



REVIEW

Surface Pressure Distribution in High-Speed Aerodynamics: A Critical Review of Theory, Computation, Experiments, and Design Implications

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ABSTRACT: Surface pressure distribution is one of the primary factors governing the aerodynamic performance, stability, controllability, and structural loading of high-speed aerospace vehicles. Accurate prediction of surface pressure is therefore essential for the design, optimization, and safe operation of flight systems ranging from supersonic aircraft to hypersonic vehicles and atmospheric re-entry platforms. Over the past several decades, extensive theoretical, computational, and experimental research has sought to characterize pressure distributions over canonical configurations, including wedges, cones, and delta wings, across a broad spectrum of flow conditions. This review provides a critical and comprehensive assessment of the current state of knowledge on surface-pressure prediction in these cases. Particular attention is devoted to the influence of Mach number, angle of attack, geometric characteristics, shock-wave structure, and viscous effects on pressure-distribution behaviour. Classical analytical approaches, including shock-expansion theory, Newtonian theory, hypersonic similitude, and piston theory, are examined alongside modern Computational Fluid Dynamics (CFD) techniques and experimental investigations. Their assumptions, domains of applicability, strengths, and limitations are critically evaluated and compared across different flow regimes. The review further examines the impact of shock-wave/boundary-layer interactions, aerodynamic stability derivatives, unsteady flow phenomena, and active and passive flow-control strategies on surface-pressure characteristics. By synthesizing results from a broad body of literature, it identifies consistent physical trends, reconciles apparent discrepancies among previous studies, and highlights the principal sources of uncertainty that continue to limit predictive accuracy. The analysis demonstrates that reliable aerodynamic assessment increasingly relies on an integrated framework combining analytical methods, high-fidelity numerical simulations, and carefully validated experimental measurements. Finally, the review outlines promising directions for future research, with particular emphasis on high-Mach-number aerodynamics, real-gas and thermochemical nonequilibrium effects, uncertainty quantification, data-driven modelling, and advanced predictive methodologies.

KEYWORDS: High-speed aerodynamics; surface pressure; CFD analysis; supersonic; wedge angle; mach number

1 Introduction

In space exploration, high-speed flow study is a strict requirement and essential constituent. High-speed flow is usually characterized by freestream Mach values, which are dominated by strong shock waves, prominent compressibility effects, entropy formation, and high aerodynamic heating. These events affect the pressure distribution and unstable loading that high-speed vehicles, particularly those with narrow

