Journal of Sound and Vibration ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Journal of Sound and Vibration

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

Hybrid simulation theory for a classical nonlinear dynamical system

Paul L. Drazin [a], Sanjay Govindjee [b,*]

[a] Department of Mechanical Engineering, University of California, Berkeley, Berkeley, CA 94720, United States
[b] Department of Civil and Environmental Engineering, University of California, Berkeley, Berkeley, CA 94720, United States

ARTICLE INFO

Article history:
Received 23 June 2016
Received in revised form
17 November 2016
Accepted 20 December 2016

Keywords:
Hybrid simulation
Hybrid simulation error analysis
Nonlinear dynamics
Chaos
Lyapunov exponent
Lyapunov dimension
Poincaré section

ABSTRACT

Hybrid simulation is an experimental and computational technique which allows one to study the time evolution of a system by physically testing a subset of it while the remainder is represented by a numerical model that is attached to the physical portion via sensors and actuators. The technique allows one to study large or complicated mechanical systems while only requiring a subset of the complete system to be present in the laboratory. This results in vast cost savings as well as the ability to study systems that simply can not be tested due to scale. However, the errors that arise from splitting the system in two requires careful attention, if a valid simulation is to be guaranteed. To date, efforts to understand the theoretical limitations of hybrid simulation have been restricted to linear dynamical systems. In this work we consider the behavior of hybrid simulation when applied to nonlinear dynamical systems. As a model problem, we focus on the damped, harmonically-driven nonlinear pendulum. This system offers complex nonlinear characteristics, in particular periodic and chaotic motions. We are able to show that the application of hybrid simulation to nonlinear systems requires a careful understanding of what one expects from such an experiment. In particular, when system response is chaotic we advocate the need for the use of multiple metrics to characterize the difference between two chaotic systems via Lyapunov exponents and Lyapunov dimensions, as well as correlation exponents. When system response is periodic we advocate the use of L^2 norms. Further, we are able to show that hybrid simulation can falsely predict chaotic or periodic response when the true system has the opposite characteristic. In certain cases, we are able to show that control system parameters can mitigate this issue.

© 2016 Elsevier Ltd All rights reserved.

1. Introduction

Hybrid simulation (or hybrid-testing) is a popular experimental method that is primarily used in Civil Engineering laboratories [1,2]. It originated roughly 30 years ago [3] and has been used continuously and extensively as a methodology to experimentally assess structural systems under earthquake loadings. Occasionally the methodology has also been used in other disciplines to assess dynamic phenomena; see e.g. [4–6]. The central problem that hybrid simulation addresses is that it is very difficult and expensive to test full-size civil structures for their structural capacities under seismic loads. The largest testing facility in the world is the E-Defense facility [7] which can test structures with a 20 m × 15 m plan and 12 MN

---

* Corresponding author.
E-mail addresses: pdrazin@berkeley.edu (P.L. Drazin), s_g@berkeley.edu (S. Govindjee).

http://dx.doi.org/10.1016/j.jsv.2016.12.034
0022-460X/© 2016 Elsevier Ltd All rights reserved.

Please cite this article as: P.L. Drazin, & S. Govindjee, Hybrid simulation theory for a classical nonlinear dynamical system, *Journal of Sound and Vibration* (2016), http://dx.doi.org/10.1016/j.jsv.2016.12.034

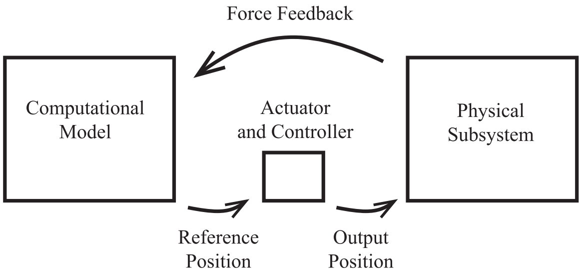

Fig. 1. A simple diagram of a hybrid system setup.

weight. While this represents a large capacity, it precludes the testing of many types of structures, is very expensive due to the need to build full-size prototypes, has limited throughput, and does not easily allow for design exploration.

