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Efficient nonlinear reduced-order modeling for synthetic-jet-based control at high angle of attack

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ABSTRACT

A low dimensional model for synthetic jet control has been developed which uses Kriging surrogate to predict the unsteady aerodynamic loads and the nonlinearities at high angle of attack. First, parametric analyses are performed by Computational Fluid Dynamics (CFD) to study the effect on the improvement of aerodynamic characteristics for different governing parameters, especially cavity shape. It is found that the proposed cavity shape could enhance the aerodynamic performance of active flow control. Further, for the optimized cavity shape, the nonlinear Reduced-Order Model (ROM) of synthetic jet control is constructed via Kriging surrogate, and the accuracy and efficiency of the proposed ROM are validated by comparing with the direct CFD solutions. The simulation results show that the established ROM can mimic the nonlinear and unsteady aerodynamic response of synthetic jet control accurately without exhaustive computational resources.

1. Introduction

Flow separation on the upper surface of an airfoil, which often occurs at high angle of attack, would result in the sharp drop of lift along with the rise of drag. To improve the aerodynamic performance of airfoil after the stall angle, synthetic jet control located near the separation point has been used to prevent or delay the separation of the flow, which is governed by the interactions between the vortex pairs shed from leading and trailing edges [1,2]. For its low weight and minimal mechanical complexity, synthetic jet actuator has a good potential in application for active flow control, flight stability, acoustic control and flutter suppression [3–6].

A challenge in synthetic jet control is to tackle the impact of lots of parameters on aerodynamic performance. Xu and Zhou [7] studied the effects of forcing frequency, blowing magnitude and actuator position on the improvement of the aircraft's longitudinal stability. It was found that the larger blowing magnitude can yield an evident increase in the effectiveness of the active flow control. He et al. [8] performed parametric analysis for the synthetic jet control about forcing frequency, blowing magnitude, blowing direction and actuator position. Their results indicated that the synthetic jet control is not sensitive to the blowing direction when the blowing magnitude is high. Hassan [9] pointed out that aerodynamic lift can be improved mostly when the blowing direction is at 25°. Zhao and his co-worker [10] studied the effects of jet angle and jet arrays on the performance of aerodynamic forces over a rotor airfoil. The numerical simulations suggested that reasonable combinations of jet arrays have better effect than a single jet actuator on improving the aerodynamic performance. Besides, other key factors of synthetic jet control were considered to delay or prevent the separation of the flow more efficiently, such as duty cycle of actuation [11], arrays of multiple-orifice [12], synthetic jet location [13], and spanwise actuator density [14]. Yet, the effect of cavity shape on the improvement of the aerodynamic characteristics had not been taken into account in previous works.

Because of the aerodynamic nonlinearities of synthetic jet control at high angle of attack, high-fidelity CFD solver has become the most reliable tool to predict the nonlinear unsteady response of the aerodynamic systems. However, those computations based on CFD solver require expensive computational costs. To capture the physics of synthetic jet control more efficiently, it is necessary to construct ROM instead of the expensive full-order CFD model to predict the aerodynamic response. At present, the methods for reducing the order of an unsteady aerodynamic system can be mainly classified into two types: the first method for constructing ROMs is mainly based on the Proper Orthogonal Decomposition (POD) technique; the others are based on the system identification

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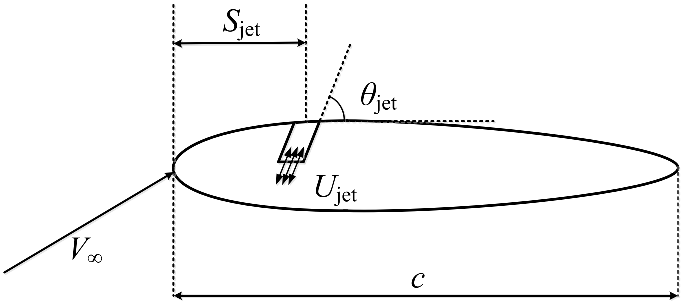

Fig. 1. Impact parameter of synthetic-jet control.