forms such as wedges, delta wings, and reentry bodies, experience. Accurate prediction of aerodynamic forces and moments is particularly crucial in this regime for vehicle stability, control, and structural integrity. Similarity and scaling concepts were developed to simplify the governing equations at high Mach numbers. The theoretical underpinning of hypersonic aerodynamics was thus achieved. Tsien [1] illustrated the concept of similarity rules for irrotational and unsteady hypersonic flow. His results showed good conformity to experimental values. Later, Hayes [2] developed hypersonic similarity by generalizing this concept of converting stable hypersonic flow problems into corresponding unsteady problems. Hayes showed that global characteristics and similarity variables, as opposed to the absolute Mach number, are the main variables determining the pressure coefficient and aerodynamic forces in hypersonic flow. Morgan et al. [3] theoretically investigated panel flutter in the higher supersonic Mach number range through linear plate theory and two-dimensional first-order aerodynamics. Theories concerning the effects of damping and the relationship between traveling wave theories and standing wave theories on panel flutter were clarified. Hayes and Probstein [4] later consolidated and formalized these concepts to create a comprehensive framework that is still imperative in hypersonic aerodynamics research. Later researchers focused on aeroelastic phenomena and unstable hypersonic aerodynamics, where the interaction between surface oscillations and shock motion is equally important. Zartarian et al. [5] studied unsteady aerodynamic loading in high-speed compressible flows and developed a piston theory to approximate surface pressure on slender bodies for aeroelastic analysis. It was found that the results gave good agreement with exact solutions within the hypersonic regime and thus verified the one-dimensional flow assumption at high Mach numbers. However, the same study also noted reduced accuracy for complex geometries and at lower Mach number conditions. After the development of the piston theory, Sychev [6] attempted to generalize this concept into three-dimensional hypersonic flow involving slender bodies at high angles of attack. Using the slender-body thickness feature, he managed to reduce the complicated nature of hypersonic flow using a piston similarity concept. This work resulted in the development of basic relations for pressures and aerodynamic forces that are dependent on the transverse sections of the body. This concept indicated that approximate piston models are reliable and useful for Mach number simulations. Cole and Brainerd [7] obtained a Newtonian-theory formulation for a flat plate normal to a hypersonic stream. In the case of a slender flat wing, the results were applied in spanwise strips, and the heat-transfer rates were evaluated based on boundary-layer theory. Fair agreement was obtained with experimental results for delta wings at angles of attack near 90° . Pike [8] developed a technique for expressing the wing pressure in supersonic flow in relation to a thin wing of the same geometry. This technique was applied to the caret-shaped wing, flat wings with a delta geometry, with leading edge flow, and the results were found satisfactory when compared with past data, apart from regions with strong pressure gradients behind shock waves. An analysis of the expansion surfaces indicated that changing wing geometry, like reducing the angle of attack, could cause a minor increase in the lift-to-drag ratio for the caret wing. Hui [9] studied the stability of inviscid unsteady supersonic and hypersonic flows about wedge-like configurations with attached bow shocks using exact solutions of the perturbations. Exact stability derivatives and conditions for neutral damping were obtained for wedges and caret wings, and these were found to be dependent on the Mach angle of attack but not on aspect ratio. Later, Hui [10] derived a consistent analytical theory for supersonic or hypersonic flows with attached shock waves over delta wings at angles of attack, to improve numerical or analytic approaches in coping with the hybrid supersonic-subsonic crossflow. Hui's analysis achieves good agreement between predictions for pressure distributions and numerical solutions, which is unique in identifying a square-root singularity located at the crossflow sonic line. Orlik-Ruckemann [11] surveyed research and facilities about the dynamic stability requirements for the next generation of aerospace

craft and identified that there was a large research and facility deficiency related to wind tunnel testing capabilities for dynamic stability derivatives beyond Mach numbers of 0.1 and angles-of-attack greater than 25° , with respect to cross-coupled and coning motion forces and motions. Carrier [12] presented a modified theoretical formulation for an oscillating wedge, finite chord and infinite span, undergoing small oscillations about its leading edge. Perturbation-wave functions and reduction formulas for associated coefficients were derived and compared results with no-shock airfoil cases; these showed consistency in limiting behavior. Later, Hui [13] and Liu and Hui [14] examined unsteady oscillatory flows past slender delta wings in hypersonic flows with attached or detached shock waves using perturbation and thin shock layer methods. Hui and Hemdan [15] studied unsteady hypersonic flow over delta wings in the case of detached shock wave. Analytical solutions demonstrate the independence of the derivatives of the forces and moments from the incidence angle, with primary dependence on the frequency of oscillation, thus ascertaining the dynamic stability of the wings. Ericsson [16] determined the dynamic effects of hypersonic viscous-inviscid interaction in laminar flow, finding good agreement with experimentally observed changes in the inviscid unsteady aerodynamics of finite-thickness airfoils. The investigation demonstrated that the influence of viscous effects and elastic deflection can be computed using an embedded flow concept. Rossow [17] demonstrated that viscous effects cause substantial variations in inviscid unsteady aerodynamic forces, which can be modeled effectively using simplified embedded or interactive flow models. The piston theory was first derived by Lighthill [18] for oscillating airfoils over a large range of Mach numbers. Lighthill introduced the term “Piston Analogy” by relating the two-dimensional unsteady problem to the gas flow in a tube driven by a piston. Ashley and Zartarian [19] explored the piston theory as a new aerodynamic tool for aeroelasticity. The theory establishes a similarity between the behavior of a one-dimensional fluid column confined in a cylinder with a moving piston and a high-speed aerodynamic flow over a surface. Appleton [20] made an analytical investigation into the aerodynamic pitching derivatives of a two-dimensional wedge in hypersonic flow. Employing hypersonic similarity and inviscid High-Mach-number assumptions with an attached shock, closed-form expressions were obtained for static and dynamic pitching moment derivatives. The results show that pitching stiffness and damping depend on wedge angle and reduced frequency. At the same time, at very high Mach numbers, the derivatives tend to be approximately Mach-number independent, consistent with hypersonic similitude. McIntosh [21] extended the earlier work by Lighthill for hypersonic flows and introduced theoretical frameworks for the unsteady response of hypersonic flows to body motions, i.e., small-amplitude harmonic oscillations for sharp-edged canonical shapes such as wedges. Landahl [22] further extended the perturbation velocity potential for unsteady flow past slender wing bodies using an M^{-2} series expansion that incorporates both linear and second-order effects. The computed pressure distributions show good agreement with the Hayes-Lighthill piston theory, with improved accuracy achieved by accounting for Mach number effects and weak three-dimensional influences. The results exhibit close agreement with exact linearized solutions for Mach numbers greater than or equal to 1.5. Miles [23] develops the basic mathematical framework for the study of unsteady aerodynamic forces at hypersonic speeds, with particular regard to the validity of linearized theory and the influence of thickness effects. This work is crucial for understanding the pressure distribution and stability derivatives of oscillating thin airfoils and bodies of revolution at high Mach numbers; he concluded that, at high Mach numbers, the behavior of unsteady flow is highly sensitive to the geometry of the body as well as the shock wave location. The damping and stiffness derivatives are highly influenced by the interaction of the shock layer with the body surface, which requires nonlinear corrections to the acoustic approximations. The present review focuses specifically on surface pressure distribution characteristics of wedge, cone, and delta-wing configurations across different flow regimes. Related studies involving other geometries are

