NUMERICAL STUDY ON SHOCK WAVE–BOUNDARY LAYER INTERACTION AND ITS CONTROL

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EXECUTIVE SUMMARY

The overarching objective of this project is to study and improve the numerical modeling of ramp-induced shock wave–boundary layer interaction (SWBLI) control by micro-vortex generators (MVGs) in high-speed flows. The research team utilizes high-order large-eddy simulation (LES) with a large grid system to study the correlation between SWBLI low-frequency and vortex motion.

SWBLI, which causes boundary layer separation and adverse pressure gradients, is a prominent problem faced by the air-breathing propulsion systems of high-speed aero vehicles. The consequences of the interaction include degraded engine performance and decreased overall propulsive efficiency of a high-speed vehicle. MVGs can alleviate or overcome the adverse effects of SWBLI and, therefore, improve the "health" of the boundary layer. An improved physical understanding of how MVGs reduce shock-induced boundary layer separation will contribute significantly to the understanding of the complex viscous–inviscid interactions that dominate high-speed aerodynamics.

RESEARCH CHALLENGE

SWBLI, which causes boundary layer separation and adverse pressure gradients, is the prominent problem faced by the air-breathing propulsion systems of high-speed aero vehicles. Particularly, SWBLI in high-speed inlets can significantly reduce the quality of the flow field by inducing large-scale separation, causing total pressure loss, flow distortions, localized heating and peak pressures, and unsteadiness. The consequences of the interaction are generally degraded engine performance and also the decreased overall propulsive efficiency of a high-speed vehicle. An improved understanding of SWBLI and flow-control technologies will directly benefit aeronautics research.

METHODS & CODES

As a result of advances in computer and code capability, high-order and high-resolution LES has become an important tool to study flow mechanisms. To capture details of instantaneous flow structure and reveal the mechanism of interaction between the vortices and the shock wave, large-scale LES was carried out.

The research team used body-fitted grids for discretizing the domain. In order to obtain high-order accuracy, an elliptic grid generation with orthogonal and smoothness requirements was adopted to generate the grids [3]. The three-dimensional, time-dependent, conservative Navier–Stokes equations in a curvilinear coordinate were applied as the governing system. A fully developed turbulent inflow was generated by high-order direct numerical simulation (DNS) on a flat plate with flow transition from laminar to turbulent [6]. A million inflow files were recorded as a time-dependent turbulent inflow. Adiabatic and no-slip conditions were enforced at the wall boundary on the flat plate. Periodic boundary conditions were assumed for the spanwise direction. On the inflow (the inflow could be subsonic in the lower part of the boundary layer) and the outflow boundaries, nonreflecting boundary conditions [7] were applied.

RESULTS & IMPACT

The research team collected MVG-controlled ramp flow data at two different Mach numbers (2.0 and 2.5). More data (at Mach numbers 3.0, 3.5, and higher) will be collected in the future. The study of supersonic ramp flow controlled by MVG array is ongoing and data are being collected.

A series of ringlike vortices generated behind an MVG array was discovered by high-order and high-resolution LES (Fig. 1). The mechanism of the evolution and interaction of these vortices will be investigated both numerically and analytically.

The numerical results obtained through this project will lead to a better understanding of the driving source of low-frequency unsteadiness of the SWBLI and thus may aid in developing methods to improve flow control in high-speed flows. The methods presented in this study as well as the resulting numerical solutions and mathematical model can pave the way for fully understanding the mechanisms of SWBLI.

