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Efficient reduced-order modeling of unsteady aerodynamics robust to flight parameter variations

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A B S T R A C T

In this study, a computational fluid dynamics (CFD) based reduced-order modeling (ROM) approach robust to flight parameter variations is presented. The approach, which uses Kriging surrogates and recurrence frameworks together for unsteady aerodynamic loads predictions, does not need to reconstruct the ROM with flight parameters changes. To illustrate the approach, the aeroelastic problem of a NACA 64A010 airfoil undergoing pitching and plunging motions at zero mean angle of attack is studied. The results predicted via the proposed approach agree well with those obtained via the high-fidelity CFD solver over the selected range of Mach numbers.

1. Introduction

The techniques of computational fluid dynamics (CFD) have played an important role in the design of various flight vehicles, ground vehicles, and ships. Yet, high-fidelity CFD solvers based on either Euler equations or Navier–Stokes equations require expensive computational costs, especially for the computation of unsteady aerodynamic loads. Hence, the linear doublet-lattice method is most frequently used for the aeroelastic analysis in engineering although CFD techniques are more accurate. As a matter of fact, the double-lattice method is inaccurate for geometrically complex problems and valid for the subsonic regime only. The ideal aerodynamic model is simple and computationally efficient, but accurate enough. Thus, increasing attention has been paid to CFD based reduced-order models (ROMs), which meet these requirements and provide an effective way to model unsteady aerodynamic loads. Once constructed, ROMs run orders of magnitude faster than full CFD simulations, and preserve a high level of accuracy.

In recent years, many studies on the ROMs for unsteady aerodynamics have been performed. These studies can be classified into two types. One is based on the flow eigenmode characteristics and the other on the system identification. The first type of ROMs for unsteady aerodynamics is mainly based on the Proper Orthogonal Decomposition (POD) approach developed by Beran et al. (2004), Dowell et al. (2004) and Thomas et al. (2003) and the Harmonic Balance (HB) approach proposed by Liu et al. (2007), Thomas et al. (2004) and Ekici et al. (2013). To construct a ROM via either POD approach or HB approach, it is necessary to change the high-fidelity CFD solvers accordingly. On the contrary, the ROMs based on the system identification are sought from the input and output time histories obtained from high-fidelity CFD solvers. This type of ROMs mainly includes the Volterra expansion proposed by Silva (2005) and Balajewicz et al. (2010), the linear state space model via eigen-system realization algorithm proposed by Silva (2007) and Silva and Bartels (2004), the Auto Regressive-Moving-Average

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(ARMA) model identified from CFD response to a 3211 signal developed by Cowan et al. (2001), the surrogate models via artificial neural networks proposed by Zhang et al. (2012) and Marques and Anderson (2001), the radial basis function interpolation and Kriging technique proposed by Mackman et al. (2013). The Volterra expansion is accurate only for the case of weak nonlinearities and the Volterra kernels of a nonlinear dynamic system are difficult to compute as shown by Ghoreyshi et al. (2013). The linear state space model and the ARMA model are constructed under the same basic assumption of small perturbations about the steady-state flow as shown by Raveh (2004). Compared with other ROMs for unsteady aerodynamics in previous studies, the study on surrogate models has called much attention recently as shown by Queipo et al. (2005), Glaz et al. (2013) and Mannarino and Mantegazza (2014).

Although a significant progress has been made on the ROMs for unsteady aerodynamics, almost all aforementioned ROMs are only valid for fixed flight conditions. For example, an ARMA-based ROM is very sensitive to the free-stream Mach number and even a tiny change of Mach number requires a new ROM. It is very time-consuming, therefore, to generate the ROMs applicable to a range of parameters. However, many engineering problems, such as the optimal design of aeroelastic systems and aeroservoelastic systems, must deal with parameter changes. A successful ROM, hence, should be robust to the variation of parameters, such as the Mach numbers. Glaz and his co-workers used a surrogate-based recurrence framework ROM to model the unsteady aerodynamics on a rotating airfoil as shown by Glaz et al. (2010). Yet, they had to take a few independent parameters for harmonic input signals to construct the surrogate model and required large computational costs to obtain enough training information. Amsallem presented a ROM adaptation approach based on the interpolation in a tangent space to a Grassmann manifold as shown by Amsallem et al. (2010). It should be noted that reduced-order basis vectors of different local ROMs, which are inaccessible for system identification method, have to be known at first. Skujins proposed a single ROM which can be applied to multiple Mach regimes by combining linear convolution with a nonlinear correction factor as shown by Skujins and Cesnik (2012). As presented in their study, however, a distinct phase shift was observed at higher oscillation frequencies.

