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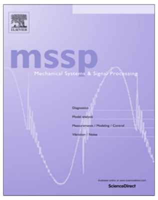

Nonlinear model of a servo-hydraulic shaking table with dynamic model of effective bulk modulus

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ABSTRACT

In this paper, based on fluid mechanical expressions and a new modified effective bulk modulus model of hydraulic oil built upon IFAS model (developed at the Institute für Fluidtechnische Antriebe und Steuerungen, RWTH Aachen university), an empirical nonlinear model for a servo-hydraulic uni-axial shaking table is developed. This new model can precisely simulate the acceleration, velocity and position outputs of the system with respect to different kinds of inputs such as pulse and sinusoidal signals for a wide range of frequencies and different weights of the specimen. Therefore, it can be helpful for designing and optimizing the parameters of a model-based controller for tracking reference force or acceleration signals, which is the goal of the shaking table with only position sensor. In the new modified IFAS model, the effective bulk modulus of hydraulic oil on both sides of the piston has been considered as two nonlinear springs, which are connected serially. The minimum stiffness of the spring effect of the hydraulic oil in a symmetric double-acting hydraulic cylinder occurs, when the piston is in the center of its travel, which can be characterized with differential pressure on its both sides. When the differential pressure is less than a specific threshold pressure, these springs have the minimum stiffness and reserve energy in themselves. Based on the experimental observations, this effect has been modeled with a function, which multiplies the IFAS model. The experimental acceleration output of the system demonstrates the dynamic behaviors of the effective bulk modulus of hydraulic oil, which occurs in the center of the piston travel. The parameters of the simulated model are estimated with the nonlinear least square method in MATLAB. Finally, the accuracy of the proposed model for simulating the motion states of the shaking table, by comparing the experimental and simulated results in different ranges of amplitudes and frequencies with respect to the new and the previous model of the hydraulic servo-systems have been shown.

1. Introduction

Shaking table is an important experimental device for simulating dynamic response of complex mechanical systems to high natural dynamical forces. It has been widely used in many industrial applications such as aerospace, automotive and civil engineering. In recent years, its usage stands out in civil engineering for analyzing and simulating dynamic response

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of high rise buildings and structures to earthquakes and wind storms [1–3]. Due to requirement of large forces and displacements in the shaking tables, they are mostly driven by servo-hydraulic actuators.

Hydraulic actuators in comparison with other driving powers have many advantages, including high force to weight ratio, high durability and fast responses [4–7]. In spite of these advantages, the dynamic features of these systems are highly nonlinear and designing a high accuracy tracking control for them is a difficult problem. Most nonlinearities of these systems arise from compressibility of the hydraulic fluid, the complex flow properties of the servo-valve, valve overlap and friction in the hydraulic cylinder [7]. Aside from the nonlinear nature of the hydraulic dynamics, there are many considerable model uncertainties, such as internal and external leakages and external disturbances, which cannot be modeled exactly. Therefore, in order to design a high performance model-based controller for simulating the acceleration behavior that is the goal of a servo-hydraulic shaking table, a suitable dynamical model of the system needs to be formulated.

Many researchers use the dynamic model of hydraulic actuator based on fluid mechanical expressions in [4–7] to model the nonlinear behavior of the system (see for instance [8–12]). The results in these papers show that even with considering different nonlinear friction models, the simulated velocity for small ranges of amplitude and frequency is fairly accurate and so is the simulated acceleration. Additionally, in [4,13,14] have been shown that the acceleration output of the system to the sinusoidal input is distorted and it contains harmonics with the fundamental frequency and its integer multiplications. In [15–17], for simulating the acceleration response, a function consisting of sinusoidals with known frequencies have been considered. Then, the amplitudes and phases of each function are calculated based on the least mean square method [15], the Kalman filter [16] and the unscented Kalman filter [17]. However, the input frequency of the system in all these methods is assumed to be known and the acceleration sensor data are always needed for updating the identification parameters. Furthermore, as stated in these papers, it takes $0.5[\mathrm{s}]$ for the parameters to converge to the actual amplitude and phase of harmonics which is suitable for the control process up to $1[\mathrm{Hz}]$. Therefore, these methods are not suitable for the shaking table which has operating frequency range $(0-15)[\mathrm{Hz}]$. In [18], the acceleration of the system based on feed-forward neural network method, has been simulated. This method needs high computation resources and it has $2[\mathrm{s}]$ convergence window at the first run which in some cases, it causes instability in control feedback loop. Thus, in order to model the acceleration behavior to any kind of inputs precisely, it is needed to model the main nonlinear features of the system such as effective bulk modulus (E-Modulus) and friction, as accurately as possible.