WHY BLUE WATERS

Computational fluid dynamics is one of the best techniques to study complicated flows. The major scientific challenge in this study is the need to mimic the turbulent boundary layer; shock waves; the flow separation induced by the strong ramp shock; interaction between the vortices and shock waves; and the transfer of momentum, heat, and mass in the flow field. The evolution of high-performance computing (HPC) has led to significant advances in the numerical simulation of fluid flows, including turbulence, and has encouraged the direct numerical simulation of some flows. Major challenges still remain, however, and the computational requirements for turbulence-related research, driven by well-established physical scaling laws, are likely to remain at the limit of the available HPC resources for some time. The main challenge in this study is to capture numerous small-scale vortices and the detailed process of the vortex–shock wave interaction in such a complex system with the existence of the turbulent boundary layer and flow separation. This requires very powerful massively parallel processing systems along with large memory and a very large amount of storage. As one of the most powerful supercomputers in the world, Blue Waters is the best choice for this project.

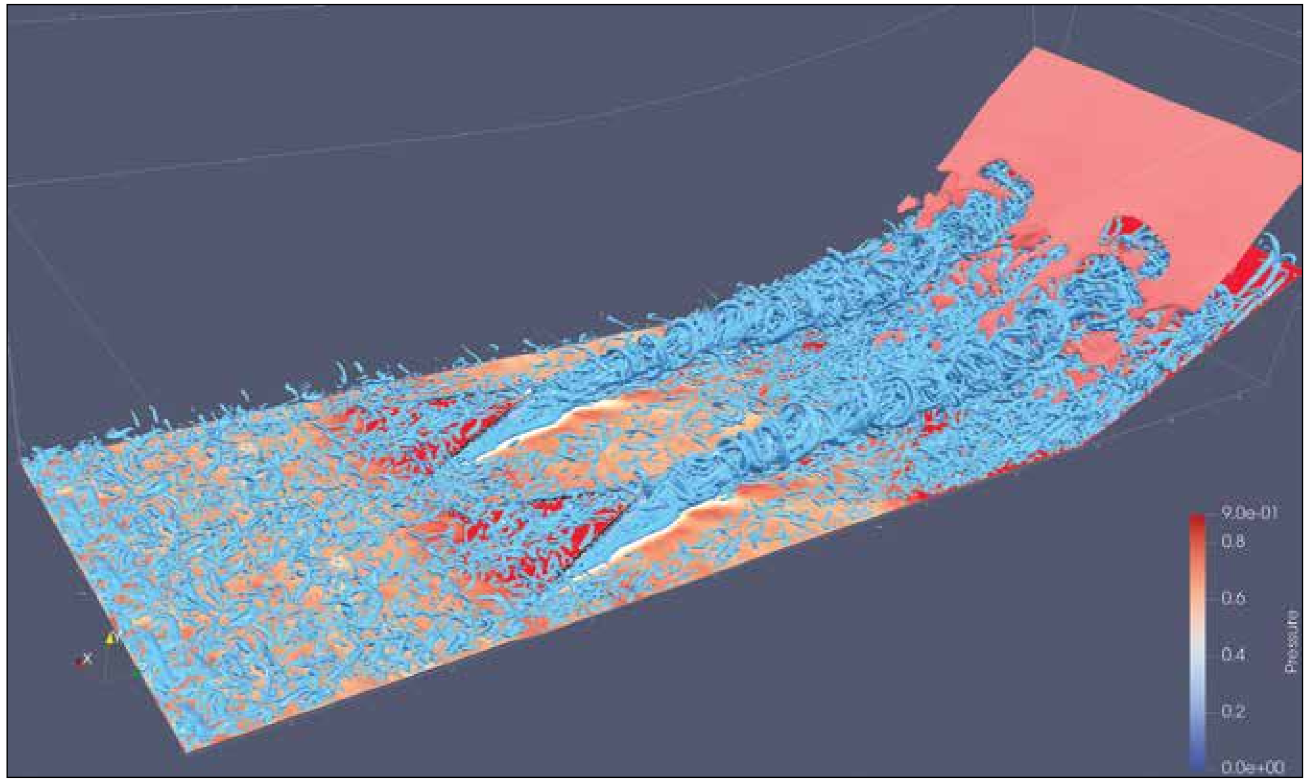

Figure 1: Vortex structures (in blue) after an MVG array (two installed). Red iso-surface represents shock wave at the ramp.