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Efficient unsteady aerodynamic loads prediction based on nonlinear system identification and proper orthogonal decomposition

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ABSTRACT

In the present work, an efficient surrogate-based framework is developed for the prediction of motion-induced surface pressure fluctuations and integral force and moment coefficients. The model construction is realized by performing forced-motion computational fluid dynamics (CFD) simulations, while the result is processed via the proper orthogonal decomposition (POD) to obtain the predominant flow modes. Subsequently, a nonlinear system identification is carried out with respect to the applied excitation and the resulting POD coefficients. For the input/output model identification task, a recurrent local linear neuro-fuzzy approach is employed in order to capture the linear and nonlinear characteristics of the dynamic system. Once the reduced-order model (ROM) is trained, it can substitute the flow solver within unsteady aerodynamic or aeroelastic simulation frameworks for a given configuration at fixed freestream conditions. For demonstration purposes, the ROM approach is applied to the LANN wing in high subsonic and transonic flow. Due to the characteristic lambda-shock system, the unsteady aerodynamic surface pressure distribution is dominated by nonlinear effects. Numerical investigations show a good correlation between the results obtained by the ROM methodology in comparison to the full-order CFD solution. In addition, the surrogate approach yields a significant speed-up regarding unsteady aerodynamic calculations, which is beneficial for multidisciplinary computations.

1. Introduction

Unsteady aerodynamic phenomena and fluid-structure interaction effects are playing an important role with respect to safety requirements and environmental sustainability of existing and future highly-flexible aircraft. Especially, the flight at transonic flow conditions is still challenging for aeroelastic analyses. This is because the highly-efficient, linear approaches based on potential flow theory are not suited to capture the nonlinear characteristics of a transonic flow field. In contrast, sophisticated computational fluid dynamics (CFD) methods based on the Euler (Eu) or Reynolds-averaged Navier-Stokes (RANS) equations are able to reproduce the flow-induced loads at significantly higher accuracy. In this context, the position and strength of shock waves separating subsonic and supersonic flow regimes are estimated with sufficient fidelity, which can have a crucial influence on the local pressure distribution as well as on the integral forces and moments (Bendiksen,

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2011). However, a CFD-based aeroelastic analysis increases the numerical cost substantially due to the large number of parameter permutations (number of structural degrees of freedom, freestream Mach numbers, incidence angles, flap angles etc.) in combination with the high effort for each individual simulation.

For this reason, the development of reduced-order models (ROMs) in terms of aeroelastic predictions or (local) loads estimations is a research area of rising importance. The objective of these auxiliary models is the reduction of the full-order flow problem to a numerically less costly and simpler system description under the premise that the essential static and dynamic characteristics of the underlying system are preserved. Within the present work, a ROM is considered as a mathematical framework conditioned by high-fidelity CFD simulations in order to fulfill a specified prediction task. Recently, several ROM concepts have been published for fluid-structure interaction applications. In the following, a brief description of the context-relevant approaches is given.

In the last decade, Lucia et al. (2004) and Dowell and Hall (2001) presented a comprehensive overview of some established reduced-order techniques; e.g., harmonic balance (HB) (Thomas et al., 2002), Volterra theory (Silva, 1997; Raveh, 2001), and proper orthogonal decomposition (POD), while showing their application to unsteady aerodynamic as well as aeroelastic test cases. The latter method, namely the POD, is a popular parameter reduction technique used by various authors within the aeroelasticity and fluid dynamics community. The application examples vary from steady to unsteady two- and three-dimensional flow field decompositions (see Lucia et al., 2003; Hall et al., 2000; Willcox and Peraire, 2002; Iuliano and Quagliarella, 2013 for instance). The basic idea of the POD is to describe the flow by means of a comparatively small set of representative modes and, thereby, reduce the degrees of freedom of the underlying problem. Hence, there is an analogy between the modal transformation applied within the structural mechanics community and the POD usage in terms of aerodynamic ROMs. Several variants can be found in the literature to incorporate the POD approach into time and frequency domain CFD solvers. Though, the focus in this work is on the utilization as a post-processing tool, which leads to the so-called snapshot method (see Sirovich, 1987).

