Shock Wave-Boundary Layer Interaction: A Survey of Recent Development

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Abstract. This paper reviews the latest research advancements in shock wave boundary layer interactions. These interactions are crucial in aerospace engineering, particularly in design of hypersonic vehicle inlets, flow control, and thermal protection systems. The paper first revisits the fundamental physical phenomena and theoretical models of SWBLI, then delves into recent experimental and numerical studies under various flow conditions, including supersonic inlets, turbomachinery, the effects of expansion waves, and the impact of roughness elements. Through an analysis of these research findings, we summarize the main characteristics, influencing factors, and control methods of SWBLI, and highlight future research directions and challenges.

Keywords: Shock wave boundary layer interactions; Hypersonic; Numerical simulation; flow separation; thermal protection.

1. Introduction

Shock Wave/Boundary Layer Interaction (SWBLI) is an important and complex phenomenon in high-speed aerodynamics, particularly pronounced in supersonic and hypersonic flows. This interaction involves nonlinear flow characteristics and the coupling of multiple physical processes, significantly impacting the performance and structural integrity of aircraft or blades in the Gas Turbine. When a shock wave meets the boundary layer, the flow within the boundary layer decelerates due to the high-pressure effects behind the shock wave. This deceleration can cause flow separation, forming a so-called separation bubble. This separation bubble and its accompanying complex flow structures, such as shock-induced vortices and reverse flow regions, can adversely affect the aircraft's control performance and structural safety, including lift loss, increased drag, surface heating, and increased local loads. [1]

In hypersonic flows, shock waves are close to the surface, and the flow field between the shock wave and the surface is called the shock layer. In this case, the boundary layer and the shock layer cannot be clearly distinguished, and the viscous effects and temperature variations within the layer must be considered as a whole.

In-depth research into the mechanisms of shock wave and boundary layer interactions is crucial for understanding these flow characteristics and has direct implications for designing and optimizing high-performance aerospace vehicles. Researchers utilize various experimental and computational methods to study these interactions. Experimental research typically involves advanced flow visualization techniques such as Particle Image Velocimetry (PIV), Laser Induced Fluorescence (LIF), and schlieren methods, along with precise pressure and temperature measurements. Computational methods include using Computational Fluid Dynamics (CFD) models to simulate and understand flow phenomena, which can be traditional methods based on Reynolds-Averaged Navier-Stokes (RANS) equations or higher fidelity methods like Large Eddy Simulation (LES) or Direct Numerical Simulation (DNS).

The structure of Shock Wave/Boundary Layer Interaction (SWBLI) mainly results from the boundary layer's response to the sudden local compression imposed by the shock wave. One of the most notable side effects of SWBLI is the induction of flow instability. When the shock wave strength is sufficient to cause flow separation, this instability can be particularly severe. This instability, when associated with turbulent eddies, may manifest as high-frequency oscillations; when related to the instability of the separation bubble, it may occur at lower frequencies.

Given the importance and complexity of SWBLI phenomena, extensive research continues in both academia and industry to improve the performance and safety of aerospace vehicles under extreme flight conditions. This paper aims to review the key scientific issues, recent research progress, and future research directions of SWBLI, providing readers with a comprehensive scientific and technical perspective.

2. Literature Review

2.1. Basic Phenomena of Shock Wave/Boundary Layer Interference

In the study of high-speed aerodynamics for scramjet engines, scientists such as Huang Rong and Li Zhufei observed a phenomenon of periodic large-amplitude low-frequency oscillations of shock trains in the high Mach number intake during experiments. Detailed analysis by the team revealed that the primary frequency of these oscillations is mainly related to the interaction between the shock front separation and the upstream boundary layer, influenced by interference from the background wave system. Such periodic shock oscillations can affect the engine's performance stability and efficiency; therefore, accurately predicting and controlling these oscillations is crucial for engine design. This finding provides new perspectives for the aerodynamic design of scramjet engines. [2]

In the field of high-speed aerodynamics, researchers such as Sheng Fajia and Tan Huijun have conducted in-depth studies on the interaction between double-swept shocks and a turbulent boundary layer in a double-fin/flat-plate system using numerical simulation techniques. This research has revealed significant flow coherence between the two shock interaction zones, providing new insights into the understanding of complex shock wave-boundary layer interactions. In the study, the first interaction zone exhibited traditional quasi-conical similarity, indicating that the flow characteristics in this region possess a certain degree of self-similarity along the conical path. Additionally, unique lambda (λ) wave structures were formed in both interaction zones, which developed along the flow direction and gradually approached and merged in the downstream region, forming a more complex lambda wave structure. [3]

