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Parametric model of servo-hydraulic actuator coupled with a nonlinear system: Experimental validation

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ABSTRACT

Hydraulic actuators play a key role in experimental structural dynamics. In a previous study, a physics-based model for a servo-hydraulic actuator coupled with a nonlinear physical system was developed. Later, this dynamical model was transformed into controllable canonical form for position tracking control purposes. For this study, a nonlinear device is designed and fabricated to exhibit various nonlinear force-displacement profiles depending on the initial condition and the type of materials used as replaceable coupons. Using this nonlinear system, the controllable canonical dynamical model is experimentally validated for a servo-hydraulic actuator coupled with a nonlinear physical system.

1. Introduction

Hydraulic actuators are extensively used in structural control systems and for experimental testing to investigate the behavior of structural systems subjected to dynamic loads. However, researchers have demonstrated a natural velocity feedback which tightly couples the dynamic characteristics of a hydraulic actuator to the dynamics of the system to which it is attached [1,2]. Disregarding this coupling can severely limit both the performance and robustness of experiments and protective system [1,3]. For instance, in many active structural control situations, poor, or perhaps catastrophic, performance of the controlled system can occur due to the unmodeled or mismodeled dynamics of the actuator coupled with the structure [1]. Effective force testing methods have been found to be challenging due to a physical phenomenon known as *control-structure interaction* (CSI) in which the actuators attached to lightly damped structures have a significantly limited ability to apply control forces at the natural frequencies of the structure [1,4,5].

In most cases when hydraulic actuators are used for structural engineering purposes, success depends on the accurate application of forces or displacements to the structure (a.k.a. physical specimen). For instance, in *real-time hybrid simulation* (RTHS), hydraulic actuators serve as transfer system to enforce the interface conditions between the computational and physical substructures [6,3]. The first step to achieve accurate application of forces and displacements is to develop a model for hydraulic actuators (typical of those used in such structural testing) coupled with the physical specimen, see Fig. 1. Such a

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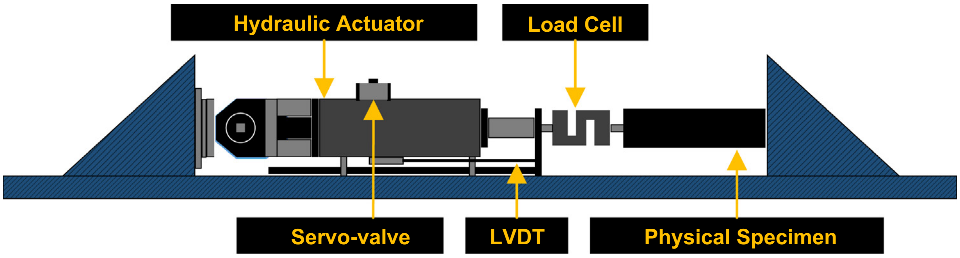

Fig. 1. Schematic diagram of a typical plant: a hydraulic actuator coupled with a general physical specimen with appropriate sensors.

model can be further used as a plant for designing controllers and compensators to enhance the accuracy of the forces or displacements to be provided by hydraulic actuators, therefore ensuring that their responses are as close as possible to the desired trajectories.

In this study, *plant* refers to the servo-hydraulic actuator coupled with the physical specimen. To develop a physics-based model for the plant, DeSilva linearized the fluid flow rate in the actuator about the origin [7]. In this linearized model, a natural velocity feedback path exists between the hydraulic actuator and the servo-valve input. The coupling between a hydraulic actuator and a physical specimen was explored by Dyke et al. [1]. In a set of experiments, they demonstrated that whenever a hydraulic actuator is attached to a linear physical specimen, the actuator has limited ability to apply forces at the natural frequencies of the physical specimen. Later, this model was extended to a nonlinear dynamical model for the case when a hydraulic actuator is coupled with a nonlinear physical specimen [3]. In addition, this dynamical model was further transformed to controllable canonical form for position tracking control purposes.

Controllability is a significant property of a control plant. Transforming the plant model into a controllable canonical dynamical model makes it appealing for displacement tracking. Adopting such model becomes especially important in two cases: (1) when control-structure interaction dominates the dynamics of the coupled system, and (2) when the hydraulic actuator is coupled with an unknown physical specimen (such as in the case of real-time hybrid simulation). In such cases, after identifying the parameters associated with the servo-hydraulic actuator [2,8], parametric and non-parametric uncertainties are incorporated in the model due to uncertainties in the physical specimen. The controllable canonical model is formulated so that the measured forces applied to the physical specimen are used as a feedback signal. Therefore, the measured force signal is used as an additional piece of information by the control law for accurate displacement tracking of the plant with a high level of uncertainty.

The objective of this study is to experimentally validate the controllable canonical dynamical model for nonlinear physical systems. For this purpose, a nonlinear specimen has been designed and fabricated, such that it has certain characteristics: (i) it exhibits a nonlinear force-displacement profile; (ii) it is a damage-controlled specimen and the damaged parts are easily replaceable (coupons); and (iii) various force-displacement profiles can easily be generated using different coupons.

2. Controllable canonical model

In [3], a nonlinear dynamical model was developed for a hydraulic transfer system coupled with a linear/nonlinear physical specimen. In addition, a simple technique was demonstrated to identify the parameters associated with the hydraulic system. A brief overview of this dynamical model is provided here. A block diagram representation of a typical servo-hydraulic actuator coupled with a nonlinear physical specimen is provided in Fig. 2.

Consider a single-degree-of-freedom nonlinear physical specimen, expressed in the generalized form

$$x_3 = h(x_1, x_2) + f/m, \quad (1)$$

where x_2 and x_3 denote $\dot{x}_1$ and $\ddot{x}_1$, respectively, and f and m are the actuator force and specimen mass, respectively. In [3], it was demonstrated that Fig. 2 can be reduced to the dynamically equivalent form shown in Fig. 3 which represents the

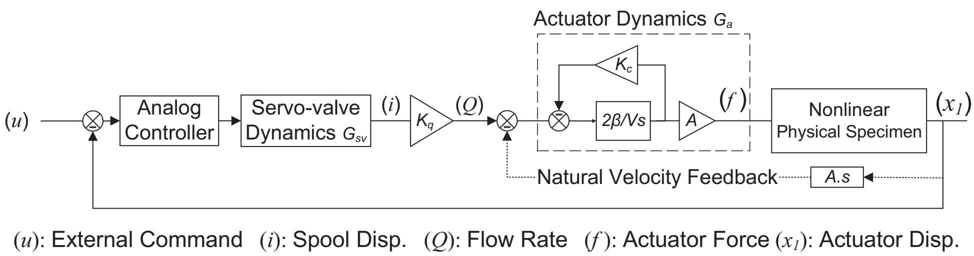

Fig. 2. General dynamics of the plant: a hydraulic actuator coupled with a nonlinear physical specimen.