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On the merging of turbulent spots in a supersonic boundary-layer flow

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Abstract

The complex transition flow physics associated with the merging of turbulent spots in a Mach 2 boundary-layer has been studied using direct numerical simulation. Dynamics of an isolated turbulent spot, merging of laterally displaced spots, and merging of two spots in tandem are considered. The coherent structures associated with the wingtip region of the spot are found to play a major role in destabilising the surrounding laminar fluid. In the merging of laterally displaced spots a strong velocity defect, resulting in unstable inflectional velocity profiles, is observed in the interaction zone. These local inflectional instabilities within the interaction region trigger new large scale coherent structures. During the inline merging, the calmed region behind the tail of the downstream spot is found to suppress the growth of the upstream spot. The upstream spot is ultimately engulfed by the downstream spot.

Keywords: Turbulent spots; Transition to turbulence; Compressible boundary layer; Spot merging

1. Introduction

The growth and breakdown of disturbances initiates laminar-to-turbulent transition. Large amplitude disturbances can bypass the initial linear growth stage and directly enter the non-linear growth phase. Finally, the disturbances break down into regions of intermittent turbulence in an otherwise laminar flow. Emmons (1951) named these localised islands of turbulence as 'turbulent spots'. The growth and the merger of these turbulent spots leads to fully developed turbulent flow. The length of the transition region depends on the spot creation rate and on spot growth characteristics such as the convective speed of the leading and trailing edges of the spot, lateral growth rate and interactions between spots. A schematic of a turbulent spot is depicted in Fig. 1, showing how the turbulent fluid overhangs laminar fluid at the front and sides of the spot. Behind the spot there is a region known as the calmed region (Schubauer and Klebanoff, 1955), where disturbances are low, but skin friction is higher than in the surrounding laminar boundary layer.

Narasimha (1985) reviewed the transition process and turbulent spots in a variety of flows. A classical spot photograph (Fig. 2) of Cantwell et al. (1978) reveals streaky structures in the sublayer trailing the rear interface of the spot. To date, these streaky structures were identified only in the incompressible flow visualisation studies. Earlier, Elder (1960) showed experimentally that a spot can be successfully triggered if the perturbation amplitude exceeds a critical level of about 0.2 times the free-stream velocity. He also suggested that the region of turbulent flow is the sum of the areas of individual turbulent spots. This simple superposition is possible only if the spots grow independently of each other. Savas and Coles (1985) constructed a synthetic turbulent boundary layer by triggering an array of spots in a hexagonal pattern. They suggested that the dynamics of the spot interactions are important and questioned the simple superposition of spot areas. Moreover, the recent experiments by Makita and Nishizawa (2001) showed a stronger velocity defect in the interaction zone and demonstrated that the spot merging process is different from a simple superposition of spots.

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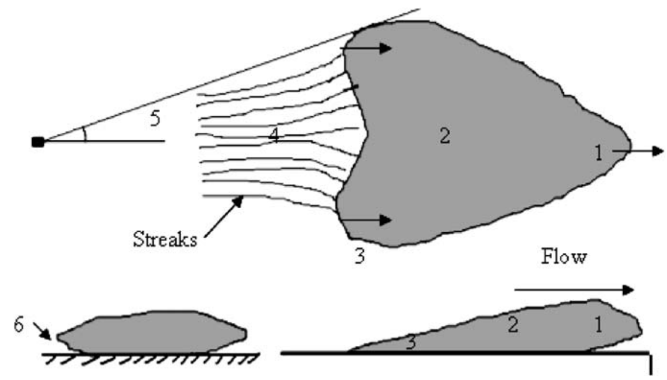

Fig. 1. Turbulent spot nomenclature: (1) front overhang, (2) turbulent core, (3) lateral wingtip, (4) calmed region, (5) lateral spreading half-angle, (6) spanwise overhang.

Fig. 2. Spot flow visualisation showing the sublayer streaks (Cantwell et al., 1978).

Direct numerical simulations (DNS) of turbulent spots in an incompressible boundary layer were presented by Henningson et al. (1987). They showed that turbulent patches embedded within an arrowhead-shaped region grow at a half-spreading angle of about 7°, with estimated front and rear convection speeds of about $0.83u_\infty$ and $0.50u_\infty$. Numerical simulation of bypass transition in an initially laminar boundary layer beneath free-stream turbulence was carried out by Jacobs and Durbin (2001). They found the near-wall streaks to be stable whereas the lifted streaks became receptivity sites for smaller scale free-stream turbulence and triggered turbulent spots. This work showed the formation of spots in flows with top–down perturbations (i.e. free-stream disturbances) in contrast to the more conventional bottom–up perturbations (caused by near-wall disturbances).

Most of the studies to date have been performed to explore the dynamics of spots in an incompressible flow. The physics associated with the spot spreading mechanism and the spot interactions are only vaguely described in the literature. A clear understanding of the transition physics is required for the design of supersonic and hypersonic vehicles, yet data for compressible spots in the literature is very limited.

Krishnan and Sandham (2004a) used DNS to show that an increase in the Reynolds number has a destabilising effect while the Mach number inhibits the growth of a single hairpin structure into a turbulent spot in a plane Poiseuille flow. The effect of compressibility on the spreading of isolated turbulent spots in a compressible boundary layer was reported by Krishnan and Sandham (2004b). They found a marked reduction in the lateral half-spreading of the spots from 5° to 1.7° with the flow Mach number varying from 2 to 6 in agreement with experiments (Fischer, 1972). Spot visualisations clearly revealed that young spots consist of an array of hairpin and quasi streamwise vortices. Spanwise-coherent structures which are connected to the supersonic modes (Mack mode) were seen under the front overhang of the spot in a Mach 6 boundary layer. Krishnan and Sandham (2004c) investigated the complex flow physics associated with the interaction of a turbulent spot with an oblique shock-induced laminar separation bubble. The passage of the spot completely collapsed the bubble in the interaction region and the lateral half-spreading angle increased by a factor of about three compared to an isolated spot.

Previous experimental results were based on ensemble-averaged flow measurements and planar visualisation images. A complete picture of the flow field can be obtained using DNS, which may facilitate the interpretation of the complex three-dimensional structure of a spot. The present computations are primarily carried out to improve our understanding of the physics associated with the merging of turbulent spots in a supersonic boundary layer flow.

2. Spot simulations

2.1. Numerical approach

The unsteady compressible Navier–Stokes (N–S) equations for dimensionless density ρ, velocity u_i, pressure p, temperature T and total energy E, in cartesian coordinates are

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u_j}{\partial x_j} = 0 \quad (1)$$

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial \rho u_i u_j}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{1}{Re}\frac{\partial \tau_{ij}}{\partial x_j} \quad (2)$$

$$\frac{\partial E}{\partial t} + \frac{\partial (E+p)u_j}{\partial x_j} = \frac{\partial u_i \tau_{ij}}{\partial x_j} + \frac{1}{(\gamma-1)RePrM^2}\frac{\partial}{\partial x_j}\left(\mu \frac{\partial T}{\partial x_j}\right) \quad (3)$$

where the stress is given by

$$\tau_{ij} = \mu\left(\frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j} - \frac{2}{3}\delta_{ij}\frac{\partial u_k}{\partial x_k}\right) \quad (4)$$

The temperature is given by

$$T = \gamma(\gamma-1)M^2\left(\frac{E}{\rho} - \frac{1}{2}u_i u_j\right) \quad (5)$$

The equation of state can be written as

$$p = (\gamma-1)\left(E - \frac{1}{2}\rho u_i u_j\right) = \frac{1}{\gamma M^2}\rho T \quad (6)$$