discussed only where they provide fundamental insights into pressure-field development, shock formation, boundary-layer interaction, or flow-control mechanisms directly applicable to these configurations.

The structure of this review is organized as follows. The review methodology is presented in Section 2, and the literature review is presented in Section 3, which covers all aerodynamic characteristics for subsonic, transonic, supersonic, and hypersonic flows. The key findings on surface pressure distribution, aerodynamic stability derivatives, flow control techniques, and shock-wave/boundary-layer interaction (SWBLI) are discussed in Section 4 as results and discussion. The conclusion is presented in Section 5, which shares the authors' own views and next research directions.

2 Review Methodology

This review was conducted using a structured literature review survey approach to identify, evaluate, and classify studies related to surface pressure distribution over wedges, cones, and delta-wing configurations across subsonic, sonic, supersonic, and hypersonic flow regimes.

2.1 Literature Search Strategy

The publications were gathered from major scientific sources such as Scopus, Web of Science, Google Scholar, ScienceDirect, SpringerLink, and various aerospace engineering journals. The literature search covered publications from 1950 to 2025 to include both classical theoretical developments and recent advances in computational and experimental aerodynamics.

The primary search keywords included: surface pressure distribution, Wedge aerodynamics, Cone aerodynamics, Delta wing aerodynamics, Supersonic flow, Hypersonic flow, Sonic flow, Suddenly Expanded flow, Active-Passive flow, Piston theory, Oblique Shock wave, Conical Shock wave, Shock wave boundary layer interaction, CFD simulation, and High-speed aerodynamics. Various combinations of these keywords were employed to ensure comprehensive coverage of the available literature.

2.2 Inclusion and Exclusion Criteria

Studies were included if they:

- Investigated wedges, cones, delta wings, or closely related configurations.
- Reported surface pressure distribution, pressure coefficient, aerodynamic loading, or stability derivatives.
- Used analytical, numerical (CFD), or experimental approaches.
- Were published in peer-reviewed journals, conference proceedings, or recognized aerospace reports.

Studies were excluded if they:

- Focused exclusively on unrelated geometries without direct relevance to pressure-distribution mechanisms.
- Did not provide aerodynamic pressure-related results.
- Contained insufficient technical details or duplicate findings.

