# Comparative Study of Numerical Simulation Methods for Flow Field Characteristics of Inlet Isolators

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## Abstract

Focusing on shock wave boundary layer interaction phenomena in inlet isolators, this study systematically compares the capabilities of the shock relation method, Euler method, RANS method, and DDES method in predicting shock train structures and wall pressure fluctuations. Back-to-back validation analysis is performed by incorporating limited wind tunnel experimental data (schlieren images and high-frequency pressure measurements) to reveal the high modeling requirements for scale-resolving methods (such as DDES) to accurately capture the unsteady behavior of shock trains and pressure fluctuation intensities. The research demonstrates that compared with the RANS method, the DDES method exhibits higher fidelity in key unsteady characteristics including the wave system structure on the forebody compression surface, separation bubble size, shock train oscillation characteristics, and the intensity and frequency of pressure fluctuations. Building upon this, the DDES method is employed to investigate shock train oscillation modes and pressure fluctuation intensities under various blockage degrees (varying wedge blocker height ratio h / H). The results indicate that under high blockage conditions (h / H = 0.3), a large-scale subsonic recirculation zone forms within the isolator, with the shock train oscillating longitudinally in the isolator at a frequency of approximately 110 Hz, and the pressure fluctuation intensity in the isolator reaching up to 180 dB; under no-blockage conditions (h / H = 0), the dominant flow mode is the high-frequency coupling interaction between the turbulent boundary layer and the shock train, wherein the boundary layer fluctuation frequency is significantly higher than the shock foot oscillation frequency by 1-2 orders of magnitude, and the pressure fluctuation intensity in the isolator reaches up to 156 dB.

## Full Text

# Comparative Study of Numerical Simulation Methods for Flow Characteristics in Inlet/Isolator Configuration

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## Abstract

Focusing on shock-boundary layer interaction phenomena in inlet/isolator configurations, this study systematically compares the capabilities of shock-relation methods, Euler methods, RANS methods, and DDES methods in predicting shock-train structures and wall pressure fluctuations. Back-to-back validation is performed using limited wind tunnel experimental data (schlieren images and high-frequency pressure measurements) to reveal the stringent modeling requirements of scale-resolving approaches (such as DDES) for accurately capturing shock-train unsteady behavior and fluctuating pressure intensity. Results demonstrate that DDES achieves significantly higher fidelity than RANS in predicting key unsteady features, including wave structures, separation bubble size, shock-train oscillation characteristics, and the amplitude and frequency of pressure fluctuations. Building upon this foundation, DDES is employed to investigate shock-train oscillation modes and fluctuating pressure intensity under varying blockage ratios (adjusted through wedge-height-to-channel-height ratio h/H). At high blockage conditions (h/H = 0.3), a large-scale subsonic recirculation zone forms within the isolator, with the shock-train oscillating longitudinally at approximately 110 Hz and pressure fluctuation intensity reaching 180 dB. Under unblocked conditions (h/H = 0), the dominant flow mechanism involves high-frequency coupling between turbulent boundary layers and the shock-train, where boundary layer fluctuation frequencies are 1–2 orders of magnitude higher than shock-foot oscillation frequencies, yielding pressure fluctuation intensities of approximately 156 dB.

**Keywords:** supersonic inlet; isolator; shock wave/boundary layer interaction; shock-train oscillation; wall pressure fluctuation; delayed detached-eddy simulation (DDES)

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The scramjet engine represents the core propulsion system for hypersonic vehicles, comprising an inlet, isolator, combustor, and nozzle. The inlet captures and efficiently compresses atmospheric air, while the isolator further decelerates and pressurizes the captured high-speed flow while isolating dynamic high back-pressure effects from the combustor. The compressed high-temperature, high-pressure flow then enters the combustor for thorough fuel mixing and combustion, after which it expands and accelerates through the nozzle to generate thrust for vehicle propulsion. A critical requirement for efficient scramjet operation is ensuring stable and orderly flow conditions within the inlet/isolator configuration [1].

