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Numerical simulation of the effect of local volume energy supply on high-speed boundary layer stability

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ABSTRACT

Two-dimensional direct numerical simulations and the linear stability analysis are performed for a flat-plate boundary layer in the Mach 6 free stream with the presence of local volume energy supply. It is expected that this technique can be used for the laminar flow control at high speeds where the second mode waves dominate. It is shown that the heat source produces different effects depending on its streamwise distance from the plate leading edge and its wall-normal distance. If the source is located upstream from the neutral point and its center is close to the boundary-layer edge, it reduces the second-mode growth rates and thereby diminishes the maximum amplitude of instability. If the source is shifted downstream from the neutral point and its center is within the boundary layer, the stabilization effect becomes weaker while the scattering of unstable waves by the source-induced non-uniformity of the mean flow comes into play. By variations of the wall-normal distance of the heat source located near the neutral point it was found that the maximal stabilization effect is achieved if the source center is near the critical layer.

1. Introduction

Prediction of laminar-turbulent transition is important for aerothermal design of high-speed vehicles [1]. The first reason is that early transition leads to the increase of drag and hence the decrease of lift-to-drag ratio. The second is associated with the significant increase of heat fluxes to the vehicle surface. This motivates extensive experimental, theoretical and numerical studies of transition and laminar flow control (LFC) concepts at supersonic and hypersonic speeds [2]. Progress made in the transition prediction methodology for high-speed flows is reviewed in [3]. Thermal non-uniformities (natural or artificially induced) in the near-wall region may significantly affect the boundary-layer mean flow. This, in turn, affects excitation of unstable modes (receptivity problem), the downstream propagation of instability (stability problem) and, ultimately, the transition locus. Investigation of physical mechanisms associated with the foregoing effects may help to design new thermal protection systems with LFC capabilities.

The wall-temperature jump effect was investigated for laminar mean flows in [4]. Two-dimensional direct numerical simulations (DNS) of receptivity and stability of a flat plate boundary layer in the Mach 6 free stream were carried out in [5] with emphasis on the case where there is a wall temperature jump ΔT_w. It was shown that this jump affects both stability and receptivity of the boundary layer flow. The total growth of unstable wave of fixed frequency strongly depends on the sign and locus of ΔT_w.

Localized surface heating or cooling can be considered as a technique for LFC. This method was used to suppress the first mode disturbances (Tollmien–Schlichting waves) by local heating [6,7]. Stability of the boundary layer flow on a surface heated near the plate leading edge was analyzed while the mean flow was computed using the boundary layer equations. The heating strip effect on transition in compressible subsonic flow over a flat plate was theoretically studied in [8]. A heating strip can be used for stabilization of the first-mode waves at supersonic speeds also. This was shown in [9] for the boundary layer in the free-stream at Mach number 3.5.

The foregoing studies for subsonic and supersonic flows revealed the following mechanism [10]. In the relaxation region developed downstream of the heating strip, the boundary-layer temperature is larger than the wall temperature so that the boundary layer "sees" a relatively cold wall. According to the linear stability theory (LST) this leads to decreasing of the first-mode growth rates.

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Nomenclature

A	amplitude ratio
c	disturbance phase speed
M	Mach number
Re	Reynolds number
γ	specific heat ratio
Pr	Prandtl number
p	pressure
T	temperature
u, v	longitudinal and vertical velocity components
x_0, y_0	longitudinal and vertical coordinates of the heat source locus
σ	spatial growth rate of unstable wave
σ_0	radial size of the heat source
ω	angular frequency

Superscripts

*	dimensional

Subscripts

∞	free stream
w	wall surface
n	neutral

The localized wall heating and cooling effects on stability of the boundary layer on a sharp cone of 7-deg half angle were analyzed in [11] at the free-stream Mach number 6 and zero angle of attack. The steady-state laminar flow was calculated using the Navier–Stokes equations. These solutions were used for computations of the growth rates and amplification factors of the Mack second mode. It was shown that the results [11] for hypersonic boundary layer are not consistent with the LFC concept suggested earlier in [10] for the first mode stabilization at subsonic speeds. In the case of heated strip, the hypersonic boundary layer temperature is higher than the wall temperature so that the wall is relatively cold. In this case, we can expect an increase of the second-mode growth rate while the calculations [11] demonstrate an opposite trend. This discrepancy may be due to additional effects associated with the mean-flow changes.

