Numerical evaluation of the asymptotic theory of receptivity for subsonic compressible boundary layers

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Motivation

Receptivity theory studies the process of interaction between the boundary layer and external perturbations, which leads to the excitation of boundary layer instabilities, e.g. the Tollmien--Schlichting (TS) waves. The objectives of the receptivity analysis are to identify how the external perturbations can be converted into instability modes of the boundary layer and to determine the initial amplitude of these modes. Progress in this field has been achieved mainly thanks to the studies based on the asymptotic analysis of the Navier-Stokes equations at large values of the Reynolds number. When dealing with the process of generation of TS waves in boundary layers, this approach relies on the triple-deck theory. However, the applicability of the asymptotic theory is not clear and a detailed evaluation of its capabilities is currently missing. Therefore, the main aim of this project is to assess the accuracy of the asymptotic theory of receptivity of TS waves in subsonic compressible boundary layers through comparisons with high-fidelity compressible Navier--Stokes simulation results.

Research

A detailed parametric study has been performed, where numerical solutions of the compressible Navier-Stokes equations have been compared with the theoretical predictions. The investigation focuses on two important receptivity scenarios: the TS wave receptivity due to a vibrating ribbon on the wall of a flat-plate and that due to the interaction between free stream sound and wall roughness elements; the latter scenario being one of the most important causes of excitation of boundary layer instabilities during flight. The parametric study was designed to test the limits of the theory, and included variations of the roughness element shape and dimensions, Reynolds number, Mach number and acoustic wave frequency. The numerical results are in very good agreement with the theory, which validates the use of high-Re theoretical results for real life finite-Re applications.

Application to industry

The receptivity process is the first and arguably the most important step in the laminar-turbulent transition of the boundary layers developing over aircraft wings and fuselage; yet it is currently completely disregarded when modeling transition to turbulence in the early stages of aircraft design. This would enable us to better predict the laminar-turbulent transition location in the boundary layer and to design novel control strategies to delay transition.