Beyond the previously introduced methods, the use of linear and nonlinear system identification techniques is suggested in various references in order to obtain an efficient model for the prediction of integral aerodynamic forces. A well-known example from this branch is based on the eigensystem realization algorithm (ERA) that is employed by Silva and Bartels, 2004 to construct a linear time-invariant (LTI) state-space model. Moreover, some linear aerodynamic ROMs have been derived from the external dynamics/recurrence framework approach, which is a well-known system identification concept (Ljung, 1999). Examples regarding these ROMs are the autoregressive moving average (ARMA) (Raveh, 2004; Won et al., 2005) and the autoregressive with exogenous input (ARX) method (Zhang and Ye, 2007). The aforementioned models are suited to capture the linear dynamic characteristics around linear and nonlinear reference states, i.e., subsonic, transonic, and supersonic steady-states. However, when the dynamical system behavior is governed by nonlinear effects, a nonlinear model architecture has to be trained and employed. Nonlinear dynamics can result from large amplitude motions and the associated moving shocks. Another possible source of nonlinearities is the laminar-turbulent transition or the presence of separation phenomena induced by the flow's viscosity.

Consequently, various methods based on nonlinear system identification (NSI) principles have been developed. In 1997, Faller and Schreck (1997) proposed a recurrent multi-layer-perceptron neural network (MLP-NN) for the identification of experimentally gathered aerodynamic coefficients. Subsequently, Marques and Anderson (2001) used a multi-layer-based temporal neural network to predict unsteady aerodynamic forces in transonic flow. Consequently, Voitcu and Wong (2003) demonstrated the suitability of neural networks for modeling the dynamic behavior of aeroelastic systems. Subsequently, Zhang et al. (2012) and Winter and Breitsamter (2014) employed radial basis function neural networks (RBF-NN) for the accurate modeling of unsteady aerodynamic force coefficients in transonic flow. Recently, Winter and Breitsamter (2016) utilized local linear neuro-fuzzy models to construct an unsteady aerodynamic ROM that is valid across a range of freestream Mach numbers covering the subsonic, transonic, and supersonic flight regimes.

Additionally, some combinations of the methods originating from system identification principles with the POD-based approaches have been published. Within an aeroelastic optimization framework, Park et al. (2013) employed the POD and a neural network for the ROM construction with respect to static flow fields. Recently, a successful combination of a RBF-based nonlinear system identification approach (Zhang et al., 2012) with the POD had been proposed by Lindhorst et al. (2014) and Lindhorst et al. (2015).

In the present work, a surrogate modeling approach based on neuro-fuzzy models and proper orthogonal decomposition is proposed for the prediction of motion-induced surface pressure fluctuations. Therefore, nonlinear system identification and parameter reduction are conjointly used for efficient unsteady aerodynamic computation purposes. Here, a recurrent input-output-optimized model is applied, which employs the feedback of the neuro-fuzzy model to realize a highly-efficient, low-dimensional reduced-order model. Concerning the calibration of the surrogate model, a finite set of forced-motion CFD-based training samples is exploited to extract the embedded system information. Therefore, the POD is carried out with respect to the unsteady pressure coefficient distribution to extract the dominant flow modes. Subsequently, the neuro-fuzzy model is utilized to train the dynamic relationship between the excitation and the corresponding POD coefficients. The presented multidisciplinary approach is applied to the LANN wing (Zwaan, 1982) undergoing a pitching motion in order to demonstrate and validate the method. For this purpose, the aerodynamic loads predicted by the ROM are compared with the corresponding time-accurate CFD results in the high subsonic and transonic flow regime. Furthermore, the time-domain surface responses induced by harmonic pitching motions are transformed into the frequency domain via Fourier analysis in order to show the method's potential for classical aeroelastic analyses. Finally, the integral force and