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Model-less forecasting of hopf bifurcations in fluid-structural systems

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ABSTRACT

Predicting critical transitions and post-transition dynamics of complex systems is a unique challenge. In this paper, a novel approach is introduced to forecast Hopf bifurcations and the post-bifurcation dynamics of nonlinear fluid-structural systems. The forecasting method is model-less and uses measurements of the system response collected only in the pre-bifurcation regime. To demonstrate the method, it is applied to a cantilever high aspect ratio wing exposed to gust loads as perturbations. To generate surrogate measurements required for forecasting bifurcations in this large-dimensional complex system, a nonlinear strain-based finite element formulation coupled with unsteady aerodynamics is used to model the fluid–structure interaction. Results show that the method successfully forecasts the linear flutter speed and the amplitude of the limit cycle oscillations that occur in the post-bifurcation regime. The procedure is shown to be time efficient, model-less, and to require only few measurements, which makes the proposed forecasting method a unique tool for nonlinear analysis of complex systems.

1. Introduction

A pervasive need for engineered systems when creating new designs is to improve the efficiency of existing systems while ensuring safety and reliability. Such new designs may be complex both in shape and dynamics, and often exhibit nonlinear behavior.

Studying the dynamics of nonlinear structures is an important engineering topic because such systems can exhibit a wide variety of possible behaviors. Hence, the dynamic response of such systems needs to be accurately evaluated under different operational conditions. More specifically, it is important to study the dynamic stability of systems when some of their parameters are varied, and that includes the study of their bifurcations. Bifurcations occur in the dynamics of complex nonlinear systems and lead to different types of instability problems.

There are many studies focused on analysis and identification of bifurcation diagrams in nonlinear systems. These methods apply to systems with a known model and vary from common time-marching (Patil et al., 2001; Tang and Dowell, 1993), to normal forms and nonlinear normal modes (Nayfeh, 2011; Vakakis, 1997), to multiple scales (Ghommem et al., 2010; Luongo, 2015), and to harmonic balance (Liu and Dowell, 2005; Raghothama and Narayanan, 1999), to name a few. Although these methods are well capable of identifying bifurcations and build their diagrams, they have drawbacks that make them difficult or impossible to use for a variety of large dimensional systems frequently encountered in real applications. First, these methods are model-based and creating an accurate model for the desired system can be infeasible

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or impractical especially when the system is exceedingly complex. Second, even if a mathematical model is established, due to complex dynamics and nonlinearity, massive theoretical and numerical computations are required to analyze its dynamics. Furthermore, models may be incomplete or inaccurate due to assumptions and uncertainties as well as due to parameter variations over time, making the accurate representation of the system a challenge in itself.

Similar to theoretical and computational methods, experimental methods to determine bifurcations and bifurcation diagrams of complex systems have their own challenges. For example, some methods are only capable of predicting the bifurcation point (Lind et al., 1998). Other methods include nonlinear analysis and system identification (Kukreja and Brenner, 2006; Rico-Martınez et al., 2003), but they need large sets of data and have difficulties in identifying complex nonlinear system parameters. Other approaches include set-and-observe methods (Rico-Martınez et al., 2003), i.e. place the system in different operational conditions including the post-bifurcation regime to construct the bifurcation diagram. However, this is not an easy task and may also result in the collapse of the system.

