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Reduction of transonic buffet onset for a wing with activated elasticity

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ABSTRACT

Transonic buffet, a kind of aerodynamic instability at a certain combination of Mach number and angle of attack, limits the aircraft flight envelope and fatigue life. The traditional method on transonic buffet onset prediction has an obvious limitation for an elastic wing, which ignores the feedback of oscillatory structure to the fluid. In this paper, the reduction of transonic buffet onset is observed when the feedback is considered for a wing with an activated pitching degree of freedom; that is, buffet will be provoked at some special structural parameters in pre-buffet flow conditions. This phenomenon is not caused by the static deformation of the structure but the coupling effect between fluid and structure. Besides, the dynamical characteristic and instability mechanism are significantly different from the SDOF (single degree of freedom) flutter [18]. The SDOF flutter is caused by the instability of the structural mode, and the flutter frequency locks into the structural frequency, while the present instability is governed by the fluid mode and the coupling frequency follows the buffet frequency in post-buffet conditions.

1. Introduction

In the transonic flight regime, shock–boundary layer interactions give rise to large-amplitude self-sustained shock oscillations and dramatic lift fluctuations. This phenomenon, commonly known as transonic buffet, is in essence the result of global fluid mode instability [1–4]. Transonic buffet, especially the consequent unsteady load, acts as a negative impact on the aircraft performance, diminishing handing quality and fatigue life. It is no doubt that the study on transonic buffet has significant theoretical and practical values in aeronautical engineering [5–7].

Prediction of buffet onset is one of the important research topics in the field of transonic buffet. Buffet onset is a certain combination of Mach number and freestream angle of attack, which is the boundary of the shock shifting from the stationary status to the oscillatory. In the classical conception of aeroelasticity, transonic buffeting is a dynamic response of an aircraft structure, such as a wing, to unsteady buffet loads [8,9]. As a result, the traditional transonic buffeting analysis, for a long time, has been divided into two steps—first predict the buffet onset and buffet loads towards the rigid wing and then calculate the vibration level of the actual elastic wing under preceding buffet loads. However, this process ignores the feedback effect of the oscillatory structure on the buffet flow, which dramatically simplifies the difficulty of the analysis in industrial application. Based on such traditional viewpoint, previous investigations on transonic buffet mainly focus on the prediction of buffet onset and buffet loads with regard to the rigid wing/airfoil.

Moreover, traditional uncoupled buffeting analysis has an obvious limitation—the actual aircraft wing must be elastic, and the interaction between transonic flow and elastic structure often cannot be ignored. Some wind tunnel experiments conducted on the spring-suspended wing section [10] or the flexible transport-type swept-wing configuration [11] have explicitly shown the transonic buffeting loads can cause a significant fluid–structure interaction (FSI) that is strong enough to dominate the system dynamics. Besides, many complex aeroelastic phenomena in transonic regime are associated with the FSI in transonic buffeting flow. Zhang et al. [12] investigated the interaction between classical bending-torsion flutter and transonic buffet by numerical simulations. Due to the FSI effect, the resulting response is a form of nodal-shaped oscillation of alternating diverging and damped behavior. In addition, frequency lock-in is another abnormal phenomenon, in which the response frequency does not follow the buffet frequency but locks into the structural frequency. Some researchers attributed it to the nonlinear resonance from the framework of the traditional buffeting analysis [13–16]. Very recently, Gao et al. [17] clarified that the physical mechanism under frequency lock-in in transonic buffeting flow is the coupled-mode flutter. Elastic characteristic, therefore, is an important factor in the study of transonic buffeting phenomenon.