At its heart, one can think of experimental testing of this variety as the use of an analog computer (algorithm) to simulate the behavior of a structure. Hybrid testing and its many variants (see e.g. [8,9]) tries to leverage this viewpoint in the following manner: (1) The determination of the dynamic response of a structural system is thought of as the integration of the equations of motion for the structure; (2) The integration of the system of equations is done by a hybrid mix of numerical and analog computing. In practice, this means that part of the structural system is physically present in the laboratory and the remainder is represented by a computer model. Both parts of the structure are subjected to dynamic excitation and they interact via a system of sensors and actuators in real- and/or pseudo-time [10]. Fig. 1 provides a schematic of the setup. Its advantage comes about when one can place the bulk of the structure in the computer due to a confidence in its model; the physical part typically represents a subset of the structure for which one does not have a good model; see e.g. [11].

Despite the long history of hybrid-testing, very little is understood about the theoretical errors involved when one uses this methodology to simulate the response of a structure. The bulk of the literature on hybrid-testing has focused on improving the accuracy and speed of the numerical computation and the fidelity of the control system [12–14] – all with the implicit assumption that improvements in these aspects will render a result that is more faithful to an untested physical reality. There have also been attempts to see how the location of the hybrid interface can affect the overall dynamics of the hybrid system [15]. Recently, however, efforts have been put forth to try and understand the theoretical limitations of hybrid testing [16,17] independent of the systematic and random errors that arise from numerical issues and sensor errors. These works utilized a reference structural system that was fully theoretical, split the system into fictitious physical and computational parts, and then explored the fidelity of the hybrid equations with respect to the reference equations. In this way, the true dynamical response of the reference system was known *a priori* in analytic form and could be compared to the hybrid-system response which was also known in analytic form. The overall methodology thus illuminated directly the central feature of all hybrid simulation methodologies – viz., the presence of a split system that is patched together with an imperfect interface.

The works of [16,17] focused on two linear structural systems – Euler-Bernoulli beams (elastic and viscoelastic) and Kirchhoff-Love plates (elastic). In this paper, we attempt to extend this analysis framework to a nonlinear dynamical system in order to understand the behavior of hybrid-simulation in the presence of kinematic nonlinearities. We solely consider the *theoretical* performance of real-time hybrid simulation as an experimental method, ignoring all of the numerical and random errors, as this leads to a best case scenario for a hybrid experiment; see e.g. [2] or [18]. This approach eliminates the errors associated with time integration methods and signal noise and focuses only on the errors that are generated by systematic interface mismatch errors – an element that is always present in hybrid simulations. As a model problem we focus upon the damped, driven nonlinear pendulum; see [19] for an in depth analysis of the dynamics of this system. This system is one of the most basic nonlinear systems that has a clear physical representation. Despite the simplicity of this system, it has a wide variety of properties that make it interesting to study. For instance, this system exhibits a rich dynamical response with both periodic and chaotic trajectories. We can use these two behaviors to help us study how a hybrid split affects the overall dynamics of a nonlinear mechanical system. We also include a spring-mass-damper actuator system which is controlled by a PI controller. This setup for the hybrid system gives a more advanced representation of the hybrid system in comparison to the constant error methodology used in [16,17].

2. General theory of hybrid simulation

In this section we will set up a general framework for thinking about hybrid simulation.

2.1. The reference system

First, we need to set up the reference system to which the hybrid system will be compared. A mechanical system with domain $\mathcal{D}$ is considered, as shown in Fig. 2a. The mechanical response of the system is characterized by a state vector,

Please cite this article as: P.L. Drazin, & S. Govindjee, Hybrid simulation theory for a classical nonlinear dynamical system, *Journal of Sound and Vibration* (2016), http://dx.doi.org/10.1016/j.jsv.2016.12.034

Download English Version:

https://daneshyari.com/en/article/4924373

Download Persian Version:

https://daneshyari.com/article/4924373

Daneshyari.com