The highly integrated airframe/engine design represents a typical layout for hypersonic vehicles, where the shock system at the scramjet inlet entrance exhibits strong internal/external flow coupling with the wave system from the vehicle forebody [2]. This coupled flow field contains unsteady flow features including turbulent boundary layers, shock-expansion wave systems, shear layers, and separation bubbles. Shock wave/boundary layer interaction phenomena [3] manifest as shock trains within the viscous boundary layer and supersonic mainstream region of the isolator, capable of self-sustained oscillations driven by unsteady turbulent boundary layer fluctuations. The combined effects of turbulent boundary layers, separation bubbles, and shock oscillations create a complex multi-physics dynamic loading environment involving forces, heat, and acoustics [4-6], which can catastrophically lead to thrust loss, inlet surge, structural fatigue, avionics damage, or even vehicle disintegration. This environment exhibits high sensitivity to disturbances including freestream Mach number [7], inlet boundary layer characteristics [8], incident shock strength [9], sidewall effects [10], and combustor unsteady pressure [11].

With rapid advances in high-performance computing and compressible computational fluid dynamics algorithms, integrated numerical simulations of inlet/isolator internal/external flow coupling have progressed toward high accuracy, high resolution, and refined prediction capabilities. Numerical methods primarily fall into three categories: shock-relation methods, low-fidelity numerical methods [12], and high-fidelity numerical methods [13]. Shock-relation methods employ shock-expansion wave theory to predict flow field wave structures, offering high computational efficiency but neglecting viscous boundary layer effects and thus cannot predict frictional drag. Low-fidelity methods primarily refer to Reynolds-Averaged Navier-Stokes (RANS) approaches, which exhibit strong numerical stability and low resource consumption, dominating scramjet internal/external flow coupling simulations for an extended period [12]. However, RANS methods exhibit limitations in predicting complex unsteady flow phenomena (e.g., shock oscillations, flow separation, shear layer evolution), making accurate prediction of complex dynamic loading intensity and frequency within isolators challenging. Researchers have increasingly employed high-fidelity scale-resolving flow simulation methods [13-15] (such as Direct Numerical Simulation (DNS), Large Eddy Simulation (LES), and Delayed Detached-Eddy Simulation (DDES)) to predict unsteady flow phenomena and complex fluctuating pressure loads in inlet/isolator configurations.

One mechanism driving shock-train oscillation in isolators is unsteady pressure perturbations from the combustor. In previous numerical studies, time-varying excitations were commonly applied at computational domain outlets to create combustor dynamic loading environments, as implemented by Gnani et al. [14], Ram et al. [15], and Xie et al. [16] using forced excitation methods to model combustor unsteady pressure fluctuation behavior. While numerically straightforward, such boundary implementations differ significantly from actual wind tunnel configurations, making precise back-to-back validation against wind tunnel results difficult. In wind tunnel experiments [17-20], adjustable-height blocks are typically placed downstream of the isolator to throttle the channel area and create unsteady back-pressure environments [21-22]; however, experimental techniques are limited by high-resolution three-dimensional flow field measurements, providing restricted flow details. Therefore, constructing geometric models consistent with experimental configurations and considering real blockage effects is necessary.

This study investigates the predictive capabilities of numerical simulation methods for wave system characteristics and fluctuating load environments in inlet/isolator configurations. Focusing on a classic two-dimensional inlet configuration, systematic comparisons are conducted among shock-relation, Euler, RANS, and DDES methods, with numerical results validated against wind tunnel schlieren images and fluctuating pressure measurements in a blind-to-blind manner. This reveals limitations of low-fidelity methods in predicting shock-train dynamic behavior and demonstrates the necessity of high-fidelity scale-resolving simulation approaches. Building upon this foundation, the influence of isolator blockage ratio (adjusted through internal blockage wedge height) on shock-train oscillation characteristics and fluctuating loads is further investigated, providing references and basis for predicting dynamic acoustic loads within inlet/isolator configurations.

