DIRECT NUMERICAL SIMULATION OF ROUGHNESS AND UNSTEADY WAKE EFFECT ON SEPARATED BOUNDARY LAYERS

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Abstract The combined effects of discrete surface roughness and unsteady wake forcing on the development of laminar separated boundary layer will be studied using direct numerical simulation (DNS) approach. The accurate and reliable prediction of both effects are of great practical interest.

INTRODUCTION

Flows encountered in many engineering applications involve boundary layers under the influence of adverse-pressure-gradient. This type of flow is typically found on the suction side of low-pressure turbine blades and contains complex phenomena with unsteady separation, reattachment, wakes, and vortex interactions, which might have impeded a more thorough study. The general difficulty in the study of this flow is the comprehensive effects of the wide range of parameters, such as, the upstream turbulence, the parameters related to the wakes, the surface roughness, and the pressure gradient and its functional form, hence the flow characteristics cannot be expressed as a function of a single parameter. In particular, wake flow impinges on the surface of the following turbine blade and periodically changes the portion of the laminar boundary layer to turbulent and affects the turbine aerodynamics, efficiency, performance and heat transfer.

In a previous study [3], we systematically investigated the wake-forcing effect on boundary layer development by varying the wake passing frequency and shape. In that study, we found that, the wake passing frequency is the key parameter to control the separation. The separation bubble size, and therefore the separation induced losses decreased significantly. Recently, we have initiated a DNS study to identify the key parameters of the trip elements that control the size of the separation bubble, by simulating separated boundary layers [2]. The location, the type, and the size of the trip elements are varied to study the effects on boundary layer development and turbulent transition, and it was found that the laminar separation and turbulent transition are mainly affected by the type, the height, and the location of the trip element.

The objective of this study is twofold. One is to investigate the impact of the periodic unsteady inlet flow conditions on the development of the roughly disturbed separated boundary layers. The other one is to provide detailed steady and unsteady boundary flow information to understand the underlying physics of the onset and the extent of the separation zone under the unsteady wake effects and discrete surface roughness. With these objectives in mind, a direct numerical simulation of a flat plate boundary layer subject to adverse pressure gradient will be presented.

RESULTS

The laminar separation bubble of interest is formed on a flat plate boundary layer due to a strong adverse pressure gradient similar to those encountered on the suction side of typical low-pressure turbine blades. It has been observed that the uncontrolled flow is initially laminar, separates, transitions within the separation bubble, reattaches as a result of the transition, and finally develops into an attached turbulent adverse-pressure-gradient [5]. The discrete surface roughness is modeled using the immersed boundary method [1, 6]. The numerical wakes designed to mimic the mean wake deficit created by a linear row of cylinders [4] moving in a direction perpendicular to the plate are superimposed at the inflow velocity profiles.

The following results indicate the individual effect of the roughness and wakes on the development of boundary layer. The instantaneous flow structures and mean flow statistics are shown in Fig. 1 in comparison with the uncontrolled flow [5]. Both shape factor and maximum turbulent intensity shown in Fig. 1 (c) and (d), respectively indicate that both roughness and wake alter the boundary layer development in a similar manner. The enhanced displacement due to the large separation bubble reduces significantly, resulting in lower losses. Furthermore, the separation location is shifted downstream and the reattachment point is moved upstream, while the height of the separation bubble is reduced. The maximum turbulent intensity provides a clear view of the turbulent activity along the flat plate. Initially the flow is laminar, the inflow disturbances stay almost constant up to the separation point. Further downstream those disturbances grow due to the inflectional instability of the velocity profiles. After the separation the two-dimensional instabilities grow linearly up to the transition location where the three-dimensionality controls the flow dynamics and the flow becomes fully turbulent. Due to the enhanced momentum transfer the bubble reattaches. The comparison between the individual influence of wakes and roughness on the separation indicates that the transition of the separated boundary layer with wakes occur almost at the same streamwise location as that induced by the roughness element. This indicates that the unsteady transition process and the growth rate of the disturbances are independent of the control mechanism.