Further research indicates that in the design of supersonic and hypersonic inlets, the interference phenomena of multiple swept shocks with the boundary layer are prevalent. Such interference induces large-scale three-dimensional flow separation within the inlet, causing the accumulation of local low-energy flow and the formation of localized high heat flux areas, which are detrimental to the aerodynamic performance and structural integrity of the inlet. As the flow progresses downstream, these structures converge, ultimately forming a single, stronger lambda (λ) wave and vortex structure. The increase in downstream shock intensity expands its interference range upstream, leading to an increase in the spanwise deflection angle of the upstream low-energy flow. [4]

Wang Dexin's research deeply explored various complex flow phenomena, covering scenarios such as V-shaped blunt leading-edge shock wave interference, shock wave-boundary layer interaction in convex corner regions. In the convex corner region study, particularly under high back-pressure environments where these interactions lead to complex flow separation and reattachment phenomena, significantly impacting the performance of the inlet. Additionally, Wang Dexin's research addresses the issue of shock train oscillations in axisymmetric inlets. Under high back-pressure conditions, the oscillations of shock waves have a significant impact on airflow stability and efficiency. [5]

Volf Y. Borovoy, Ivan V. Egorov, and other scholars indicated that due to the formation of a high-entropy layer behind the oblique shock wave, the length of the flow separation region increases and the gas density decreases, significantly reducing the peak heat transfer coefficient in the reattachment region on the blunt plate. They found a relationship between the bluntness radius and the free-stream Mach number, which affects the efficiency of heat transfer. [6]

Yang Guang and Fang Jian, along with other researchers, investigated the impact of micro-vortex generators (MVGs) on the interaction between oblique shock waves and turbulent boundary layers using Large Eddy Simulation (LES) technology. They found that in the time-averaged flow field, a pair of counter-rotating streamwise vortices forms in the wake region of the MVG. These streamwise vortices enhance momentum exchange within the boundary layer, thereby improving the boundary layer's resistance to separation.In the transient flow field, the researchers observed that the shear layer in the wake of the MVG curls into a series of spanwise vortices due to Kelvin-Helmholtz (K-H) instability. This indicates that MVGs can effectively manipulate the flow field to improve the interaction between oblique shock waves and turbulent boundary layers, which is of significant application value in high-speed aerodynamic design.Overall, Yang Guang and Fang Jian's study provides valuable insights into understanding and designing flow control strategies to manage shock wave and boundary layer interactions. Their detailed analysis of the impact of MVGs on flow field structure and dynamics offers important guidance for developing effective flow control solutions. [7]

Jiao Hao, Chi-Yung Wen said that considering three-dimensional effects results in a smaller predicted size of the separation bubble, as well as reduced surface heat flux and pressure peaks. Real gas effects tend to reduce the size of the separation bubble and lessen the far-field effect of the separation shock caused by the second wedge. [8]

Yue Zhang, Hui-jian Tan found that under the influence of expansion waves, empirical formulas derived from shock wave/flat plate boundary layer interaction data fail.The research demonstrates that the impact of expansion waves on the interaction between shock waves and the boundary layer on the cowl is significant, and this impact varies with the relative position. In particular, when the cowl shock is near the shoulder region, the interaction modes of shock-shock-expansion wave and shock-expansion wave-shock tend to produce positive effects on shock wave/boundary layer interference, helping to suppress boundary layer separation. [10]

2.2. Impact of Interaction Effects on Other Physical Processes

In Zhang Yang's research, to gain a deeper understanding of the impact of shock bifurcation on flame propagation, focusing on unveiling the intrinsic mechanisms by which shock bifurcation in the flow field leads to flame acceleration.The study found that when the flame front enters the shock bifurcation region, the inhomogeneous recirculation zones in the flow field stabilize the flame. This bifurcation structure not only allows the flame front to continuously supply energy for the accelerated movement of the shock wave but also promotes rapid flame propagation forward in the localized supersonic regions. As a result, the flame can propagate closely following the shock wave. [11]

