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A comparison of laminar-turbulent boundary-layer transitions induced by deterministic and random oblique waves at Mach 3

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ABSTRACT

A numerical investigation of transition processes initiated by deterministic and random disturbances is presented for a Mach 3 flat-plate boundary layer. In both cases, disturbance forcing is localized slightly downstream of the leading edge of the flat plate. The targeted kind of disturbance for laminar-turbulent transitions is an oblique wave but it is introduced with two different ways: deterministic suction and blowing at the wall, or random volume forcing at the edge of the boundary layer. Moreover, the forced perturbations are sinusoidal in spanwise direction with a single fixed wavenumber in the deterministic case and multiple harmonics in the random case. In the latter case, the random disturbance evolution is characterized by the RMS values of Fourier transformed velocities in a band of frequency to cover the amplifications of multiple frequency components. The observed path to turbulence with respect to the two cases are compared in three stages: linear stage, non-linear regime, and breakdown to turbulence. In the initial stage, the amplitude of unsteady disturbances grows exponentially due to a linear instability of the boundary layer, as it could be observed in the deterministic forcing case. This exponential growth is also observed after considering a broad band of frequencies in the random forcing case. In the second stage, non-linearity leads to the formation of streamwise streaks via the lift-up effect. In the deterministic case, these streaks are steady, while they take the form of low-frequency traveling waves in the case of random forcing. However, in the random forcing case a streak instability could not clearly be identified. In the final stage, sudden breakdown to turbulence occurs at a fixed streamwise location in the deterministic case, marked by a sharp rise in skin friction. Non-periodicities appear only downstream of the breakdown location. In the random forcing case, breakdown takes place within a transition zone in which one can observe the formation of distinct turbulent spots.

1. Introduction

The prediction of laminar-turbulent transition in compressible, high-speed boundary layers is important for the design of aerospace vehicles but remains not well understood. Transition to turbulence can be desirable or undesirable according to the specific application. For example, turbulence can enhance mixing so that combustors of scramjet engines are more efficient. However, it can also lead to excessive surface heat-transfer and damage heat shields of (re-)entry vehicles.

In realistic engineering problems, disturbances which cause the breakdown to turbulence have broad frequency content and appear randomly in space and time, although only single-mode, deterministic perturbations are considered in many numerical and theoretical studies. Laminar-turbulent transition initiated by random disturbances is rarely investigated. Here, we present a numerical investigation of the laminar-turbulent transition process for high-speed boundary layers caused by random disturbances. A case with randomly forced perturbations will be compared to the classical situation in which transition is caused by deterministic forcing.

1.1. Compressible boundary layer instability

For a high-speed boundary layer, Mack (1969, 1975) pointed out that two significant types of instabilities exist. The first one is generated by the generalized inflection point of the streamwise velocity profile in a boundary layer. The second one belongs to a family of trapped acoustic waves, for which the boundary layer acts as a waveguide due to supersonic mean flow relative to the disturbance phase velocity in the boundary layer (Fedorov, 2011).

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The former one is the so-called 'first mode' and the latter one is the 'second mode' or 'Mack mode'. In order to analyze numerical results and compare them with linear stability theory, it is more convenient to distinguish two different discrete boundary-layer eigenmodes, stemming from the fast and slow acoustic modes in the free stream. These are commonly denoted as modes F and S, respectively (Tumin, 2007; Fedorov, 2011; Fedorov and Tumin, 2011; Lifshitz et al., 2012). However, the Mach number considered in this paper is sufficiently low so that only the inflectional instability occurs and the single unstable eigenmode, mode S, can be denoted as first mode.

Many researchers investigated the effect of additional factors on high-speed flat-plate boundary-layer instability. Marxen et al. (2010) studied disturbance amplification in a Mach 4.8 flat-plate boundary layer with a two-dimensional roughness. They noted that a localized two-dimensional roughness transiently increases disturbance amplitudes due to constructive interferences of a stable mode with the unstable mode downstream of the roughness. Moreover, they showed that a localized two-dimensional roughness can amplify disturbances in a limited bandwidth of frequencies. Yan and Gaitonde (2010) studied the effect of steady and unsteady thermal perturbations on transition to turbulence in a Mach 1.6 flat-plate boundary layer.