## 1 Inlet Geometry Model

The two-dimensional supersonic inlet consists of a cowl surface, multi-stage compression ramps, a constant-area isolator, and a downstream wedge blockage. Geometric parameters are illustrated in Figure 1 [Figure 1: see original paper]. Key coordinate points include: the leading edge of the first compression ramp (L1) at (-356.92 mm, -75.33 mm), the compression ramp inflection point (L2) at (-216.57 mm, -58.03 mm), the cowl shoulder point (S) at (0 mm, 0 mm), and the cowl lip at (-57.50 mm, 30.00 mm). The isolator height H is 30 mm. The design Mach number is 4, following shock-on-lip design principles where the two oblique shocks from the external compression surfaces intersect at point C (-61.91 mm, 30.0 mm) ahead of the cowl lip. A wedge blockage is placed downstream for throttling, with the wedge leading edge located 292.5 mm downstream of the shoulder point S. The wedge base length is 25 mm, the leading edge angle is 45°, and the wedge height h is variable. Adjusting the wedge height simulates combustor unsteady back-pressure, enabling investigation of dynamic high back-pressure effects on shock-train position, intensity, and oscillation characteristics. The relative height h/H represents the throttling coefficient (or blockage ratio). In this study, wedge absolute heights of mm, mm, and mm are employed, corresponding to relative heights h/H of 0, 0.1, and 0.3, respectively. At the design Mach number (M = 4), the freestream total pressure is kPa, total temperature is K, the Reynolds number based on m is , the static pressure is kg/m$^3$, static temperature is K, and density is .

## 2 Numerical Setup

Numerical simulations of the inlet flow illustrated in Figure 1 are conducted using an in-house developed compressible-flow, full-speed-range, high-order finite-difference solver. The solver employs a geometric conservation high-order cell-centered finite-difference method [23] to discretize the Navier-Stokes equations on arbitrary curvilinear grids. The solver demonstrates high-resolution simulation capabilities for complex turbulent flows [23-25] and supports various numerical approaches including full-speed-range Euler, RANS, DDES, LES, and DNS.

For the inlet geometry, the GK-01 two-dimensional inlet [26] with an inlet Mach number of 7 is selected for validation. Three grid resolutions are designed for grid convergence verification: coarse (40,000 cells), medium (100,000 cells), and fine (200,000 cells). The pressure coefficient distribution along the isolator is presented in Figure 2 [Figure 2: see original paper], where medium and fine grid results show good agreement with each other and with experimental data from the literature [26]. Based on the fine grid distribution from this validation case, the grid for the current two-dimensional inlet is designed with a topology shown in Figure 3 [Figure 3: see original paper] and approximately 500,000 cells. The two-dimensional grid is extruded in the spanwise direction to create a three-dimensional grid with a spanwise width of mm and 25 uniformly distributed grid points, employing periodic boundary conditions. The final three-dimensional grid contains approximately 12.5 million cells. In subsequent discussions, Euler and RANS simulations are steady-state two-dimensional simulations, while DDES simulations are unsteady three-dimensional simulations. For temporal discretization, unsteady simulations employ a dual-time-stepping algorithm with second-order backward differencing for physical time and an Alternating Direction Implicit (ADI) algorithm for pseudo-time advancement. Steady simulations use a pseudo-time-based implicit time-marching method. The pseudo-time step is determined by stability criteria with a Courant number of 10,000, ensuring residual reduction by three orders of magnitude. The physical time step is selected based on flow characteristics.

## 3 Wave System Analysis

### 3.1 Shock-Relation-Based Wave System Analysis

The majority of the narrow isolator channel in supersonic inlets comprises supersonic mainstream regions. Oblique shock relations determine the wave system positions and pre/post-shock flow parameters for the two-dimensional inlet entrance section (Table 1 ). Based on these relations, Figure 4 [Figure 4: see original paper] clearly shows that the two compression ramp oblique shocks intersect at point C ahead of the cowl lip, with the cowl lip shock impinging downstream of the shoulder point S and subsequently forming a reflected shock train within the isolator.

### 3.2 Euler-Based Wave System Analysis

Euler simulations neglect viscous boundary layer effects, focusing solely on supersonic mainstream wave structures and positions. The Mach number contour for the inlet entrance section at M = 4 is presented in Figure 5 [Figure 5: see original paper], revealing a small triangular supersonic expansion fan region downstream of the shoulder point S—a characteristic feature of inviscid Euler simulations. Comparing Figures 4 and 5 demonstrates excellent agreement between shock systems obtained from oblique shock relations and Euler simulations. Additionally, for high-throttling conditions (h/H = 0.4), a detached bow shock forms on the compression surface with subsonic spillage downstream (Figure 6 [Figure 6: see original paper]).