The research by Jian Liu and Weiyang Qiao found that when an inlet jet is introduced, although the strength of the incident shock wave and the interaction between the shock wave and the boundary layer (Shock Wave/Boundary Layer Interaction, SWBLI) are enhanced, the length of the separation bubble is observed to decrease.Additionally, when the inlet jet is introduced, the pressure fluctuation levels on the suction surface downstream of the jet increase, but the flow unsteadiness caused by SWBLI is significantly reduced. [12]

Jiawei Li, Jiangfeng Wang~~,~~ showed that the continuous impact on the wall surface by supersonic "jets" caused by shock wave interference leads to an increase in the maximum pressure coefficient on the wall by approximately 9 times, while the maximum heat flux on the wall increases by approximately 4.7 times. [13]

2.3. Structural Characteristics and Dynamic Behavior of Interfering Flows

The research by Fulin Tong, Jiayu Zhou reveals that the incident position of the shock wave significantly affects the length and height of the separation zone, particularly when the shock wave occurs at the corner or downstream of it. Specifically, changes occur in the logarithmic and wake regions of the velocity profile, leading to an increase in the inner layer flow structure parameters and a decrease in the outer layer. This change indicates that the near-wall flow tends to deviate from the typical turbulent state. This study is of great significance for understanding and controlling the complex flow phenomena commonly encountered under high-speed flight conditions, particularly in the design of aircraft aerodynamic layouts and the improvement of their performance. [14]

The research by Youxi Zhao, Yue Zhang found that in the uncoupled model, the separation zone presents a scimitar shape, with its maximum value occurring near the side wall (y = -0.19H). In contrast, in the coupled model, the formed separation zone has a symmetrical crescent shape, with the maximum value located at the symmetry plane (y = 0).[15]

Yao Yao and Gao Bo conducted a parametric study on the height of separation bubbles. Their analysis indicates that the height of the separation bubble initially decreases slightly and then increases with the increase in the incoming Mach number. Additionally, the height of the separation bubble increases with the increase in the external compression angle and flight altitude. [16]

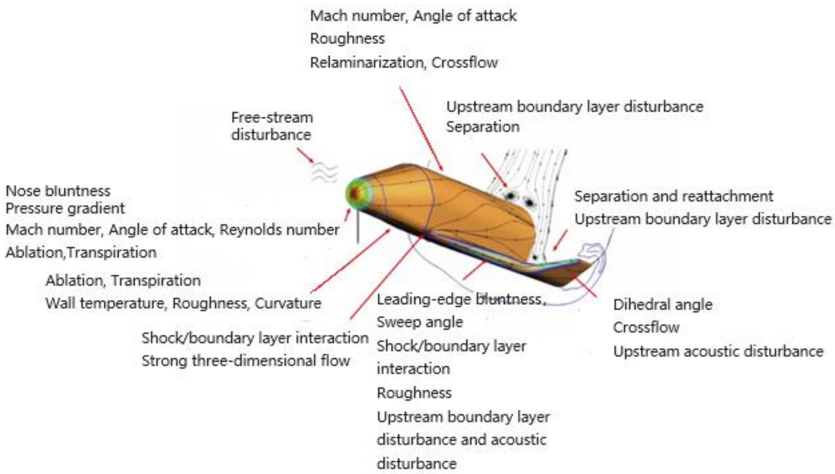

Figure 1. For the boundary layer transition phenomenon on the surface of hypersonic vehicles, crossflow instability is the dominant factor.

2.4. Research on Interfering Flow Control and Suppression Mechanisms

Yue Zhang, Huijun Tan point out that the complexity of inlet-related devices, particularly due to their multi-wave system and variable cross-section characteristics, causes the shock wave/boundary layer interaction within the inlet to exhibit significant peculiarities. Researchers have developed a series of flow control methods, such as boundary layer suction and micro-vortex generators. [9]

In the experimental study of supersonic inlets with a suction function, researchers observed the behavior of shock trains under different backpressure conditions. Under lower backpressure conditions, the shock train was observed to be suppressed downstream of the suction device, accompanied by oscillation phenomena. In contrast, under higher backpressure conditions, the shock train was restricted to oscillate near the suction slot. This indicates that the use of suction devices increases the complexity of the shock train oscillation characteristics in the inlet/isolator section, influenced by factors such as backpressure and background wave systems. However, despite the observed complexity introduced by the suction device, there is currently a lack of systematic research reports on the self-excited oscillation characteristics and mechanisms of shock trains in high Mach number inlets/isolator sections without the influence of backpressure. Therefore, the specific role of the suction device in the oscillation phenomena of shock trains still requires further research and exploration. These findings are of great significance for understanding and controlling complex flow phenomena in high-speed inlets. [2]

