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Characteristic analysis of lock-in for an elastically suspended airfoil in transonic buffet flow

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Abstract Numerical simulations are performed to study the aeroelastic responses of an elastically suspended airfoil in transonic buffet flow, by coupling the unsteady Reynolds-averaged Navier-Stokes (RANS) equations and structural motion equation. The current work focuses on the characteristic analysis of the lock-in phenomenon. Great attentions are paid to studying the frequency range of lock-in and the effects of the three parameters, namely the structural natural frequency, mass ratio and structural damping, on lock-in characteristic of the elastic system in detail. It is found that when the structural natural frequency is close to the buffet frequency, the coupling frequency of the elastic system is no longer equal to the buffet frequency, but keeps the same value as the structural natural frequency. The frequency lock-in occurs and stays present until the structural nature frequency is near the double buffet frequency. It means that the lock-in presents within a broad range, of which the lower threshold is near the buffet frequency, while the upper threshold is near the double buffet frequency. Moreover, the frequency range of lock-in is affected by mass ratio and structural damping. The lower the mass ratio and structural damping are, the wider the range of lock-in will be. The upper threshold of lock-in grows with the mass ratio and structural damping decreasing, but the lower threshold always keeps the same.

1. Introduction

In transonic flow, due to the shock-boundary-layer interaction, the self-sustained, low frequency, large amplitude shock oscillations along the airfoil chord are observed for certain combinations of Mach number and mean angle of attack, even in the absence of airfoil motion. We define it as shock buffet. The transonic buffet flow is so highly unsteady and nonlinear, making the corresponding study on flow stability difficult and complicated. So far, there is not yet a clear mechanism which can fully explain the transonic shock buffet phenomenon. Lee[1] proposed a self-sustained feedback model to explain the mechanism of shock oscillation, but there were some defects. Crouch et al.[2,3] provided a new perspective to study the mechanism of transonic buffet from the view of global instability, but still had its flaw. The actual transonic shock buffet

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mechanism is still a subject of discussion and worthy of a long deep fine study.

For a long time, a large number of experiments[4,5] and numerical simulation researches[6–11] are carried out on transonic shock buffet phenomena, but mostly focus on the rigid airfoil and always study the prediction of the buffet onset. There are less studies on the transonic buffet characteristics of the elastic airfoil, even less on the buffet responses. In the classic concept of aeroelasticity, buffet is usually defined as forced vibration. Under this condition, the aerodynamic loads have no relation with structure motion, so it is not necessary to analyze buffet by coupling the aerodynamic loads with structure motion. The influences of the structural elastic mode on flow characteristics and aeroelastic responses can be ignored. However, the practical aerodynamic load is not only related to flow state (Mach number, angle of attack, dynamic pressure, et al.), but also associated with structure vibration more or less. The airfoil structural motion can affect flow characteristics to a certain extent and present obvious fluid-structure interaction characteristic. Steimle et al.[12] carried out unsteady transonic flow experiments on elastic wing. It is clearly shown that the interaction of shock/boundary-layer and separated flow produces huge pressure fluctuations and also results in a strong fluid-structure coupling. Therefore, the elastic effect of the airfoil and the associated buffet response problem should not be ignored in transonic buffet analysis.

In recent years, numerical simulations have been carried out to investigate the effects of prescribed airfoil harmonic oscillation on flow patterns and responses characteristics via uncoupled method and the lock-in phenomenon has been observed. Raveh and Dowell[13,14] simulated the response of a prescribed oscillation airfoil in transonic buffet flow and found that lock-in occurred when the shock buffet frequency synchronized with the prescribed airfoil pitch motion frequency and the amplitude was above a certain threshold. The system response predominantly assumed the frequency of the airfoil motion. Iovnovich and Raveh[15] found that resonance and phase lead appeared near the buffet onset when the airfoil forced movement frequency was close to the buffet frequency. Nitzsche and Giepman[16] studied the aerodynamic resonance response of a two-dimensional (2-D) airfoil under pre-buffet flow conditions to prescribed harmonic flap, pitch, and translational motions. Young and Lai[17] found the vortex lock-in phenomenon in the case of an oscillating airfoil in plunge at Reynolds number of 2.0×10^4. Harmann et al.[18] carried out experiments to study the influence of coupled heave and pitch oscillations in the transonic flow. It was found that at forced oscillation at excitation frequencies in the buffet range, the shock oscillation locked into the excitation frequency indeed. Although the above-mentioned studies considered the influence of structure vibration on flow characteristic and found the lock-in phenomenon, they did not analyze the effect of the elastic mode on the buffet flow and response characteristics.