2.3 Literature Classification

After selection, the studies were sorted by:

- Flow regime (subsonic/sonic, supersonic, hypersonic)
- Geometry type (wedge, cone, delta wing)
- Research methodology (analytical, computational, experimental)

- Physical effects examined (shock structures, viscous influences, unsteady aerodynamics, shock-wave/boundary-layer interaction, plus flow-control approaches)

This classification enabled a structured comparison of findings across different aerodynamic conditions.

2.4 Literature Selection Summary

A structured literature search was conducted to identify relevant studies on hypersonic aerodynamics, Computational Fluid Dynamics (CFD), and artificial intelligence techniques for high-speed flow analysis. The search was performed using major scientific databases, including Scopus, Web of Science, ScienceDirect, SpringerLink, IEEE Xplore, and Google Scholar. Relevant publications were identified using predefined keywords related to hypersonic flow, pressure and temperature distribution, cone aerodynamics, and CFD simulation. The retrieved studies were screened based on their titles, abstracts, and relevance to the objectives of this review. Full-text articles were further evaluated to ensure their technical relevance and quality. Priority was given to peer-reviewed journal articles, while seminal classical studies were included to provide the theoretical foundation. Duplicate and irrelevant publications were excluded during the screening process. The final set of selected references forms the basis of the critical discussion presented in this review. Although a structured and transparent selection process was followed, this review was not conducted as a formal systematic review under PRISMA or other systematic review protocols. Fig. 1 and Table 1 show the flowchart of the literature screening and selection methodology and selection criteria.

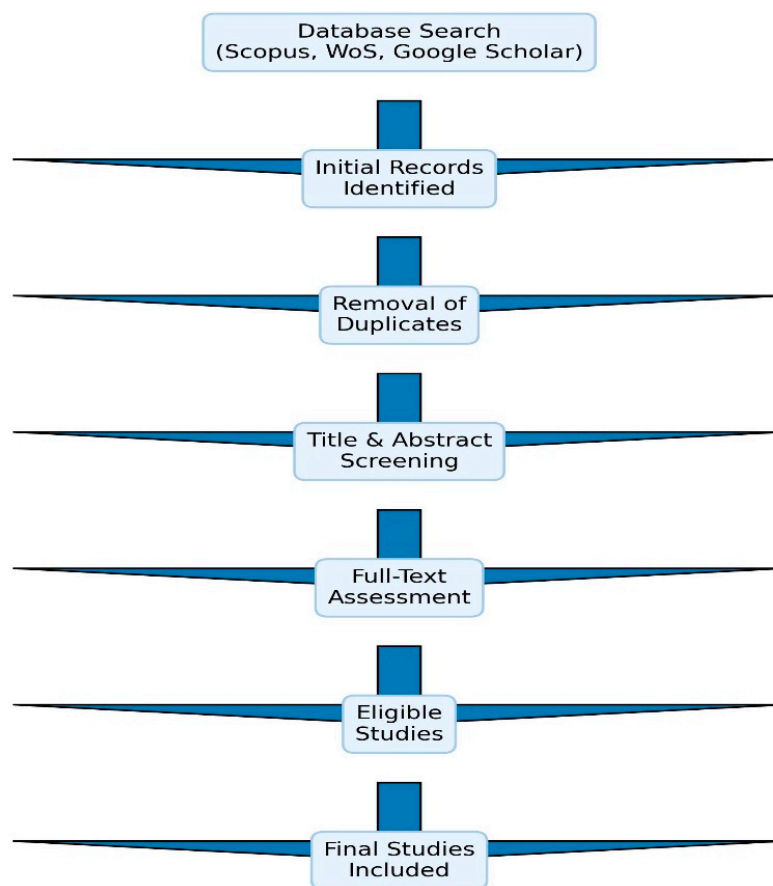


Figure 1: Flowchart of the literature screening and selection methodology.

Table 1: Literature search and selection criteria.