Gang Wang, Bo Wen focused specifically on the effects of the "herringbone riblet" flow control technique. It can effectively alter the three-dimensional features of the separation region caused by SWBLI. This control method led to an increase in the streamwise dimension of the interference region, a reduction in the height of the separation zone, and a slight increase in its length. Additionally, the pressure extremum in the reattachment region was reduced.[17]

2.5. Simplified Structural Study

Researchers proposed a simplified model for SWBLI. In this model, the separation bubble is abstracted as a triangular shape, and the total pressure increase is divided into two stages: the separation stage and the reattachment stage. It is assumed that the pressure increase in the separation stage is entirely due to the separation shock, where the separation angle is defined as the flow deflection angle that initiates the separation shock. Similarly, in the reattachment stage, the pressure increase is entirely due to the reattachment shock, with the reattachment angle being the flow deflection angle that causes the reattachment shock. Between the separation shock and reattachment shock, the wall pressure is maintained at a constant platform pressure value. To describe the wave system structure of this local flow field, the polar curve method is utilized. Through this simplified approach, the model can clearly predict the position and shape of the wave system structures such as the separation shock, reflected expansion wave, and reattachment shock, as well as provide detailed information on the flow parameters in each region. [16]

3. Experiments

3.1. Transonic and Supersonic Flow Characteristics Experiment

In the experimental study of transonic and supersonic flow characteristics, researchers Gang Wang, Bo Wen, and others utilized a pulsed suction-type transonic wind tunnel, where the airflow was expanded through a Laval nozzle to form supersonic flow. In the experiment, five herringbone riblets made from laser-cut polyester film were used. The researchers conducted detailed observations of the separation region under shock wave/boundary layer interaction (SWBLI) and determined the pressure peaks, thereby validating their research conclusions. [17]

Yazhou Liu designed experimental models of Bump inlets with top plates of different sweep angles. Using experimental methods such as pressure measurement, schlieren photography, and oil flow visualization, the flow field at the end of the inlet was investigated. The experiments, conducted in a suction-type free-jet supersonic wind tunnel, utilized various wall and lip components, as well as a plug cone for flow regulation, to validate simulation results.The study proposed the adoption of new flow control techniques, such as blowing, suction, vortex generators, and plasma jets, to control the SWBLI within the Bump inlet, aiming to enhance inlet performance. [18]

3.2. Shock Tunnel Experiments and Model Testing

Chen Suyu and colleagues also conducted experiments in the FD-14 shock tunnel. This tunnel is a reflected shock tunnel, with a driving gas mixture of hydrogen and nitrogen, while the driven gas is nitrogen. The nozzle exit diameter is 0.6 meters. By replacing the throat components, the tunnel can simulate flows with Mach numbers ranging from 6 to 12. By adjusting the total pressure, it can achieve a simulated Reynolds number range of 2.1×10^5 to $6.5\times10^7 m^{-1}$. The effective test duration ranges from 2 to 13 milliseconds. The experimental model is a cone with a half-angle of 7°, an axial length of 598.4 mm, and a variable nose bluntness of 0.2 mm, 0.5 mm, and 2 mm, respectively. [19]

Su Jiwei and other researchers conducted hypersonic boundary layer transition experiments using a sharp cone model with a 7° half-cone angle in the JF8A shock tunnel. Through heat flux measurements on the cone surface and PCB fluctuating pressure measurements, the development process of disturbance waves in the cone boundary layer was analyzed in detail. The experimental results showed that under the condition of a Reynolds number of 6.4×10^6m/s, the free stream noise of the core flow in the JF8A tunnel was 2.8%, while the noise within the nozzle boundary layer was as high as 7.8%.[20]