The motivation for this study is to construct a single ROM robust to flight parameter variations. For this purpose, a ROM approach based on Kriging techniques and recurrence solutions is presented. Filtered White Gaussian Noise (FWGN) is chosen as the input signal to reduce the number of independent parameters, which leads to a decrease in the computational cost for the generation of the training data. To illustrate this cost-effective approach, a NACA 64A010 airfoil undergoing pitching and plunging motions is considered. The Mach number is taken as a part of the input data of the Kriging interpolations and two ROMs, one for lift coefficient C_l and the other for moment coefficient C_m, valid over a range of Mach numbers, are constructed. The unsteady aerodynamic loads and the aeroelastic responses of the airfoil simulated by using the ROMs agree well with those obtained by using CFD over the selected range of Mach numbers.

The remainder of this paper is organized as follows. In Section 2, the ROM based on surrogate models is presented. Then, the main parts of the ROM approach are presented in Section 3. In Section 4, two ROMs valid over a range of Mach numbers are constructed. The predicted unsteady aerodynamic loads on a NACA 64A10 airfoil at two Mach numbers are used to assess the validity of the generated ROMs. The ROMs are coupled with a structural model to make a time-marching simulation. In Section 5, some conclusions are given.

2. Reduced-order models based on surrogate models

The nonlinear and unsteady aerodynamics of concern can be considered as the relation of Multiple-Input and Multiple-Output (MIMO) of a time-invariant discrete-time dynamic system, which yields

$$\begin{cases} \boldsymbol{x}(k+1)=\boldsymbol{f}(\boldsymbol{x}(k),\boldsymbol{u}(k)), \\ \boldsymbol{y}(k+1)=\boldsymbol{g}(\boldsymbol{x}(k+1)), \end{cases} \tag{1}$$

where k is an integer representing the discrete time. The state function $\boldsymbol{f}$ is a smooth function that converts the current state $\boldsymbol{x}(k)$ and the input vector $\boldsymbol{u}(k)$ to a new state $\boldsymbol{x}(k+1)$. The output function $\boldsymbol{g}$ maps the new state $\boldsymbol{x}(k+1)$ to the output $\boldsymbol{y}(k+1)$. The output $\boldsymbol{y}(k+1)$ is the aerodynamic loads at time moment $k+1$. The state vector $\boldsymbol{x}$ consists of the flow states, i.e., density, velocity components, and pressure, at each grid point in the computational space associated with high-fidelity CFD solvers. Therefore, the dimension of the state vector $\boldsymbol{x}$ is proportional to the number of grid points which always have the order of millions. Hence, the large amount of data results in a time-consuming task for computation of Eq. (1). Eq. (1) represents the computationally expensive system of full orders, which should be replaced with ROMs.

Leontaritis and Billings (1985) and Levin and Narendra (1996) presented that if the dimension of the state vector $\boldsymbol{x}$ is finite, the input/output relationship given by Eq. (1) is equivalent to the nonlinear system as follows:

$$y_i(k)=\Phi_i(\boldsymbol{u}(k),\boldsymbol{u}(k-1),\ldots,\boldsymbol{u}(k-m),y_i(k-1),\ldots,y_i(k-n)), \tag{2}$$

where Φ_i is a nonlinear function that maps the input to the ith component of the ouput $\boldsymbol{y}$. The terms m and n represent the number of past values of the input and output, respectively, and these two parameters account for the time-history effects of unsteady aerodynamics. Eq. (2) preserves the characteristics of the state-space model, but eliminates the dependence of the system state vector $\boldsymbol{x}$. The computation of the nonlinear function Φ is the central problem of the ROM generation. Without a closed-form expression, the nonlinear function Φ can be approximated by using the surrogate-based methods which interpolate the CFD-based input–output data to generate an approximated surrogate mapping function $\hat{\Phi}$.