Therefore, nonlinear analysis of large dimensional complex systems is still a unique challenge. To address this challenge and due to the importance of the topic, a new method of forecasting bifurcations has been introduced (Lim and Epureanu, 2011), and further developed (Ghadami and Epureanu, 2016a) for large dimensional oscillatory systems. The approach is based on the phenomenon of critical slowing down which accompanies many bifurcation phenomena including flutter, i.e. when the systems is close to the bifurcations, perturbations lead to long transient oscillations before the system reach to its stable state. This approach is capable of forecasting not only the distance to bifurcations but also the dynamics of system in the post-bifurcation regime. The unique feature of the method is that it is model-less: no mathematical model of the system is required for forecasting. Hence, it is applicable to complex nonlinear systems where a model of the system is not available, or where analysis would require massive computations. To forecast the bifurcation diagrams using this method, one measures several system responses to perturbations in the pre-bifurcation regime. As a result, the method is computationally efficient and is safe in real applications since the system is never placed in the potentially dangerous post-bifurcation regime. In those previous studies, the bifurcation forecasting method was applied to forecast bifurcation diagrams in a feedback controlled beam (Lim and Epureanu, 2011) and in ecological systems (D'Souza et al., 2015). These have a different physical behavior than oscillatory, aeroelastic systems. The forecasting method was developed further to be applied to systems exhibiting Hopf bifurcations (Ghadami and Epureanu, 2016a, b). Challenges related to oscillatory systems were addressed. For example, the co-existence of several active modes the measurements was addressed in Ghadami and Epureanu (2016a), and the need for a precise approximation of the recovery rate of slow oscillatory systems where the number of local peaks is very small and not enough for an accurate forecasting was accounted for in Ghadami and Epureanu (2016b).

An important class of nonlinear complex engineering systems prone to subcritical and supercritical Hopf (flutter) bifurcations is the fluid-structural interaction (Dowell et al., 2004; Lee et al., 1999, 1997; Kim and Strganac, 2002; Amabili, 2008; Amabili and Pellicano, 2001, 2002). These phenomena can cause dramatic changes in the system dynamics typically resulting in loss of performance is possible is total failure. Hence, one of the demanding topics of research in fluid–structure interactions is predicting the speed above which the system becomes linearly unstable, i.e. determining the flutter speed. Furthermore, identifying the flutter type (supercritical and subcritical) and the limit cycle amplitude beyond the flutter speed are also important especially when operating close to the linear flutter boundary.

This paper focuses on a forecasting method for Hopf bifurcations in complex large dimensional fluid-structural systems. The method is applied to forecast the flutter speed and the bifurcation diagrams of a cantilever flexible high aspect ratio wing as an example of nonlinear large dimensional fluid-structural system with complex fluid-structural interaction. The large dimensionality of the system causes modal interactions and allows for much more complex physical behaviors that those explored in Ghadami and Epureanu (2016a, b). Results show that the forecasted flutter speed and the bifurcation diagrams have good accuracy compared to their exact values.

2. Forecasting methodology

In this section, a bifurcation forecasting approach is introduced and adjusted to enable forecasting flutter bifurcations based on observations of the transient response of large-dimensional fluid-structural systems in the pre-bifurcation regime. Here, only the main changes made to previous approaches (e.g., Ghadami and Epureanu, 2016a), and the main concepts and steps of the new forecasting method are described.

In fluid-structural systems with Hopf (flutter) bifurcations, the system oscillates during its recovery in response to perturbations in the pre-bifurcation regime. Its recovery rate from perturbations depends on the distance to the bifurcation, i.e. the difference between the current flow speed and the flutter speed. When system approaches the bifurcation, transient oscillations last longer before the system reaches equilibrium, which means that the rate of recovery decreases. This phenomenon is known as critical slowing down (Fig. 1). The proposed method uses this phenomenon to identify the distance to the bifurcation.

There are several requirements for the forecasting method to be accurate. A first requirement is that the system is close enough to the bifurcation as to exhibit measurable slowing down in its recoveries. Moreover, measurements containing identifiable parts are on the inertial manifold to ensure that changes in the recovery rates are due to the slowing down phenomenon. The inertial manifold is an invariant set where the dynamics is slowest in time and contains main features of the system. Thus, this manifold is the slowest, and if the system starts from a state in this set, it remains in that set at all times. A second requirement is that the system dynamics and its inertial manifold vary smoothly with the bifurcation parameter, which is the flow speed in the current study.