Advances in Applied Mathematics and Mechanics
Adv. Appl. Math. Mech., Vol. **10**, No. 3, pp. 735-751

DOI: 10.4208/aamm.OA-2017-0094
June 2018

A Boundary-Layer Receptivity Mechanism Excited by the Interaction Between Free-Stream Turbulence and the Three-Dimensional Localized Wall Roughness

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Received 10 April 2017; Accepted (in revised version) 6 November 2017

Abstract. The mechanisms of the laminar-turbulent transition and the turbulent formation are always one of the important issues in the fields of fluid mechanics, and the boundary-layer receptivity plays a key role in the laminar-turbulent transition. Although there have been plenty of achievements on the boundary-layer receptivity, it is rarely to see the study about the boundary-layer receptivity excited by the interaction of free-stream turbulence and three-dimensional localized wall roughness, which is one of the urgent problems for the prediction of the laminar-turbulent transition in engineering practice. Hence, this problem is studied in this paper by direct numerical simulation. Can the wave packet structures comprised by the two- and three-dimensional T-S waves be discovered in the boundary layer? If so, and how do the group speed and propagation direction of the excited wave packet change? Subsequently, it can prove whether the boundary-layer receptivity exists; Then, the relations between the boundary-layer receptivity and the free-stream turbulence intensity, and the length, width and height of the three-dimensional localized wall roughness are established. Above all, these researches are able to promote the theoretical foundations of the hydrodynamic stability theory and turbulence formation.

AMS subject classifications: 76f65,76f40,76d33

Key words: Receptivity, three-dimensional localized wall roughness, free-stream turbulence, boundary layer.

1 Introduction

The laminar-turbulent transition process is always one of the significant issues in fluid mechanics. Generally, the transition process can divide into the stages of the receptivity, the linear increase, the nonlinear increase and the laminar breakdown to turbulence [1].

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"Receptivity" is the initial stage of the entire laminar-turbulent transition process, and it describes how the external disturbances penetrate into the boundary layer to excite the unstable waves [2].

Up to now, it has been confirmed that there are two kinds of mechanisms of the boundary-layer receptivity: One is the leading-edge receptivity; and the other is the local receptivity [3]. Despite the fruitful researches on the generating process of the T-S waves in the boundary layer, most of the achievements concentrated on the interaction between vortical or acoustic disturbances and two-dimensional localized roughness, blowing or suction. Such as, Goldstein et al. [4] used the asymptotic method to prove the existence of the local receptivity mechanism under the interaction of the acoustic disturbances and two-dimensional localized roughness, which was confirmed by Saric et al.'s [5] and Wiegel & Wlezien's [6] experiments. Then Wu's theoretical study [7] and Dietz's experiments [8] verified the boundary-layer local receptivity and the wavelength conversion mechanism under the vortical disturbances and two-dimensional localized roughness. Meanwhile, several successful cases have been made for the boundary-layer receptivity to the acoustic disturbances interacting with three-dimensional localized roughness in the boundary layer: Such as, Choudhari & Kerschen [9] and Tadjfar & Bodonyi [10] used the asymptotic method to study that the acoustic waves interacted with the three-dimensional localized roughness to excite the three-dimensional T-S waves in the boundary layer; Zhou et al. [11] and Cullen & Horton [12] experimentally verified the receptivity to the acoustic waves interacting with the three-dimensional localized roughness (e.g., oblique stripes, circular roughness, etc.) separately; Subsequently, Würz et al. [1] researched on the boundary-layer local receptivity to acoustic waves both numerically and experimentally, and achieved the quantitative receptivity coefficients.

From the above, most of the former researches on receptivity restricted to the formation process of the sound waves or vortical disturbances interacting with two- and three-dimensional localized roughness to excite two- and three-dimensional T-S waves respectively; however the study is lacked on the generating mechanism of the two- and three-dimensional T-S waves by the free-stream turbulence and the three-dimensional localized wall roughness. In addition, we have already studied the boundary-layer receptivity to free-stream turbulence interacting with two-dimensional localized wall roughness or blowing/suction respectively in [13–18]. In this paper, the boundary-layer receptivity induced by the interaction between free-stream turbulence and the three-dimensional localized wall roughness is studied with direct numerical simulation. These work aims to promote the theoretical foundations of the turbulence formation and hydrodynamic stability theory, as well as the broad application prospect.

2 Governing equations and implementation

2.1 Governing equations and numerical schemes