Gao et al. [18] also provided an insight into the dynamics of the spring-suspended NACA0012 airfoil in pre-buffet flow conditions

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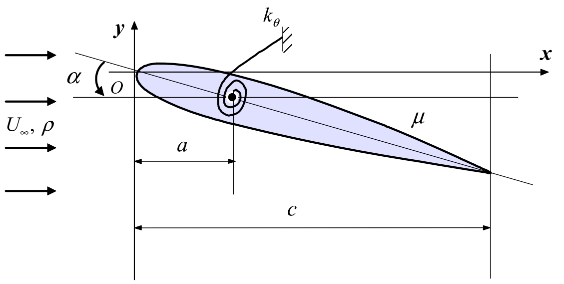

Fig. 1. Schematic of the NACA0012 airfoil with activated elasticity which can free vibrate in the pitching DOF.

through numerical simulations and reduced-order model (ROM) analysis. It is found that the instability of the structural mode, namely the single-degree-of-freedom (SDOF) flutter, will be provoked with the coupling of a structural mode and a sub-stable fluid mode. This study inspired us to further explore the following questions. Whether the instability of a fluid mode, namely the transonic buffeting phenomenon, will be provoked in the pre-buffet condition of a wing with activated elasticity? What are the dynamical differences between the flutter-pattern instability and the buffeting-pattern instability? Answers to above questions are crucial to understand the buffet onset and buffeting loads for an actual elastic wing. Therefore, in the present study we construct a linear ROM-based FSI model with the assumption of a small disturbance, and then use this model to investigate the effect of elastic characteristics on the buffet onset and dynamical responses in pre-buffet flow conditions. The CFD/CSD simulation is employed to verify the results by providing the details of unsteady flows and structural responses.

2. Investigation model and methods

In this paper, a NACA0012 airfoil with activated elasticity in pitching DOF is selected as the model. The sketch map of the fluid–elastic airfoil system is shown in Fig. 1, in which α is the freestream angle of attack. The airfoil is supported by a pitching spring and free to vibrate in the pitching degree of freedom (DOF). Defining the non-dimensional time $dt = 2U_\infty dt_{physics}/c$ ($dt_{physics}$ represents the physical time step), the dynamical equation of the pitching airfoil in Fig. 1 ignoring the system damping can be written as:

$$\frac{d\ddot{\theta}}{dt} + k_\theta^2\theta = \frac{1}{\pi\mu r_\theta^2}(2C_m), \tag{1}$$

where θ represents the airfoil pitching angle which vibrates as a function of reduced frequency $k_\theta = f_N c/(2U_\infty)$ and mass ratio $\mu = 4m/(\pi\rho c^2)$. Here $U_\infty, \rho, m, c, f_N$ respectively stand for the freestream velocity, the fluid density, the mass per unit length of the airfoil, the chord length of the airfoil and the natural frequency of the torsional spring. r_θ is the gyration radius of the airfoil around the elastic axis at $a = 0.224c$. C_m is the fluctuating pitching moment coefficient which removes the value of the steady one. It means that the effect of the deformation induced by the static aeroelasticity has been eliminated. In a word, changes in the system stability are totally caused by the release of structural pitching DOF and the consequence of elastic characteristics.

Defining the structural state-vector $\boldsymbol{x}_s = [\theta, \dot{\theta}]^T$, the structural motion equation (1) can be rewritten in the state-space form as:

$$\begin{cases} \dot{\boldsymbol{x}}_s(t) = \boldsymbol{A}_s\boldsymbol{x}_s(t) + \boldsymbol{B}_s y_a(t) \\ u(t) = \boldsymbol{C}_s\boldsymbol{x}_s(t) + \boldsymbol{D}_s y_a(t) \end{cases}, \tag{2}$$

where $\boldsymbol{A}_s = \begin{bmatrix} 0 & 1 \\ -k_\theta^2 & 0 \end{bmatrix}$, $\boldsymbol{B}_s = \begin{bmatrix} 0 \\ \frac{2}{\pi\mu r_\theta^2} \end{bmatrix}$, $\boldsymbol{C}_s = [1 \quad 0]$ and $\boldsymbol{D}_s = [0]$. y_a and u represent the pitching moment coefficient and the pitching angle, respectively. The aerodynamic responses (i.e. the lift and pitching moment coefficients) are calculated by an in-house hybrid-unstructured Unsteady Reynolds-averaged Navier–Stokes (URANS) solver with the Spalart–Allmaras (S–A) turbulence model. This solver is performed with a cell-centered finite volume approach. The inviscid flux is discretized by the second-order AUSM + scheme, while the viscous flux and the turbulence model are discretized by the second-order central scheme. For CFD/CSD simulations, the fourth-order accuracy hybrid linear multi-step method [19] is used to solve equation (2) in time domain. Radial basis function (RBF) interpolation [20] is used to match the grid deformation in each real time step. More details of the numerical method and its validation on the transonic unsteady flow and CFD/CSD simulations can be found in references [12,21].