### 3.3 RANS-Based Wave System Analysis

Real flow conditions involve viscous effects in near-wall regions; therefore, RANS simulations incorporating near-wall viscous effects and high-Reynolds-number turbulence are performed using the S-A one-equation model for eddy viscosity closure. RANS numerical simulation of the inlet shown in Figure 1 yields the time-averaged Mach number contour presented in Figure 7(b) [Figure 7: see original paper].

Comparing RANS results (Figure 7(b)) with Euler results (Figure 5) reveals similar shock positions, shock intersection points, and cowl lip shock impingement locations downstream of the shoulder. However, differences emerge in the flow morphology downstream of the cowl lip shock impingement region. Specifically, Euler simulations show flow acceleration past the shoulder point S, forming a supersonic expansion fan, because viscous boundary layer effects are neglected and the shoulder experiences only favorable pressure gradients. In contrast, RANS simulations exhibit a small separation bubble at the shoulder point S with subsonic flow, because an extremely thin viscous boundary layer exists between the supersonic mainstream and the wall. Supersonic mainstream shocks terminate at the boundary layer sonic line, and the subsonic region below the sonic line enables upstream acoustic feedback loops [27], forming self-sustaining boundary layer separation bubbles.

Varying the throttling coefficient h/H, RANS simulations investigate wave structure characteristics at different blockage ratios for freestream Mach number M = 4, with density gradient contours presented in Figure 8 [Figure 8: see original paper]. White regions indicate strong density gradient variations, identifying shock discontinuities, expansion waves, and strong shear layers. Focusing on the wave system near the downstream blockage reveals that the blockage acts similarly to a continuous forward and backward step, with the forward step creating a compression corner separation bubble and the backward step forming a recirculation zone. As blockage height increases, the bow shock ahead of the wedge strengthens and the separation region behind the wedge enlarges. Furthermore, when the shock strength induced by the forward step increases sufficiently to impinge the upper wall, a second reflected shock is generated. If this second reflected shock is sufficiently strong, it induces a secondary separation bubble and separation shock on the upper wall. After the supersonic mainstream passes the backward step, a compression shock is induced to realign the flow with the inlet mainstream direction.

Analysis of blockage ratio effects on isolator shock-train characteristics in Figure 8 indicates that when the local wave system remains relatively stable, shock-train behavior is predictable; however, when the wedge local wave system cannot stabilize, it forms an upstream-propagating shock train within the isolator. Therefore, this study defines three operating conditions: low-blockage, high-blockage, and unblocked.

### 3.4 DDES-Based Wave System Analysis

In Section 3.3, all flow fluctuations in the inlet flow were modeled, with no fluctuation information available for the shoulder separation bubble, shock-expansion wave system, or turbulent boundary layer. This section conducts DDES numerical simulations to capture unsteady turbulent boundary layer and shock-train oscillation characteristics within the inlet.

Figure 9(a) [Figure 9: see original paper] presents instantaneous flow features in the inlet entrance region. Comparing Figure 9(a) with Figures 5 and 7 reveals significant differences between DDES wave systems and those from Euler and RANS simulations. For reference and comparison, Figure 9(b) shows wind tunnel experimental schlieren results. In Figure 9(b), a pronounced dark schlieren line is observed entering the cowl interior. At the design Mach number, external compression surface shocks should always intersect ahead of the cowl lip (at point C). Therefore, this dark schlieren line is inferred to represent a virtual wall rather than external compression surface oblique shocks. Observing Figure 9(b) reveals that the cowl lip shock foot terminates in the upper half of the supersonic mainstream channel without extending to the lower wall, indicating a subsonic region in the lower channel portion. The subsonic region’ s presence implies a local separation bubble. Comprehensive analysis thus indicates that the dark schlieren line entering the cowl interior represents a virtual wall separating the supersonic mainstream region from the subsonic separation bubble, creating a new throat. Since the simulation in Figure 9(a) generally matches the wave system in Figure 9(b), DDES results demonstrate high consistency with experimental schlieren images.