1.2. Oblique breakdown mechanism

Starting with the investigation of oblique disturbances in plane Poiseuille flows by Lu and Henningson (1990), pairs of oblique waves or oblique breakdown patterns have now been observed in many types of transitional flows. For incompressible flat-plate boundary layers, oblique breakdown has been investigated numerically by Berlin et al. (1994). In their simulation, they covered the complete transition process up to the emergence of turbulent flow by spatial direct numerical simulation. They pointed out that streamwise vortices cause the rapid amplification of streamwise streaks due to the lift-up effect, and then secondary instabilities occur as a result of local shear layers caused by the streaks. Finally, streak breakdown leads to a fully developed turbulent flow field.

Fasel et al. (1993) investigated the oblique breakdown mechanism for a supersonic boundary layer. They found this mechanism to be very effective in transitioning the flow. Chang and Malik (1994) theoretically investigated the oblique breakdown mechanism using the non-linear parabolized stability equations. They showed that in addition to the pair of oblique traveling waves, a steady vortex is generated through non-linear interaction, resulting in a wave-vortex triad. They pointed out that the non-linear interaction in this wave-vortex triad is crucial for transition to turbulence. Moreover, additional higher harmonic modes are generated through non-linear interaction. Jiang et al. (2006) performed the numerical simulation of complete laminar-turbulent transition induced by oblique waves in a supersonic boundary layer. Recently, Mayer et al. (2011a) investigated the complete transition to turbulence through oblique breakdown using spatial direct numerical simulation for a Mach 3 boundary layer, triggering a pair of spatially growing oblique waves with fixed frequency and spanwise wave number. By inspecting turbulent statistics, the van Driest transformed mean streamwise velocity profiles, and skin-friction coefficients, they were able to show that a fully developed turbulent boundary layer develops downstream of the transition location also in a supersonic boundary layer.

1.3. Simulations with random forcing and excitation of wave packets

Fundamental investigations of laminar-turbulent transition typically rely on the explicit forcing of disturbances with narrow spectral bandwidth. Usually, perturbations with a fixed frequency and a fixed spanwise wave number are forced in these investigations. Most of the studies mentioned in the previous section belong to this type of investigation.

Investigations with explicitly controlled perturbations at low levels of free-stream turbulence are useful to advance our understanding of mechanisms involved in the laminar-turbulent transition process. These studies consider the so-called controlled deterministic transition. Laboratory experiments with such forcing have been successfully reproduced by means of numerical simulation, for a recent example see Mayer et al. (2011b).

Indeed, based on this type of studies, the oblique breakdown mechanism is now well known as an efficient way to trigger the transition to turbulent flow. Oblique breakdown is hence a particularly fast route to transition and may well be the most critical transition scenario. However, it is unclear if this idealized oblique breakdown mechanism occurs when the breakdown process is not triggered by explicitly forcing the necessary oblique waves.

A situation in which no explicit deterministic forcing, such as for the oblique pair of waves mentioned above, occurs is expected to better represent real-world engineering applications. In these applications, boundary-layer instability waves will appear randomly in space and time. As a result, the amplitude and frequency of these waves may be both uncertain, or known only in a statistical sense, and vary in time. Hence, an approach in which transition is caused by a limited number of forced deterministic perturbations may not be representative of operating conditions of a vehicle. Instead, studies in which the transition process is initiated more randomly may help to determine to what extent transition mechanisms are sensitive to the details of the forcing. One should employ an approach which reflects the non-deterministic nature of disturbances during transition, for instance through random forcing of boundary-layer instability waves (Herbst and Henningson, 2006; Marxen and Iaccarino, 2009; Wu and Moin, 2009). This type of study may form the basis for the development of improved transition–prediction methods for future engineering applications.

In summary, it is presently unclear whether the physical processes during laminar-turbulent transition are similar for deterministic and random forcing. The objective of this paper is to identify similarities and differences by comparing corresponding simulation results for an otherwise identical setup. The deterministic simulation will trigger the oblique breakdown scenario via wall blowing and suction, while boundary-layer perturbations responsible for transition in the case with random forcing are induced by volume forcing. In both cases, the setup is identical except for the forcing, including identical free-stream conditions, inflow and boundary conditions as well as size of the integration domain.

2. Numerical setup for flow simulations

2.1. Numerical method

The numerical method used here is based on an algorithm described by Nagarajan et al. (2003), originally developed for transitional flows in subsonic conditions in Nagarajan et al. (2007). Sixth-order compact finite differences inside the computational domain with explicit third-order Runge Kutta time integration are used to obtain time-accurate solutions to the compressible Navier–Stokes equations, i.e., we perform direct numerical simulations (DNS) for a calorically perfect gas. An explicit shock-capturing scheme is not required for the simulations as shocks are absent from these simulations. A high-order compact numerical filter is applied to avoid small-scale oscillations. The numerical discretization is constructed on a structured grid using staggered