In the hydraulic systems, the spring effect of a hydraulic oil is characterized by the value for the bulk modulus. It is a fundamental and inherent property of liquids, which indicates the stiffness of the system and the speed of transmission of pressure waves. Therefore, system performance with respect to positioning, power loss, response time and stability of hydraulic servo-systems is affected by the value of bulk modulus. Several researches have been done on the topic of the bulk modulus without considering the effect of entrained air [19–21]. However, the real bulk modulus with considering the effect of entrained air, temperature and mechanical compliance in the hydraulic systems is presented by the value for the E-Modulus. In recent years, several theoretical models have been proposed to simulate the dependency of the E-Modulus upon pressure and entrained air content [22–26]. In [27,28], based on the experimental verification of these models, have been shown that the IFAS model in [24] can simulate the behavior of the E-Modulus with higher accuracy. However, as shown in these papers, the minimum time for maximizing the input pressure are $2.5[s]$, which in our study is almost the steady state case.

The other main nonlinearity of the hydraulic systems is friction in the hydraulic cylinder. Many researchers employ an explicit dynamic friction in order to model nonlinear effects of friction which some of them have been commonly used to express the friction of hydraulic cylinder [29–33]. The steady state friction in [29], is the combination of Coulomb friction, viscous friction and static friction. The dynamic LuGre friction [30], which is implemented in the AMESim (Advanced Modeling Environment for performing Simulation of engineering systems) software [34–36], defines dynamic features of friction such as pre-sliding displacement, lag, varying break-away force and stick–slip. But this model cannot describe precisely the dynamic behaviors of friction in the sliding regime. Therefore, in [31–33] has been proposed a modified LuGre model which can simulate the dynamic behaviors of friction in the sliding regime. However, in [10] has been shown that based on the experimental results, the simulated velocity with considering modified LuGre model is fairly correct. In addition, in [12,33] have been pointed out that these models are valid with the assumption of the frequency up to $2[\mathrm{Hz}]$ and the velocity under $0.15[\mathrm{m/s}]$, that is a limit in real practical shaking tables. Aside from these problems, obtaining real values for some parameters in LuGre model are very difficult and some experiments and sensors are needed which can be expensive and time consuming [33].

In this paper, a new empirical nonlinear model for simulating the acceleration, velocity and position behavior of a servo-hydraulic shaking table in dynamic and steady state flow situations is proposed. Based on the experimental observations, this model is attained by modifying the IFAS model for simulating the E-Modulus of the hydraulic oil. The bulk modulus of hydraulic oil inside two chambers behaves like a spring. In a symmetric double-acting hydraulic cylinder which is used for driving the shaking table, the minimum stiffness of the spring effect of the hydraulic oil occurs when the piston is in the center of its travel [5]. In this new model, the nonlinear spring effect of the hydraulic oil in two interactive chambers, which are connected serially, is modeled based on differential pressure of them. When the differential pressure on both sides is less than a threshold pressure, these springs have the minimum stiffness and reserve energy in themselves. The new modified IFAS model has demonstrated this effect by a function built upon differential pressure, which multiplies the IFAS model. The experimental acceleration output of the system implies the dynamic behaviors of the E-Modulus of hydraulic oil, which occurs in the center of the piston travel. Here, for simplicity and the limitation of the LuGre model, the steady state friction