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Nonlinear dynamic analysis of complex hydraulic driving processes

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A B S T R A C T

Hydraulic driving processes are widely used in industry. The complexity and strong nonlinearity of these processes often make their dynamic behavior difficult to estimate. In this paper, a nonlinear dynamic analysis method is proposed to overcome this difficulty. First, a nonlinear model of complex hydraulic driving processes is derived. A solution method is then developed in order to obtain an analytical solution. Using this analytical solution, the conditions for stable or unstable motion are derived and the nonlinear dynamic behavior is estimated. The analytical results are then verified using both simulations and experiments conducted on actual hydraulic processes.

1. Introduction

Hydraulic actuators are widely used in the manufacturing industry, most commonly to press a material/workpiece into a desired shape. For example, most aircraft components that bear alternating and concentrated loads are formed using a hydraulic actuator, including the fuselage, rotary parts in engines, and the undercarriage. Generally, the higher quality of the manufactured product depends upon having precise and accurate control of the hydraulic actuator. In order to achieve this level of control, the dynamic behavior of the driving process should be estimated beforehand. Consequently, the dynamic analysis of the hydraulic driving process is of utmost importance in the manufacturing industry. However, an accurate dynamic analysis is often difficult to achieve for the following reasons:

- The hydraulic driving process is strongly nonlinear due to both the compressibility of oil and the nonlinear characteristics of the pump, the valve, and the pipe [1];
- Friction force is inevitable and highly nonlinear [2–8], especially during a low-velocity operation;
- The deformation force of the workpiece is complex due to the nonlinear relationship among the material properties, stress, stress ratio, and temperature, as well as the deformation caused by irregular shapes [9,10];
- There is complex dynamic coupling between the mechanism system and the hydraulic driving system due to the mutual transfer of both motion and force [11–15].

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All of these factors make the estimation of the dynamic response of the hydraulic driving process quite challenging.

Many studies have proposed methods to estimate the dynamic behavior of the hydraulic actuator using experiments [16–22] and simulations [23–31]. For example, the ADAMS, MATLAB/Simulink, and ANASYS have been used to investigate the dynamics of the hydraulic driving force [23], the influence of system operational parameters [24], the influence of variations in velocity and pressure [25–27], and modal analysis [28–31]. However, these results are only accurate under very specific conditions, and neglect to consider stable motion, vibration, and creep; thus they lack generality and subsequently, widespread application. In addition to the methods listed above, the bond graph method was also adapted to analyze the dynamics of the hydraulic driving process [32,33]. Recently, estimation methods based on linear deformation force and linear pressure were developed in order to predict the dynamics of the hydraulic driving process [34,35]. However, these methods neglect to consider the influence of nonlinearities and are thus less effective in analyzing actual complex hydraulic driving process. Moreover, some research has shown that friction is a significant factor in product oscillation and stick slip for a hydraulically driven system. A few friction models, such as the Stribeck model [36] and the LuGre model [37], have been employed to study the influence of friction on the dynamic behavior. The influence of other parameters in the hydraulic actuator on the velocity response was also investigated [38,39]. However, these studies only focused on relatively simple systems and their results are difficult to apply to the complex hydraulic driving process. Other studies have contributed to the estimation of the nonlinear dynamic response of the hydraulic actuator [40–48], such as the vibration response and bifurcation behavior. These studies focused on the dynamic effects of the hydraulic driving force on velocity and did not account for the flow equation in the driving cylinder, which often results in a less effective result. Therefore, it is still imperative to develop a nonlinear dynamics analysis method for estimating the nonlinear dynamic behavior of the complex hydraulic driving process.

In this paper, we propose a nonlinear dynamic analysis method to estimate the nonlinear dynamic behavior of the complex hydraulic driving process. A nonlinear model is derived first; a solution method is then developed in order to determine an analytical solution. Using this analytical solution, the conditions for stable or unstable motion are derived and the nonlinear dynamic behavior is estimated. The analytical results are then verified using simulations and experiments on actual hydraulic processes.

2. Modeling of the hydraulic actuator

A typical hydraulic actuator is shown in Fig. 1. A hydraulic driving force is used to drive the piston rod towards the workpiece in order to obtain the desired shape. The hydraulic driving force is produced using a hydraulic system, including a pump, cylinder, valves, and pipes.

The dynamics of the piston rod can be described as follows:

$$M\frac{\mathrm{d}^2x}{\mathrm{d}t^2} = Ap - B\frac{\mathrm{d}x}{\mathrm{d}t} - F_f - F_z \tag{1}$$

where M is the total mass of the piston rod, x is the displacement of the piston rod, A is the area of the piston rod, p is the oil pressure, B is the viscous damping coefficient, F_f is the friction at the piston cylinder, and F_z is the deformation force of the work piece.

The following Stribeck friction model is used to represent the friction at the hydraulic cylinder [36]:

$$F_f = F_c + (F_s - F_c)e^{-\left(\frac{v}{v_s}\right)^2} + \sigma_1 v \tag{2}$$

where F_c and F_s are the Coulomb frictional force and maximum static friction force, v is the velocity of the piston rod, v_s and σ_1 are the Stribeck critical velocity and the viscous friction coefficients, respectively.

The deformation force of a work piece is often complex: it is a nonlinear function of the displacement x and velocity v, as well as the shape, material, and the temperature of the work piece [49].

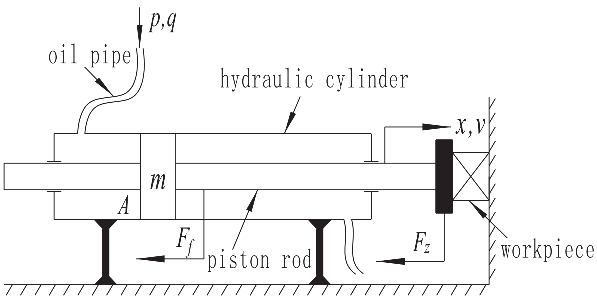

Fig. 1. Hydraulic actuator.