Detailed analysis of DDES-simulated inlet entrance flow features is conducted by creating the schematic diagram in Figure 10(a) based on the instantaneous flowfield contour in Figure 10(b) [Figure 10: see original paper]. The large-scale separation (recirculation zone) on the lower compression surface acts similarly to a virtual wall, deflecting the supersonic mainstream direction while inducing a separation shock on the inclined compression surface, causing partial supersonic spillage and flow distortion. The entrance separation zone dynamically adjusts its size and position to achieve dynamic equilibrium among freestream dynamic pressure, internal channel pressure, and supersonic spillage mass flow. Figure 10(b) also reveals that the reattachment shock downstream of the lower wall separation reattachment point exhibits very high intensity; consequently, after the reattachment shock impinges the upper wall, it excites a secondary separation bubble and similar wave structures on the upper wall. Theoretically, whenever an oblique shock impinges a solid wall, a small separation bubble forms due to local adverse pressure gradients. However, as shock reflection count increases within the channel, shock intensity gradually weakens, and local small separation bubbles diminish and eventually disappear.

Further quantitative analysis of numerical predictions is presented in Figure 11 [Figure 11: see original paper], which plots the time-averaged pressure distribution along the isolator upper wall. DDES numerical predictions show good agreement with wind tunnel experiments [21] in magnitude, further confirming DDES result reliability.

The cause of the large-scale separation bubble in the inlet entrance section shown in Figure 10 is investigated using classical inlet starting theory. Based on empirical formulas from Kantrowitz [28] and Van Wie [29] for predicting inlet starting limits, Figure 12 [Figure 12: see original paper] is constructed. The current inlet’ s geometric contraction ratio (CR) is 3.511 (design Mach number 4), and the internal contraction ratio (ICR) is 1.463 (throat Mach number 3.01). According to starting limit theory 判定 in Figure 12, the inlet operating condition falls within the “dual-solution region,” where non-unique started/unstarted states are possible. Excessive geometric variation in the contraction section prevents captured flow from efficiently entering the throat, causing separation on the compression surface. However, since the mainstream region maintains supersonic flow, unstarting remains a local phenomenon—hence termed local unstarting or soft unstarting.

Based on analysis of Figures 9-12, DDES simulations exhibit the highest credibility in characterizing entrance wave systems. Therefore, DDES simulations are employed to investigate wave system characteristics varying with blockage ratio.

Adjusting the throttling coefficient h/H, wave system evolution within the isolator is observed (Figure 13 [Figure 13: see original paper]). Noting that separation bubble positions on the compression surface remain relatively stable across different throttling coefficients, the focus shifts to isolator flow. Longitudinal comparison of blockage region wave systems in Figure 13 yields the following conclusions: 1) When the channel is dominated by oblique shock-train and turbulent boundary layer interaction, each shock foot undergoes self-excited oscillation with similar patterns, where oscillation intensity correlates directly with incident shock strength and turbulent boundary layer dynamic evolution; 2) When near disturbances propagate upstream but back-pressure is weak, propagation capability is limited, affecting only local regions, with shock feet in unaffected oblique shock trains continuing self-excited oscillation; 3) When disturbance information upstream propagation range increases, the separation zone ahead of blockage enlarges, and the shock train system attached to the separation zone is pushed toward the cowl lip, exhibiting pronounced periodic large-amplitude oscillation characteristics (Appendix A).

## 4 Analysis of Fluctuating Load Frequency and Intensity in Isolator

This section focuses on analyzing the influence of throttling coefficient h/H on dynamic pressure fluctuation characteristics within the isolator. Wind tunnel experiments deployed pressure sensors on the upper wall; therefore, dynamic pressure probes are placed at identical locations in numerical simulations. Spectral analysis identifies pressure fluctuation amplitude and frequency, revealing fluctuation features and their connection to instantaneous flow structures.

### 4.1.1 Low-Frequency Fluctuating Load Analysis

Pressure fluctuation characteristics near the wedge region are analyzed first. Figures 14(a), (b), and (c) [Figure 14: see original paper] present pressure fluctuation time histories for sensors A, B, and C near the blockage under three operating conditions. Sensor coordinates are indicated by solid circles in Figure 14(a). Spectral analysis specifically examines sensor B’ s pressure fluctuations, as shown in Figure 15 [Figure 15: see original paper].