Category	Description
Databases	Scopus, Web of Science, Google Scholar, ScienceDirect
Time Period	1950–2025
Keywords	Wedge, Cone, Delta Wing, Pressure Distribution, Hypersonic Flow
Inclusion Criteria	Analytical, CFD, Experimental Studies
Exclusion Criteria	Unrelated geometries, insufficient data
Classification	Flow regime, geometry, methodology

3 Review of Literature

Recent analytical, experimental, and computational studies on wedge-type designs under high-speed flow conditions are summarised in this review of the literature. The evolution of rolling moment characteristics, aerodynamic stiffness, aerodynamic damping, and surface pressure distributions over subsonic/sonic, supersonic, and hypersonic flow regimes is methodically examined using a regime-wise, physics-based approach. The chosen method ensures geometric consistency while allowing the major aerodynamic mechanisms to change with Mach number, allowing for useful cross-regime comparisons. The surveyed literature is arranged based on shock attachment properties, analytical formulation, and flow regime. High-fidelity computational fluid dynamics (CFD) simulations and experimental observations supplement the analytical framework of the reviewed studies, which is mainly based on classical aerodynamic theories such as strip theory, piston theory, linearised unsteady aerodynamics, and supersonic and hypersonic similitude principles. When taken as a whole, these approaches validate aerodynamic response predictions for wedge-type geometries under high-speed flow conditions and offer physical insight into the controlling flow phenomena.

3.1 Distinction between Wedge, Cone, and Delta-Wing Configurations

Although wedges, cones, and delta wings are frequently employed as canonical configurations in high-speed aerodynamics, their flow characteristics are fundamentally different. Therefore, results obtained for one configuration cannot be directly generalized to the others without careful consideration of the underlying flow physics. A two-dimensional wedge generates oblique shock waves and exhibits pressure variations primarily along the streamwise direction. The flow may be reasonably approximated as two-dimensional under attached-shock conditions, making wedge geometries suitable for analytical studies based on shock-expansion theory and piston theory. In contrast, an axisymmetric cone produces a conical shock wave and exhibits radial variations in pressure and flow properties. The pressure distribution depends on both the cone semi-vertex angle and the axisymmetric shock structure. Consequently, cone aerodynamics cannot be directly represented using two-dimensional wedge formulations. Delta wings represent fully three-dimensional configurations. Leading-edge shocks, vortex formation, spanwise pressure gradients, and angle-of-attack effects strongly influence their aerodynamic characteristics. At high incidence angles, vortex-dominated flow structures significantly alter the pressure distribution compared with wedges and cones. Therefore, the reviewed studies are interpreted according to their respective geometric classifications to avoid direct equivalence between two-dimensional, axisymmetric, and three-dimensional aerodynamic configurations shown in Table 2.

Table 2: Comparison of aerodynamic characteristics of wedge, cone, and delta-wing configurations.

Configuration	Flow Type	Shock Structure	Pressure Distribution	Dominant Mechanism
Wedge	2D	Oblique shock	Streamwise variation	Compression and expansion waves
Cone	Axisymmetric	Conical shock	Radial variation	Axisymmetric compression
Delta Wing	3D	Leading-edge shock and vortices	Spanwise and streamwise variation	Shock-vortex interaction

3.2 Fundamental Aerodynamic Parameters and Subsonic Flow Regime

To facilitate a consistent interpretation of the reviewed studies, the principal aerodynamic parameters governing pressure distribution in compressible flows are briefly summarized. The Mach number (M), which is the ratio of freestream velocity to the local speed of sound, is the key quantity driving compressibility effects, shock-wave creation, and pressure changes. Depending on the Mach number, the flow can be grouped as subsonic, transonic, supersonic, or hypersonic. The pressure coefficient is a normalized pressure; it is the ratio of the local pressure to the freestream dynamic pressure, so it provides a standardized assessment of the aerodynamic loading. The angle of attack (α) plays a significant role in surface pressure distribution, aerodynamic forces, stability characteristics, strength of the shock waves, and pressure gradients. Generally, the pressure on the windward surface increases as the angle of attack is increased, while the shock-wave structure is altered. Finally, geometric parameters have an important influence on the flow field, pressure, and entire aerodynamic characteristics of high-speed configurations. For wedges, the wedge angle (θ_w) decides whether oblique shock waves show up and how strong they become. For cones, the semi-vertex angle (θ_c) controls the conical shock system and the axisymmetric pressure distribution. For delta wings, the sweep angle (Λ) and the leading-edge shape influence shock generation, vortex development, and the way pressure varies in the spanwise direction. Across this review, the effects of Mach number, angle of attack, geometric parameters, and shock-wave behavior are treated as the core basis when comparing analytical, computational, and experimental work shown in Table 3.

