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Numerical Investigation of Passive Flow Control Using Grooves and Dimples for LPT Blades

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Extended Abstract

The demand for reducing the number of blades per stage in gas turbines aims to decrease overall engine weight, leading to lower costs and improved fuel efficiency. The low-pressure turbine (LPT) contributes nearly one-third of the engine's weight; therefore, even a small improvement in LPT blade efficiency can significantly reduce overall engine weight, resulting in considerable annual savings in aircraft operating costs. A key challenge in achieving high-efficiency LPT performance is addressing the effects of low Reynolds numbers experienced by aircraft during cruise conditions at high altitudes and higher aerodynamic loading due to the reduced blade count. These conditions can lead to a flow separation over the suctions surface of the LPT blade. When the boundary layer separates, it undergoes rapid transition and reattaches as a turbulent layer, forming a laminar separation bubble (LSB) [1,2]. The formation of the LSB causes unsteady flow and dictates the downstream evolution of the boundary layer, deteriorating aerodynamic performance by increasing drag and decreasing lift on turbomachinery components such as turbine blades and aircraft wings [3]. Thus, controlling flow separation and associated transition over the suction surface of LPT blade is crucial to enhance the overall performance of a turbomachine.

Both active and passive techniques have been explored in the past for controlling flow separation and transition. Active techniques, such as vortex-generating jets, plasma actuators, fluidic oscillators, and dynamic humps, require additional devices and external energy sources [4]. In contrast, passive methods are easier to implement in real engines, offering a cost-effective and reliable solution as they operate without external energy input [5]. In this study, the effects of various surface modifications on the boundary layer development and LSB behaviour over a LPT blade are investigated. Two passive surface modifications are considered: two-dimensional transverse groove and dimples inspired by a golf ball. To accurately capture complex flow structures and provide a time-resolved description of the flow field, a high-fidelity computational approach is essential. The filtered, Navier–Stokes equations were solved using the finite volume approach in Ansys Fluent v20, employing Large Eddy Simulation with a dynamic subgrid-scale model. Simulations are performed over a flat plate under an imposed adverse pressure gradient, similar to the suction surface of LPT blade, at a Reynolds number of 340 (based on the inlet velocity and displacement thickness δ^*) with a freestream turbulence of 1.02%.

For the smooth surface, the normalized velocity and streamwise RMS profiles show good agreement with available experimental data at mid-span ($z = 25\delta^*$), with flow separation and reattachment observed at streamwise locations $x = 410\delta^*$ and $x = 510\delta^*$, respectively [2]. For the grooved surface, both the onset of separation and reattachment are shifted downstream, and the length of the primary separation bubble is reduced by approximately 14.5%, relative to the smooth surface. In the case of the dimpled surface, at a plane $z = 25\delta^*$, the onset of separation is shifted downstream to approximately $x = 419\delta^*$ attributed to the geometric features. Additionally, along the centreline ($z = 12.5\delta^*$), the flow separates at the beginning of the dimple and does not reattach before the primary separation, unlike the two-dimensional groove case. At both locations, the reattachment of the bubble occurs close to $x = 519$. Furthermore, the turbulent quantities are reduced in magnitude and confined closer to the wall for both kinds of surface modification. This behaviour contrasts with the smooth surface, where peak turbulence typically occurs within the shear layer, away from the wall, indicating a significant alteration in the near-wall turbulence dynamics due to surface structuring.

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