When considering the elastic effect of the structure, the structural movement and the shock buffet oscillation will be interacted with each other, having a significant impact on the transonic buffet flow and aeroelastic responses. Raveh and Dowell[19] firstly studied the aeroelastic response of an elastically suspended airfoil in transonic buffet flow using RANS solver and found the frequency lock-in occurs, when the frequency of the elastic system is close to the buffet frequency and the oscillation amplitude is above some threshold. The study is useful and directive for the lock-in research of an elastic airfoil in transonic buffet flow.

In current study, an aeroelastic system comprised of a NACA0012 airfoil, suspended on a pitch spring, is simulated in transonic buffet flow by coupling the unsteady flow solver with structural motion equation. The work focuses on the characteristic analysis of the lock-in phenomenon, which can be observed in the responses of an elastic airfoil in transonic buffet flow. A series of computations is carried out to mainly study the frequency range of lock-in and the influences of the structural natural frequency, mass ratio and the structural damping on the lock-in characteristics in detail.

2. Numerical method

2.1. Unsteady flow solver

The unsteady transonic buffet flow is simulated by a finite volume method for the unsteady RANS solver. Xiao[7], Iovnovich[8] and Barakos et al.[9] have used the RANS equations to investigate the buffet flow around several 2-D airfoils and have good agreements with experiment datas, which demonstrate that current RANS has good capability to capture shock buffet phenomenon.

Based on Morkovin's assumption, the RANS equations ignore density fluctuations, and approximate turbulence flow as the sum of a mean steady flow and a small-disturbance unsteady flow, which is represented by a turbulent model. The two-dimensional integral governing equations for unsteady Reynolds-averaged Navier-Stokes equations are expressed as[20,21]

$$\frac{\partial}{\partial t}\int\int_{\Omega}\boldsymbol{Q}\mathrm{d}S+\int_{\Gamma}\boldsymbol{F}(\boldsymbol{Q},\boldsymbol{V}_{\mathrm{grid}})\cdot\boldsymbol{n}\mathrm{d}\Gamma=\int_{\Gamma}\boldsymbol{G}(\boldsymbol{Q})\cdot\boldsymbol{n}\mathrm{d}\Gamma \tag{1}$$

where Ω is the control surface element, S the surface, t the time, Γ the boundary of the control surface element, and $\boldsymbol{n}$ the identity normal vector. $\boldsymbol{Q}$, $\boldsymbol{F}(\boldsymbol{Q},\boldsymbol{V}_{\mathrm{grid}})$, $\boldsymbol{G}(\boldsymbol{Q})$ represent the conservation vector, the inviscid flux vector considering grid moving velocity, and the viscous flux vector respectively. $\boldsymbol{V}_{\mathrm{grid}}$ is the moving grid velocity vector. By dimensional analysis, the equations can be expressed in terms of dimensions of the chord length, free stream density, speed of sound, as well as temperature.

The AUSM + up scheme is adopted for spatial discretization to capture the shock discontinuity accurately and suppress numerical oscillations in space. An implicit dual-time stepping method is used for time discretization to ensure that the numerical method has second-order accuracy in time. At sub-iteration, the fourth stage Runge–Kutta scheme is applied with local-time stepping, also using the residual smoothing technique and multi-grid for convergence acceleration.

The Spalart–Allmaras (S–A) turbulence model is used for all computations. S–A model has good robust and numerical convergence, which can well simulate the attached flow and thin free shear layer flow.

The grid deformation is realized by a radial basis functions (RBF) interpolation scheme.[22] In order to avoid additional