3.3. Interference Characteristics Study

To further verify the credibility of simulation results and to observe the characteristics of the flow field, Sheng Fajia and colleagues designed and implemented experimental research on a same-side double-wedge fin/plate model. This experimental model includes replaceable double-wedge fins and a plate, as well as a plate bracket to fix these components. By measuring the pressure distribution and surface flow patterns on the plate surface, they set up different double-wedge fin configurations to study their impact on shock wave boundary layer interference characteristics. A combination of dynamic and steady-state pressure measurement systems was used to capture flow field data, and the complex three-dimensional separated flow field was visualized using the oil flow method. Through the comprehensive application of pressure measurement and oil flow visualization techniques, detailed flow field measurements and observations of the same-side double-swept shock wave/boundary layer interference phenomenon were conducted. The high consistency between experimental and simulation results not only verified the reliability of the methods used but also confirmed the accuracy of the research conclusions. [4]

3.4. Panel Response and Interference Heat Transfer Experiment

In the study exploring the response of a thin flexible panel to shock turbulent boundary layer interactions, various advanced measurement techniques were employed, including 3D Digital Image Correlation (DIC), Pressure Sensitive Paint (PSP), Temperature Sensitive Paint (TSP), foil strain gauges, K-type thermocouples, and a fiber optic Laser Doppler Vibrometer (LDV). The research primarily focused on the application and extension of 3D DIC and fast-response PSP full-field measurement techniques to characterize the pressure, temperature, and displacement response of the panel in supersonic wind tunnel tests as comprehensively as possible. Although the attempt to combine PSP and TSP for simultaneous temperature and pressure measurement was unsuccessful, these efforts significantly enhanced the understanding of the panel's dynamic response and provided valuable data support for future modeling work. [21]

Volf Y. Borovoy et al. conducted experimental studies on the flow structure and heat transfer related to the interaction of oblique shock waves with near-wall flow on sharp and blunt plates under conditions of laminar and turbulent undisturbed boundary layers. The study involved varying the bluntness of the plates, the position and strength of the shock waves. The findings indicated that bluntness significantly reduced the maximum heat transfer coefficient in the reattachment region due to the increased length of the separation zone and the reduced density of the high-entropy layer gas. The effect of bluntness on heat transfer increased with the free stream Mach number, while the threshold bluntness radius decreased with increasing free stream Mach number. [6]

4. Measurement and Control Technology

4.1. Flow Field Visualization Technology

4.1.1 High-Speed Schlieren Method

The high-speed schlieren method is a non-intrusive flow field visualization technique, particularly suitable for capturing transient phenomena in high-speed flows, such as shock waves and turbulence. The advantage of this method lies in its ability to provide real-time intuitive images of density changes in the flow field. When combined with high-speed cameras, it enables high temporal resolution capture, offering researchers a powerful tool to visually understand complex flow phenomena.

This technique has been used in various studies, including the impact of chevron-shaped micro-ribs on shock wave boundary layer interactions, the morphology and oscillation characteristics of shock wave trains in dual-inlet/isolator sections with suction slots, the observation of airflow boundary layers, shock waves, and in high-speed schlieren visualization research of hypersonic boundary layer transition. [2][17][19]

4.1.2 Oil Flow Visualization Technique

The oil flow method is a flow field visualization technique that reveals flow characteristics by applying oil mixed with pigment to the surface of a model and observing the flow traces formed under the influence of airflow. This method is cost-effective and easy to operate, capable of intuitively displaying streamlines, making it particularly suitable for low-speed and medium-speed flow field studies in wind tunnels. Its advantages include intuitiveness and broad applicability, but it primarily provides qualitative information, making quantitative analysis more challenging. In the study of the interference characteristics of same-side double-swept shock waves and turbulent boundary layers, the oil flow method was used to visualize the complex three-dimensional separated flow patterns formed by the interference. [4]

4.2. Pressure Measurement Technology

Dynamic and steady-state pressure measurement technologies utilize high-precision pressure sensors capable of real-time monitoring of dynamic pressure changes and capturing transient processes. These sensors are suitable for various environments and conditions, including high-speed and high-pressure situations, providing comprehensive data to reveal complex flow phenomena. Meanwhile, wall pressure measurement based on pressure-sensitive paint (PSP) can provide full-field pressure distribution on the model surface with high spatial resolution, and its coating form minimally interferes with the flow field. Pitot tube measurements are often used to study the interaction between shock waves and turbulent boundary layers by measuring pressure changes before and after the shock wave. [4][17][20]