Figure 2 provides a summary of the cases presented in [2] as well as the ones from [3]. The size of the bubble reduces significantly as the roughness element is located further upstream of the separation location. Similarly the unsteady forcing data indicates that if the forcing period is much lower than the time required for the bubble to recover itself after the wake passing, then the size of the bubble decreases significantly. In conclusion, the combined effect would be effective as long as the roughness is located further upstream of the separation point and the wake passing period is low. This hypothesis is studied by performing a new DNS study of a flat plate subject to adverse-pressure-gradient with a discrete two-dimensional surface roughness element located upstream of the separation bubble and forced by incoming wakes. Results will be compared with our previous studies that show the individual effects of roughness and wakes, and with instability analysis of the unforced flow.

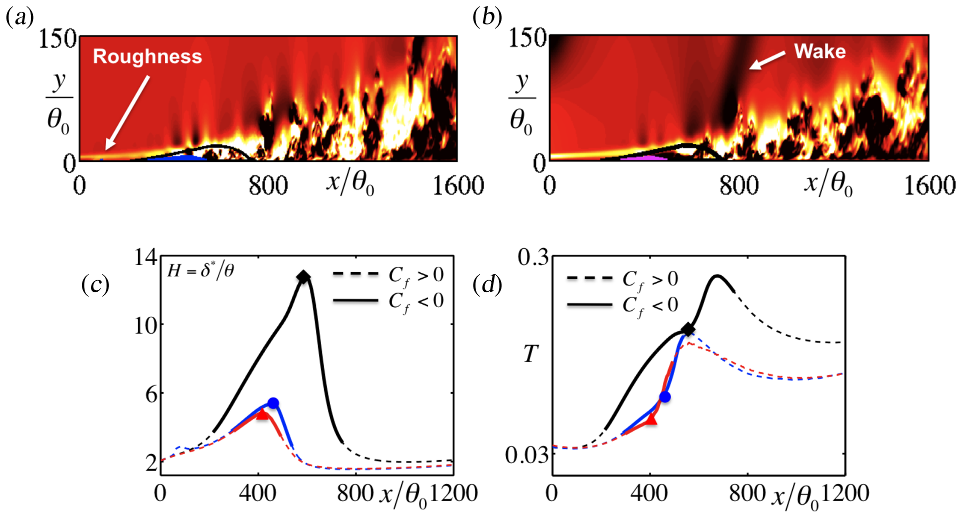

Figure 1. Instantaneous streamwise velocity fluctuations: (a) Roughness element; (b) Unsteady wake forcing. Mean flow statistics: (c) Shape factor; (d) Maximum turbulent intensity. Black: Smooth, unforced case, Blue: Roughness element, Red: Wake forcing. (c,d): Symbols mark the transition location.

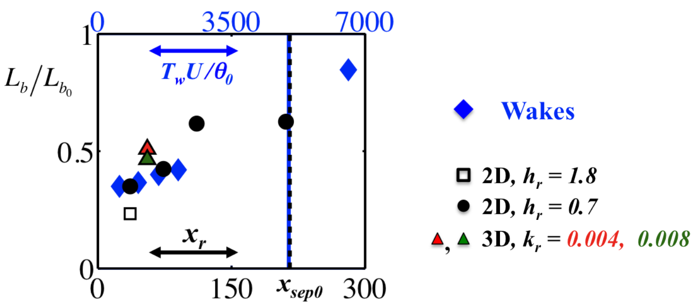

Figure 2. The effect of the roughness location x_r, height h_r, and type k_r (2D: $k_r = 0$, the roughness height is uniform in the transverse direction; 3D: $k_r > 0$, the roughness height varies as a function of the transverse direction) [2] (bottom x-axis) and wake passing period T_w [3] (top x-axis) on the size of the separation bubble L_b. Blue vertical line: The time required for the separation bubble to regenerate itself, $5000\theta_0/U_{ref}$, where θ_0 is the momentum thickness and U_{ref} is the reference velocity at the inflow.

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