easy implementation [10], but on the other hand, it is difficult to achieve satisfactory control performance because of above factors of nonlinearity, asymmetry and parameter uncertainty.

Therefore present research for electro-hydraulic servo systems is focused on nonlinear control methods, designed to change control parameters adaptively in real time so as to achieve the desired performance. Sliding mode control [11,12] has a wide range of application in hydraulic control, which is frequently along with some uncertainty learning and compensation techniques to deal with uncertainty and nonlinearity of controlled plant. The adaptive control method [13,14] is equally a research hotspot, employing adaptive laws to compensate for uncertain parameters. Other control methods, such as fuzzy PID control [15], backstepping control [16], feedback linearization control [17], robust H_∞ control [18], quantitative feedback control [19], and neural network control [20] are also designed for electro-hydraulic servo systems, but their disadvantages could not be ignored. For example, complicated calculation may be required, which cannot meet the real-time requirement in motion control systems; many parameters should be estimated in advance, which leads to difficult tuning process.

Iterative learning control (ILC) has gained considerable interests from researchers, and become a hotspot issue in recent years. Generally speaking, ILC uses information from previous executions in the iterative process of finding the learned commands so as to improve performance under repetitive motion [21]. ILC could provide a feasible solution for electro-hydraulic control issue, and some applications of ILC in hydraulic control system have proved its effectiveness. Considering the repetition of vibration in damping characteristic experiments for absorbs, the control scheme based on open-closed-loop ILC is designed for hydraulic control system with high precision.

In this paper, the hydraulically driven shaking table is developed for damping characteristic experiments on the shock absorbers, and an open-closed-loop ILC method is proposed to solve control issue. The rest of the paper is organized as follows. Section 2 introduces the damping characteristics of the double-tube hydraulic shock absorber, including force analysis, math model and relative experiment items. Section 3 describes system principle and actual components of hydraulically driven shaking table. In Section 4, the model of hydraulic actuator is derived, and its characteristic is also analyzed. In Section 5, the fundamental principle of ILC is introduced, and an open-closed-loop PD-type ILC method is designed for electro-hydraulic control in the shaking table. Section 6 gives simulation results of system principle and control method. Section 7 presents the experimental results of the hydraulically driven shaking table. Lastly, conclusions are made to summarize the main work of this paper.

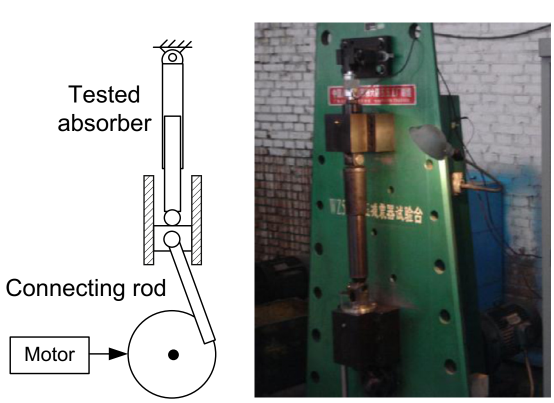

Fig. 1. The shaking table driven by electric-motor.

2. Damping characteristic of shock absorbers

2.1. Operating principle of two-tube hydraulic shock absorbers

The two-tube hydraulic shock absorber has been extensively adopted in suspension systems of various vehicles, therefore it is regarded as the tested object in this paper. Generally speaking, the hydraulic shock absorber is a kind of energy-consuming unit, turning vibration energy into thermal energy [22]. The relative motion between the frame and suspension of vehicle drives the absorber to compress and rebound repetitively, then hydraulic oil keeps flowing between different chambers via the orifice iteratively, which forms the damping force to resist the vibration [23]. The fundamental structure and operating principle of two-tube hydraulic shock absorbers can be described in Fig. 2.

The two-tube hydraulic shock absorber is made up of a piston rod, three chambers (compression, rebound and reserve chambers) and four valves (rebound, rebound intake, compression and compression intake valves). The motion of piston rod changes pressures of three chambers, and then drives hydraulic oil to flow between these chambers. The rebound intake and compression intake valves, also called bottom valves due to locating on the bottom plate, are to intake and discharge hydraulic oil between rebound and reserve chambers. The rebound and compression valves, also called piston valves due to locating on the piston, act as unloading valve with greater spring stiffness to produce the main damping force [24].

The operating principle of two-tube hydraulic shock absorber may be divided into compression and rebound stages. As shown

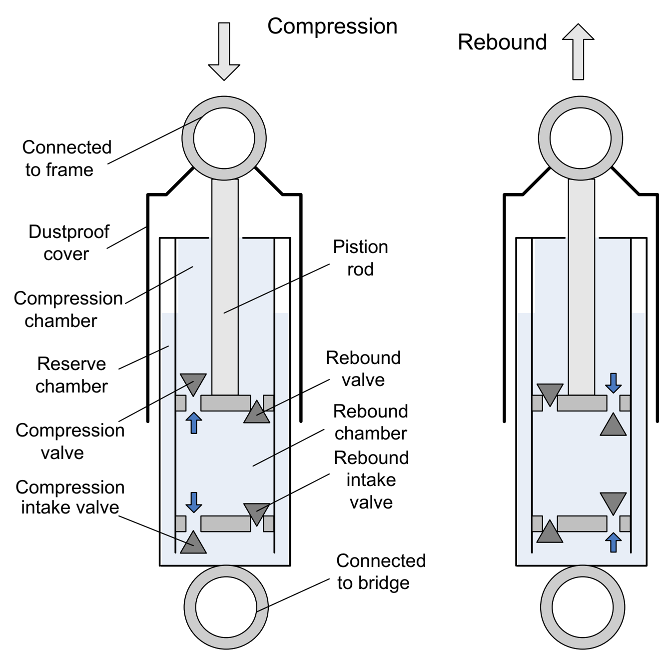

Fig. 2. Structure and operating principle of two-tube hydraulic shock absorber.