technique which is sought from the input and output information from the full-order system. Dowell et al. [15] and Thomas et al. [16] proposed the POD-based ROMs to analyze the nonlinearity and aeroelasticity in the transonic flow regime. Recently, Caraballo et al. [17] and Rediniotis et al. [18] derived the ROMs of synthetic jet control via the POD method to reveal the nonlinear characteristics of flow field. To build the ROM with flow eigenmode characteristics, the CFD solver has to be changed accordingly. Likewise, the ROMs based on the system identification, which doesn't consider the inside information of flow field, can be developed efficiently via the input/output relationship of the high-fidelity CFD solution. Silva [19–21] established the ROMs via Volterra expansion and eigensystem realization algorithm. Cowan et al. [22] presented the ROMs based on the Auto Regressive-Moving-Average (ARMA) model. Zhang et al. [23] developed the surrogate-based ROM using artificial neural networks to study the nonlinearities presented in the transonic flight regimes. Huang et al. [24] proposed a novel nonlinear ROM for multi-input/multi-output aerodynamic system and analyzed the transonic flutter of the Isogai wing model. Glaz et al. [25] provided a Surrogate-Based Recurrence Framework (SBRF) ROM for predicting the unsteady aerodynamic loads of a rotating airfoil. Besides, Gallas [26,27] constructed the ROM for the synthetic jet control system by using the lumped element method, the individual components of a synthetic jet were envisioned as elements of an equivalent electrical circuit wherein. Furthermore, the equivalent model gives an accurate prediction of frequency-response functions of a fourth-order coupled oscillator. Based on the Theodorsen aerodynamic forces, Schober et al. [28] presented a ROM to predict the response frequency with a static offset in the lift coefficient. Yamaleev et al. [29] proposed a new ROM via quasi-one-dimensional Euler equations for the prediction of active flow control, which is more efficient than the two-dimensional Navier–Stokes (NS) formulation. Although lots of ROMs for unsteady aerodynamics had been developed, few ROMs of synthetic jet control were constructed via the system identification method.

This paper concentrates on enhancing the aerodynamic performance and building the efficient nonlinear ROM of synthetic jet control at high angle of attack. The contributions of this work are: (1) A novel cavity shape is proposed to further enhance the aerodynamic characteristics of synthetic jet control; (2) No attempt is made to predict such nonlinear and unsteady aerodynamic response of synthetic jet control system after the stall angle efficiently and accurately via the surrogate-based ROM. Hence it is desirable to establish a nonlinear ROM under different combinations of pitch and plunge excitation with a wide range of frequencies, which is extremely useful for control purposes [28], aeroelastic analysis [38,39] and so on.

The paper is organized as follows. Section 2 briefly describes the concerned problem and the governing parameters of synthetic jet control. Section 3 studies the effects of the governing parameters on the improvement of aerodynamic characteristics. Section 4 constructs the nonlinear ROM via Kriging surrogate to predict the unsteady response of synthetic jet control. Section 5 gives conclusions.

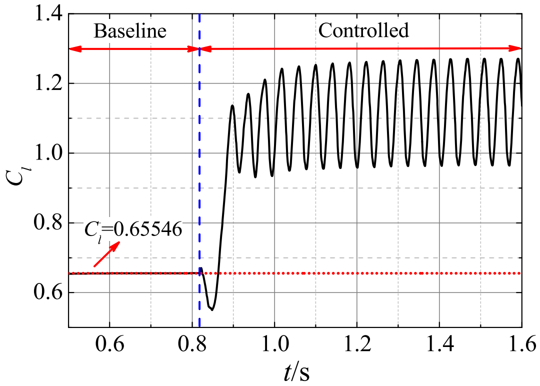

Fig. 2. Effect of synthetic jet control on unsteady lift coefficient.

2. Problem description

The impact parameters for the performance of synthetic jet control involve forcing frequency f, blowing magnitude $\bar{U}_{jet}$, blowing direction θ_{jet}, actuator position S_{jet}, and cavity shape, as shown in Fig. 1. A blowing/suction type velocity boundary condition is set to model the oscillation at the bottom of the orifice, namely

$$U_{jet} = \bar{U}_{jet} \sin 2\pi f t \tag{1}$$

The nature of separated flow is governed by the interactions between synthetic jet and the shedding vortex.

The control effect of synthetic jet control over the NACA 0015 airfoil at 18° angle of attack is shown in Fig. 2. The result indicates that the synthetic jet is capable of controlling the separated flow effectively and leading to a significant improvement on the lift coefficient. However, the aerodynamic characteristics of synthetic jet control are influenced by several parameters. It is necessary to study the effects of different parameters of synthetic jet on the control efficiency.

3. Parametric analysis of synthetic jet control

In this section, lots of numerical simulations are generated to reveal the effects of the governing parameters on the improving of aerodynamic performance.

The numerical simulations in this study are performed by using the commercially available code CFD++, which is able to solve the compressible unsteady N-S equations [30]. The Reynolds-Averaged Navier–Stokes equations and the Shear Stress Transport model are employed to analyze the synthetic jet control over NACA 0015 airfoil at 18° angle of attack. The C-grid about the airfoil shown in Fig. 3a is generated by Pointwise software. To minimize the influences of numerical reflection from the far-field boundary, the