Airfoils Admitting Anomalous Behavior of Lift Coefficient in Descending Transonic Flight

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Abstract: Airfoils admitting abrupt changes of the lift coefficient under small variations of free-stream conditions are considered. A numerical simulation of transonic flow is performed on the basis of RANS equations using BSL Reynolds stress and $k-\omega$ SST turbulence models. The simulation reveals adverse free-stream conditions for a descending flight of J-78, Boeing 737 Outboard, and Whitcomb airfoils.

Keywords: Turbulent flow, Local supersonic regions, Interaction, Instability.

In the last two decades, numerical studies demonstrated instability of shock waves on symmetric and asymmetric airfoils whose curvature is small in the midchord or nose regions. Such airfoils admit jumps of the lift coefficient under slight variations of the angle of attack or free-stream Mach number M_∞ [1, 2, 3].

In this paper, we concentrate on asymmetric airfoils at small angles of attack α that are typical for a descending flight. The descent conditions are unfavorable from the viewpoint of an airfoil response to the free-stream turbulence, which can cause heavy aerodynamic loads and possibly lead to flight accidents.

Numerical solutions of the RANS equations are obtained with an ANSYS CFX-13 finite volume solver of the second order accuracy. Initial data are either the uniform state determined by the given free-stream conditions or a flow field obtained previously for other values of M_∞ and the angle α. We use the $k-\omega$ SST and Baseline (BSL) Reynolds stress turbulence models, which predict the boundary-layer separation from smooth surfaces quite reasonably. Computations were performed on hybrid unstructured meshes of about 2×10^5 grid points which were clustered in the boundary layers, in the wake, and in vicinities of the shock waves.

First, we consider a J-78 airfoil [1] characterized by a small curvature of the upper surface in the midchord region. Numerical solutions show abrupt changes of the lift coefficient C_L at $M_\infty = 0.82,\ -0.6 < \alpha, \mathrm{deg} < 0.5$ (see Fig.1(a)). Such a behavior of C_L can be explained by the presence of interacting local supersonic regions on the upper surface of airfoil. At a larger Mach number, $M_\infty = 0.84$, computations show a discontinuity in the plot $C_L(\alpha)$ if the $k-\omega$ SST turbulence model is used, and a continuous gently sloping plot if the BSL Reynolds stress model is employed (see Fig.1(b)).

Next, transonic flow past a Boeing 737 Outboard airfoil is examined at $M_\infty = 0.823$, $u_\infty =$ 261 m/s. The numerical simulation demonstrates a drop of the lift coefficient from 0.25 to 0 with decreasing angle of attack from 1 deg to -1.5 deg. The drop is caused by an interaction of supersonic regions on the lower surface of airfoil due to a slight concavity of the surface in

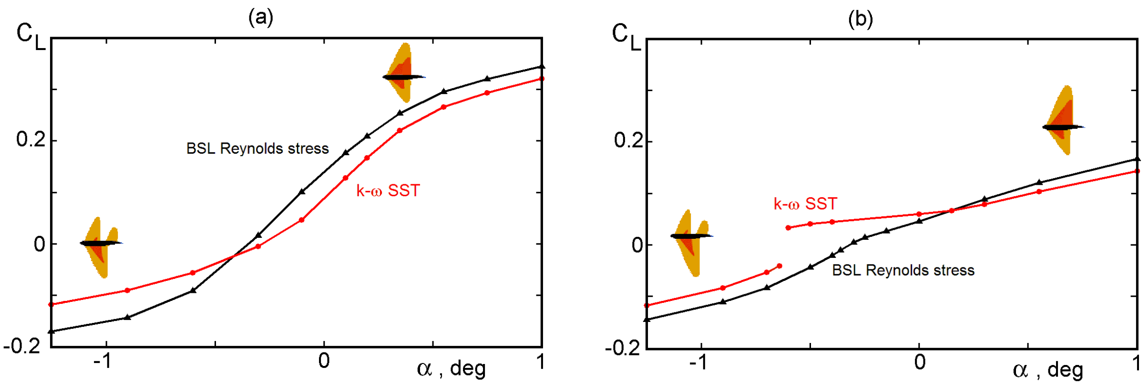

Figure 1: Lift coefficient as a function of the angle of attack for J-78 airfoil at $Re = 5.7 \times 10^6$. (a): $M_\infty = 0.82$, $u_\infty = 243.9$ m/s, (b): $M_\infty = 0.84$, $u_\infty = 249.8$ m/s, where u_∞ is the free-stream velocity.

the nose region. It follows from the above that the Mach number $M_\infty = 0.823$ is adverse for a transition from the cruise flight of the airplane to descending one. Indeed, if the angle of attack is decreased from 1 deg to 0, then a vertical gust of -7 m/s will further decrease it to -1.5 deg. This will entail a drop of C_L to zero, causing troubles or injuries to crew and passengers of the plane.

The last example concerns a Whitcomb airfoil whose aft part is modified as foloows:

$$y(x) = y_{\text{whitc}}(x) + (x - 0.7)\tan\theta \quad \text{at} \quad 0.7 \le x \le 1, \tag{1}$$

where $y_{\text{whitc}}(x)$ refers to coordinates of the original Whitcomb airfoil [4]. The modification (1) models a rotation of an aileron about the point $x = 0.7$, $y = 0$ at the angle θ. The numerical simulation of transonic flow in this case reveals that, at $M_\infty = 0.849$ and $-0.5 < \alpha, \text{deg} < 0.5$, variations of the deflection angle θ up to 8 degrees produce an anomalously small response of the lift coefficient. Therefore, the aileron deflection fails to properly control the flight at the chosen values of M_∞ and α.

A dependence of the lift coefficient on the Reynolds number is also studied for the airfoils at hand.

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