The effect of local pulse heating on receptivity and stability of a hypersonic boundary layer was studied experimentally and numerically. Schneider et al. [12–14] performed experiments on a sharp cone in a hypersonic free stream with disturbances being induced by a laser beam. It was shown that laser-induced disturbances have the radial distributions of temperature with approximately Gaussian shape. DNS of a single entropy spot evolution was carried out in [15] at flow parameters corresponding to the experiment [16]. Heitmann et al. [17,18] performed experimental and numerical simulations of the Mach 6 boundary layer response to a single laser-generated disturbance in the boundary layer on a 7-deg sharp cone.

Two-dimensional DNS of flat-plate boundary layer receptivity to the free-stream temperature spottiness in the Mach 6 free stream was carried out in [19]. The temperature spottiness was modeled by the Gaussian function vs. the wall normal coordinate and a harmonic function vs. time. The DNS results agreed satisfactorily with theoretical assessments.

Along with the wall heating or cooling a stationary and local-in-space energy supply can be considered as a technique for the stability control. As shown in [20], using this method it is feasible to reduce the instability growth rate for a subsonic compressible boundary-layer flow. In the present paper, the local heating effect on the second-mode instability is analyzed for the boundary layer flow on a flat plate in the Mach 6 free stream. The analysis is performed using DNS and LST.

2. Problem formulation and numerical method

Viscous two-dimensional unsteady compressible flows are described by the Navier–Stokes equations. Numerical simulations are carried out for a flat plate with a sharp leading edge. The flow variables are made nondimensional using the steady-state free-stream parameters (denoted by subscript "∞"): $(u, v) = (u^*, v^*)/U^*_\infty$ are longitudinal and vertical components of the flow velocity, $p = p^*/(\rho^*_\infty U^{*2}_\infty)$ is pressure, $\rho = \rho^*/\rho^*_\infty$ is density, $T = T^*/T^*_\infty$ is temperature. The nondimensional coordinates are $(x, y) = (x^*, y^*)/L^*$, and time is $t = t^* U^*_\infty / L^*$, where U^*_∞ is the free-stream velocity, L^* is the plate length. Hereinafter, asterisks denote dimensional variables. The fluid is a perfect gas with the specific heat ratio $\gamma = 1.4$ and Prandtl number $\mathrm{Pr} = 0.72$. Calculations are performed for the free-stream Mach number 6 and the Reynolds number (based on free-stream parameters and plate length) $\mathrm{Re}_L = \rho^*_\infty U^*_\infty L^*/\mu^*_\infty = 2 \times 10^6$, where μ^*_∞ is the free-stream dynamic viscosity. The viscosity-temperature dependence is approximated by the power law $\mu^*/\mu^*_\infty = (T^*/T^*_\infty)^{0.7}$. The second viscosity is assumed to be zero. The plate has a nominally sharp leading edge; i.e. the leading-edge radius is so small that the bluntness-induced entropy layer does not affect receptivity and stability of the boundary layer flow. Details on the problem formulation and the governing equations are given in [21].

The computational domain is a rectangle ($-0.1 \leqslant x \leqslant 1$, $0 \leqslant y \leqslant 0.2$) with its bottom side ($y = 0$) corresponding to the plate surface in the region $0 \leqslant x \leqslant 1$. The upper boundary is located above the plate-induced shock wave. The boundary conditions on the plate surface are: the no-slip condition $(u, v) = 0$, the adiabatic wall condition $\partial T_w/\partial y = 0$ for the steady-state solution. The symmetry conditions are imposed on the line $y = 0$ in the region $-0.1 \leqslant x < 0$. On the outflow boundary, the unknown dependent variables are extrapolated using the linear approximation. On the inflow and upper boundaries, the conditions correspond to the undisturbed free stream.

The problem is solved numerically using the implicit second-order finite-volume method described in [21]. Two-dimensional Navier–Stokes equations are approximated by a shock-capturing scheme. The advection terms are approximated by the third-order WENO scheme [22]. Although this computational scheme is dissipative, its numerical dissipation can be suppressed using a sufficiently fine computational grid. Herein the grid has 2201×301 nodes. There are at least 45 grid nodes per disturbance wavelength and approximately 400 time steps per disturbance period. The grid is clustered in the wall normal direction so that the boundary layer contains approximately 50% of grid nodes. As shown in [19,21,23], this grid is appropriate for simulations of the boundary-layer stability and receptivity. The governing equations, the code algorithm as well as its implementations and validations can be found in [21].

First, a steady-state solution is calculated to provide the mean flow. The steady pressure and temperature fields indicate that the viscous–inviscid interaction between the boundary layer and the free stream leads to a shock wave emanating from the plate leading edge.