Abstract

The pursuit of more compact and efficient aero-engine designs demands a profound understanding of complex aerodynamic phenomena within compressor components. As engine operating speeds and overall pressure ratios increase, these components face higher aerodynamic loading, leading to performance reduction. These adverse effects, particularly the increased losses due to shock boundary layer interaction (SBLI), are especially pronounced when boundary layers remain laminar. Such conditions are typical for engines operation at high altitudes, where Reynolds number reaches low values. The interaction of shock wave with the laminar boundary layer in these conditions often results in its separation, increased blockage, and severe unsteadiness, ultimately limiting the entire engine efficiency. To mitigate this, it is highly desirable to induce a laminar-turbulent transition before the boundary layer interacts with the shockwave. This effect can be achieved, among other things, through controlled modification of the compressor blade surface. This study presents an experimental investigation into the effect of surface roughness on the interaction of shock waves with the boundary layer on the suction surface of a transonic fan profile.

The experimental work was conducted in a single passage transonic fan profile, replicating typical turbomachinery operating conditions involving a high adverse pressure gradient where SBLI-induced separation is prone to occur. Five versions of test profiles were manufactured with various texture and subjected to detailed surface evaluation. A comprehensive suite of advanced, non-intrusive techniques was employed, including high-speed schlieren imaging, oil flow visualisation, computer vision-based shock tracking, and boundary layer measurements using Laser Doppler Anemometry (LDA).

A critical finding was the relationship between favorable aerodynamic effects and flow stability. While time-averaged pressure data consistently classified the overall SBLI as laminar-type due to the stable mean shock position, the high roughness forced a highly three-dimensional, turbulent flow structure within the interaction and separation zones. This turbulent state yielded a profound, dual consequence. The aerodynamic benefit was substantial, as the enhanced turbulent mixing successfully re-energised the boundary layer, leading to superior flow recovery. This gain was confirmed by a 7.95% reduction in the overall separation area and a crucial 19.4% reduction in momentum thickness at the trailing edge region.

Conversely, this localized flow modification incurred a severe unsteadiness cost. Quantitative shock tracking analysis confirmed a significant increase in shock wave oscillations, with the high-roughness profile exhibiting an increase in oscillation amplitude of 40.58% relative to the smoothest baseline. This type of instability can be attributed to a high-frequency acoustic feedback mechanism, resulting in oscillations largely dominated by large-scale, low-frequency motion originating from the separation zone.

This investigation provides an enriched dataset and effectively improves our understanding of the operational limits of compressor blade surface roughness in the context of their aerodynamic properties. The findings are vital for developing robust design strategies aimed at optimizing performance in high-speed internal flows.