Table 3: Fundamental aerodynamic parameters governing pressure distribution in compressible flows.

Parameter	Symbol	Description
Mach Number	M	Ratio of flow velocity to speed of sound
Pressure Coefficient	C_p	Non-dimensional pressure parameter
Angle of Attack	α	Angle between free stream and body axis
Wedge Angle	θ_w	Controls oblique shock formation
Cone Semi-Vertex Angle	θ_c	Controls conical shock structure
Sweep Angle	Λ	Governs delta-wing flow characteristics
Specific Heat Ratio	γ	Thermodynamic property of gas

3.3 Sonic and Subsonic Flow Regime

In the sonic and subsonic regime, shock waves will be minimal or non-existent, while compressibility effects will be small to moderate. In the sonic and subsonic regime, the methodological emphasis is on the development of the underlying aerodynamic behavior that can be used to explain various phenomena at higher speeds.

The reviewed studies are selected to examine:

- The influence of wedge geometry and other parameters on pressure distribution.
- Linearized unsteady aerodynamic formulations for oscillating wedges and flat plates.
- Evaluation of aerodynamic stiffness and damping derivatives for small-amplitude oscillations.
- Rolling moment generation due to asymmetric pressure loading.

Due to the increased need to implement faster and more agile flight vehicles, the area of investigation of unsteady aerodynamics and stability of flying objects at increased Mach numbers has evolved over several decades. Investigation of aeroelastic processes in compressible flows, especially those relating to flutter and stability of flying objects, was made theoretically possible in the past. Some of the first investigations of flutter in flying objects at increased Mach numbers were undertaken by Morgan et al. [3], when the principal objective was to examine unstable aerodynamic forces and the effect of compressibility. Their theoretical investigation demonstrated that phase lag between aerodynamic and inertial reaction was not suitably represented in incompressible flow models. Anton et al. [24] researched the stability analysis for an aircraft design using the weight function, also known as the inertia function equation. He identified several weight functions that corresponded to the number of first-order differential equations. This method was used for the longitudinal and lateral motion of a delta wing aircraft. Using computational fluid dynamics (CFD), Da Ronch et al. [25] studied how damping values change within the transonic area and how those variations behave with different combinations of movement parameters for standard dynamics model designs. Ronch et al. also compares the results obtained with actual measurements taken from a transonic cruiser test facility. The work of Rom [26] provides a comprehensive theoretical and experimental basis for the study of flow separation and vortex formation around slender bodies and wings at high angles of attack. In this work, the subsonic, transonic, and supersonic regimes have been considered for the development of a unified framework for the prediction of nonlinear aerodynamic characteristics. Mohamed et al. [27] studied the low-speed aerodynamic characteristics of non-slender delta wings at low angles of attack. They investigated the flow behavior and stability performance of delta-wing configurations operating in subsonic regimes. The research highlights that aerodynamic performance is strongly influenced by leading-edge vortex formation and separation characteristics. At low angles of attack, vortex structures remain relatively stable and contribute to lift enhancement. Mader and Martins [28] computed and presented aerodynamic stability derivatives (static, dynamic & transient) for aircraft using gradient-based optimization methods of CFD (Computational Fluid Dynamics) in three-dimensional structured-grid multi-block flow solvers with both Euler and Reynolds Averaged Navier-Stokes (RANS) equations by computing oscillatory results and deriving the various derivatives through a series of linear regressions. Barua et al. [29] performed numerical analysis of oscillating shock waves on airfoils in transonic flow by making modifications to airfoil surfaces. Computational analysis is done by using the RANS equation with $k-\omega$ SST two-equation turbulence model. Mi and Zhan [30] have evaluated the way in which dynamic stability derivatives behave with respect to aerodynamics and engineering through analytical, empirical, and numerical methods. Initial potential-flow and semi-empirical solutions provided very fast approximations but only worked with relatively simple shapes and patterns of motion. Currently, due to the development of CFD techniques, the most reliable ways of finding dynamic derivatives for various types of design are through time-domain CFD, which is based on solutions to the Euler and Navier-Stokes equations. Recently, new frequency-domain methods (e.g., harmonic balance, time-spectral methods) have been invented that significantly reduce computational resources while maintaining adequate accuracy.