Vertical comparison of amplitude axes in Figures 14(a), (b), and (c) reveals that pressure fluctuation intensity increases significantly with blockage ratio. To establish connections between fluctuation frequency/intensity at different sensors and transient flow evolution, Figure 14 also plots instantaneous flowfields corresponding to three characteristic times “t1,” “t2,” and “t3.” According to Figure 14(a), when sensors exhibit only low-amplitude, high-frequency fluctuations without obvious low-frequency components, transient contours show relatively stable shock foot positions with only very weak offset and oscillation. Therefore, shock foot oscillation frequency directly correlates with turbulent boundary layer fluctuation frequency. Sensors in Figures 14(b) and (c) show more pronounced low-frequency oscillation characteristics, with oscillation frequencies of 215 Hz and approximately 110 Hz, respectively. Transient contours indicate that shock oscillation originates from periodic contraction and expansion of the separation zone at the compression corner ahead of the blockage. Notably, when high-pressure gas near the wedge can push the shock train completely toward the cowl lip, the channel becomes filled with low-subsonic flow, resulting in higher pressure fluctuation intensity. As the shock train moves substantially forward toward the cowl lip, the separation shock foot position on the lower compression surface also moves longitudinally. According to Figures 14 and 15, as blockage ratio increases, shock oscillation frequency decreases from 215 Hz to 110 Hz, indicating that pressure fluctuation intensity increases with blockage ratio while frequency shifts progressively lower. Furthermore, wind tunnel experiments measured periodic low-frequency oscillation frequencies of 116 Hz at sensors when [21], which closely matches the DDES-predicted 110 Hz, again confirming DDES reliability and necessity.

### 4.1.2 Mid/High-Frequency Fluctuating Load Analysis

This section analyzes pressure fluctuation characteristics at sensors near the isolator throat, including time histories and power spectra. Sensors D, E, F, and G are selected on the isolator upper wall near the cowl lip, with coordinates shown in Figure 16(a) [Figure 16: see original paper]. Sensors D and F are located in strong shock-boundary layer interaction regions (shock foot zones), while E and G are situated within turbulent boundary layers at some distance from shock feet.

Based on pressure coefficient fluctuation amplitudes on the vertical axis in Figure 16(a), root-mean-square fluctuating pressure coefficient amplitudes are calculated as 0.0823 and 0.0885 for sensors D and F, respectively, and 0.0224 and 0.0167 for sensors E and G, respectively. Clearly, pressure fluctuation intensities at D and F are 4-5 times higher than at E and G. The horizontal axis in Figure 16(a) reveals that D and F exhibit significantly lower dominant frequencies than E and G, typically associated with instantaneous mass dynamic ingestion and ejection within separation bubbles in shock foot regions.

Spectral analysis of pressure fluctuations at sensors F and G from Figure 16(a) yields Figure 16(b) [Figure 16: see original paper]. Results show sensor F' s fluctuation frequency at approximately 2,400 Hz (termed medium-amplitude, medium-frequency fluctuation), while sensor G' s dominant frequency ranges between 9,500–26,500 Hz (termed small-scale, high-frequency fluctuation). Since sensor F is located at the shock foot, its 2,400 Hz medium-amplitude, medium-frequency fluctuation correlates with self-excited oscillation at the shock-boundary layer interaction. Sensor G' s 9,500–26,500 Hz small-amplitude, high-frequency fluctuation, being within the turbulent boundary layer, relates to unsteady turbulent structure evolution within the boundary layer. Sensor F' s fluctuation frequency is approximately one order of magnitude lower than sensor G' s, indicating that shock foot oscillation unsteady characteristic frequencies are one to two orders of magnitude lower than turbulent boundary layer fluctuation characteristic frequencies—consistent with numerous studies on low-frequency oscillations induced by oblique shock impingement on boundary layers [27,30-32].

### 4.2 Fluctuating Load Intensity Analysis in Isolator

This section analyzes total fluctuating load intensity at different sensors within the channel. Fluctuating pressure is collected from sensors on the isolator upper wall, and root-mean-square pressure fluctuation and total load intensity (Sound Pressure Level, SPL) are calculated using:

$$SPL = 20\log_{10}\left(\frac{p_{rms}}{p_{ref}}\right)$$

where $p(n)$ is pressure at time n, $\bar{p}$ is time-averaged pressure, $p_{rms} = \sqrt{\frac{1}{N}\sum_{n=1}^{N}(p(n)-\bar{p})^2}$, and $p_{ref} = 2 \times 10^{-5}$ Pa. Figure 17 [Figure 17: see original paper] presents the streamwise distribution of total pressure fluctuation intensity SPL along the upper wall, showing acceptable agreement between numerical simulations and experiments [21]. Comparing different blockage cases reveals that low blockage yields SPL around 156 dB, while high blockage produces SPL up to 180 dB. Pressure fluctuation intensity increases monotonically with blockage ratio.