5. Computational Methods

Spottswood and other researchers combined the advantages of the Eckert reference temperature method and the Illingworth-Stewartson transformation method to create a new boundary layer weighting algorithm. This algorithm integrates boundary layer theory with the exact algorithms of oblique shock waves and expansion waves. In the computation of fully laminar or fully turbulent boundary layers, the ERT (Eckert Reference Temperature) method was used for evaluation. The theoretical models for laminar and turbulent flows are applied before and after the transition, respectively. [21]

In the field of numerical simulation of hypersonic combustion flow fields, Yang Zhang has developed a high-order accuracy Large Eddy Simulation (LES) solver for reactive flows. This solver employs an improved virtual cell immersed boundary algorithm based on high-order finite difference methods. The TTGC scheme is characterized by its high accuracy and low numerical dissipation, making it perform excellently in simulating high-speed reactive flows. The combination of these methods provides a powerful numerical tool for achieving high-precision computational analysis of bifurcation characteristics in the flow fields involving the interaction between reflected shock waves and boundary layers. [11]

In numerous Direct Numerical Simulation (DNS) studies of supersonic flow problems, Youde Xiong has applied the high-precision differential solver Open CFD-SC. The research also utilized the Proper Orthogonal Decomposition (POD) method to analyze and compare the fluctuation characteristics of wall shear stress under strong expansion effects and to highlight the differences with the flat plate incident shock interaction problem. [22]

The unresolved terms caused by the filtering operation in the simulation are handled through a dynamic subgrid-scale model in LES to simulate SWBLI . To ensure high accuracy in smooth flow regions and numerical stability at discontinuities such as shocks, Youxi Zhao and others utilized the fifth-order Weighted Essentially Non-Oscillatory (WENO-ZQ) scheme for the discretization of inviscid fluxes. For time advancement, they employed the third-order Runge-Kutta method. [15]

Direct Numerical Simulation (DNS) is a computational method that accurately captures all scale structures in fluid flow by solving the dimensionless three-dimensional compressible Navier-Stokes equations. Specifically, in their research, Fulin Tong and colleagues employed the WENO-SYMBO-LMT scheme optimized by Martin et al. and the Steger-Warming flux splitting method to compute the inviscid terms, thereby enhancing shock capture capability and stability. To accurately simulate viscous effects, they used an eighth-order central difference scheme for the discretization of viscous terms. Time advancement was handled using the third-order Runge-Kutta method. In the interaction region of shocks and turbulent boundary layers, they applied grid refinement in the wall-normal direction near the wall using a hyperbolic tangent function. This approach helps in capturing the fine structures within the boundary layer. [23]

6. Conclusion

SWBLI has remained a central topic in the field of high-speed aerodynamics in half century . Despite extensive research, its complexity leaves many critical issues insufficiently resolved. This review article summarizes some important aspects of SWBLI research that have not been fully explored.

First, real-world configurations are mostly three-dimensional, leading to complex flow structures and shock wave patterns. Even in nearly two-dimensional cases (such as channel flows or nozzle flows), the flow field exhibits three-dimensional characteristics, but the overall impact of these characteristics has not been deeply understood and has only recently received more attention.

Additionally, research on the instability of SWBLI has primarily focused on short time scales, while the behavior of long time scale instabilities is crucial for understanding and predicting phenomena in aeroacoustics, aeroelasticity, and combustion.

Shock wave/boundary layer interactions hold significant research importance and engineering application value in the field of hypersonic flows. This paper reviews recent major research findings, covering experimental studies, numerical simulations, and theoretical analyses. The research includes oscillatory characteristics of shock trains under different back pressure conditions, the influence of expansion waves on interactions, the interaction between oblique shock waves and turbulent boundary layers, and the phenomenon of shock bifurcation in complex three-dimensional flows.

Through the exploration of various forms of shock interactions, oscillatory characteristics and interaction mechanisms of shock trains under different conditions have been revealed. For example, the influence of expansion waves on inlet design is particularly critical; research shows that expansion waves significantly alter the interaction mode between shock waves and boundary layers, thereby affecting the separation and reattachment characteristics of the boundary layer.

In recent years, with the development of high-precision numerical methods such as Large Eddy Simulation (LES) and Direct Numerical Simulation (DNS), researchers have been able to more accurately capture the micro flow structures and physical mechanisms in SWBLI. These methods have performed exceptionally well in studying the flow characteristics of MVG-controlled oblique shock and turbulent boundary layer interactions. Advances in experimental techniques, such as hypersonic wind tunnel experiments and high-speed schlieren imaging, have also provided significant support for the research.

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