While the CFD/CSD simulation can not only provide the details of unsteady flows and structural responses, but can also easily take the nonlinearity factors into consideration, this method has limitations in the parameter analysis as well as in the mechanism study of complex FSI phenomena because of the huge computational cost. In this study, therefore, we construct a ROM for the aeroelastic system and then use this model to analyze the dynamics of the coupling system. Before constructing the ROM-based aeroelastic model, we need to first establish an input-output ROM for the transonic unsteady aerodynamics under a small disturbance of the pitching motion. ARX (Auto Regressive with eXogenous input) method is applied to construct such a ROM, which can be written in the continuous time state-space form as:

$$\begin{cases} \dot{\boldsymbol{x}}_a(t) = \boldsymbol{A}_a\boldsymbol{x}_a(t) + \boldsymbol{B}_a u(t) \\ y_a(t) = \boldsymbol{C}_a\boldsymbol{x}(t) + \boldsymbol{D}_a u(t) \end{cases} \tag{3}$$

where $\boldsymbol{x}_a$ is the state vector; $\boldsymbol{A}_a, \boldsymbol{B}_a, \boldsymbol{C}_a, \boldsymbol{D}_a$ are state matrices. The convergence of the model to the identified parameters has been discussed in reference [18].

By coupling structural state equations (2) with aerodynamic state equations (3), we can obtain the ROM-based FSI model for the pitching airfoil system as follows:

$$\begin{cases} \dot{\boldsymbol{x}}_{ae}(t) = \begin{bmatrix} \boldsymbol{A}_s + \boldsymbol{B}_s\boldsymbol{D}_a\boldsymbol{C}_s & \boldsymbol{B}_s\boldsymbol{C}_a \\ \boldsymbol{B}_a\boldsymbol{C}_s & \boldsymbol{A}_a \end{bmatrix} \cdot \boldsymbol{x}_{ae}(t) = \boldsymbol{A}_{ae} \cdot \boldsymbol{x}_{ae}(t) \\ u(t) = [\, \boldsymbol{C}_s \quad 0 \,] \cdot \boldsymbol{x}_{ae}(t) \end{cases}, \tag{4}$$

where $\boldsymbol{x}_{ae} = [\boldsymbol{x}_s, \boldsymbol{x}_a]^T$. In this way, the stability problem is converted into the analysis of complex eigenvalues of $\boldsymbol{A}_{ae}$. Therefore, the effect of elastic parameters on the stability of the coupled system can be tracked from the root loci by solving the eigenvalues of $\boldsymbol{A}_{ae}$ with different structural parameters (k_θ and μ).

3. Results and discussion

From previous reports [18,21], the transonic buffet onset angle calculated by the present URANS solver at Mach number of 0.7 is $\alpha = 4.80°$ for a rigid NACA0012 airfoil. In this condition, the amplitude of the lift coefficient is about 0.055 (oscillation in a quasi-harmonic way) and the reduced buffet frequency is $k_b = 0.182$, as shown in Fig. 2. The onset angles predicted by the ROM and wind tunnel experiment [22] are about $\alpha = 4.70°$ and $\alpha = 4.74°$, respectively. In other words, the present ROM can accurately capture the dominative fluid dynamics of the transonic buffet onset.

When the freestream angle of attack is lower than the onset angle, that is $\alpha < 4.8°$, the flow is absolutely stable and the response is steady for the rigid airfoil. If the pitching degree of freedom is released, however, the system will become unstable in certain combinations of structural parameters due to the FSI effect.

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