### 4.3 Effects of High-Intensity, Broadband Fluctuating Loads in Isolator

Based on Figures 15-17, high-intensity, broadband pressure fluctuation loads exist within the isolator, impacting lightweight thin-walled inlet structures as follows: 1) Low-frequency, high-amplitude loads at approximately $10^2$ Hz result from channel-wide blockage and large-scale recirculation caused by dynamic high back-pressure, often accompanied by massive flow separation. Such low-frequency pressure fluctuations, being close to structural natural frequencies, can induce resonant fatigue while significantly degrading inlet compression performance, causing periodic thrust fluctuations, and potentially leading to complete inlet flameout. 2) Mid-frequency, medium-amplitude loads at approximately $10^3$ Hz typically occur near shock feet when reflected shock trains are present, involving multiple shock foot oscillations. Adverse pressure gradients create local high pressure, thickening boundary layers, increasing friction drag, intensifying local thermal loads, and causing structural thermal stress variations. 3) High-frequency, low-amplitude loads at approximately $10^4$ Hz and above primarily involve pressure fluctuations within high-speed turbulent boundary layers. While small in amplitude, such high-frequency pressure fluctuations increase boundary layer turbulence intensity, exciting high-frequency structural acoustic vibration and directly affecting combustion stability.

## 5 Conclusions

This study investigates the capabilities of shock-relation, Euler, RANS, and DDES methods in characterizing shock-train structures and unsteady oscillation features in a two-dimensional inlet/isolator configuration. Results demonstrate that inlet entrance wave systems are highly sensitive to numerical methodology, with DDES predictions showing closest agreement with experiments. Specific conclusions include:

1) Interaction among shocks, expansion waves, and turbulent boundary layers creates rich multi-wave structures within the inlet/isolator. The primary difference between RANS and Euler simulations lies in the shoulder region: Euler simulations produce supersonic expansion fans at the shoulder, while RANS simulations generate small separation bubbles. The distinction between DDES and RANS simulations concerns separation bubble position and size: RANS small separation bubbles remain confined to the shoulder region, whereas DDES large separation bubbles extend to the forebody compression surface. Comparison with experiments confirms that DDES simulations achieve wave system characteristics most consistent with experimental results.
2) The isolator shock train dynamically adjusts its intensity and position to achieve equilibrium between freestream dynamic pressure and wedge region high back-pressure. Changing blockage ratio significantly affects shock-train morphology. Under unblocked conditions, the isolator is dominated by shock-train and turbulent boundary layer interaction; under low blockage conditions, high back-pressure induces only local recirculation without affecting compression surface separation bubbles; under high blockage conditions, wedge-induced recirculation moves upstream, merging with compression surface separation bubbles to create a large-scale subsonic region extending to the cowl lip, intensifying low-frequency shock-train oscillation within the isolator mainstream.
3) DDES-predicted pressure fluctuation characteristics within the isolator contain three components: a) high-frequency, low-amplitude fluctuations at approximately $10^4$ Hz caused by turbulent boundary layer unsteadiness; b) mid-frequency, medium-amplitude fluctuations at approximately $10^3$ Hz occurring at shock feet due to shock-boundary layer interaction; and c) low-frequency, large-amplitude fluctuations at approximately $10^2$ Hz caused by blockage-induced separation zone contraction and expansion.

The fluctuating load environment within scramjet isolators significantly impacts total pressure loss, propulsion efficiency, structural force/heat/acoustic fatigue, and combustion stability. High-fidelity numerical simulations can identify fluctuating load environments within inlets in detail, enabling understanding and control of such high-intensity dynamic loads. This work provides methodological guidance for accurately predicting flow structure evolution and fluctuating loads in hypersonic vehicle inlet/isolator configurations.

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*Supplementary animations illustrate isolator internal wave system structure evolution under different blockage height conditions.*

*Note: Figure translations are in progress. See original paper for figures.*

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