3.4 Supersonic Flow Regime

The methodology focuses on flows with associated oblique shock waves in the supersonic region, where surface pressure distributions become highly nonlinear and compressibility effects dominant. The literature is organized based on:

- Analytical formulations using shock-expansion theory, supersonic similitude, and strip theory; studies of surface pressure distribution as a function of Mach number, wedge angle, and angle of attack.
- Determination of aerodynamic stiffness and damping derivatives for oscillating wedges and delta wings. Rolling moment analyses accounting for sweep angle and pivot location.

The investigation of unsteady aerodynamics, aeroelasticity, and dynamic stability in the supersonic regime has significantly evolved in the past two decades, driven by a dramatic increase in geometric and operational complexities of high-speed vehicles. Early efforts emphasized the development of unified computational methods, while later studies progressively incorporated viscous effects, geometric nonlinearities, and coupled aeroelastic behavior. Ghosh [31] developed a similitude approach that unified super- and hypersonic flows over non-slender cones and quasi-cones with attached shocks. Earlier analytical approaches were mainly limited to slender-body models and could not be applied to predict flow properties at different Mach numbers. This approach enhances the theoretical modeling of high-speed conical flows. The approach fills the gap between supersonic and hypersonic flows using scaling factors. As revealed by previous studies on the stability of supersonic boundary layers, leading-edge bluntness has been found to play a significant role in transition. The experimental study conducted by Balakumar [32] on blunt cones and plates revealed that the entropy layers created due to the bow shock tend to stabilize the boundary layer and delay transition. Numerical simulations based on linear stability theory and parabolized stability equations (PSE) also confirmed that leading-edge bluntness tends to reduce the growth rates of instability waves and move the neutral stability curves downstream. The receptivity analysis also indicated that acoustic waves, especially slow waves, are more receptive to instability waves, and the receptivity coefficients are reduced with increased bluntness. Strip theory was applied without considering the effect of viscosity and wave reflection, and the work was compared with Hui [9], Ghosh [33,34], and Liu and Hui [14]. Later Khan and Crasta [35] studied high-incidence supersonic similitude for a planar wedge with an attached bow shock, extending Ghosh's similitude for large deflection to supersonic flows. Khan and Crasta [35] assessed the stability derivative in pitch and roll of a delta wing under the condition of attached shock waves by supersonic similitude. The work used strip theory and piston analogy to reduce the three-dimensional unsteady problem to an equivalent one-dimensional piston motion problem. In earlier studies, Sychev, Lighthill, Hui, and Lui considered hypersonic similitude and oscillating wedges, but the studies were more complex in formulation. The current method combined supersonic/hypersonic similitudes and allowed analytical solutions for stability derivatives in pitch. Piston theory and its variants were already developed by Lighthill [18], Hui [9,10,13], Liu and Hui [14], and others for thin lifting surfaces. Still, there were some limitations in dealing with the thickness effect and angle of attack. The work aimed to fill these gaps by finding the steady flow characteristics over polygonal fin geometry and integrating them with modal structural analysis. Kazemba et al [36] discussed experimental, analytical, and computational methods employed to estimate the dynamic stability characteristics, pointing out the shortcomings of each method. It also discussed the effect of geometry, environmental factors, and test procedures, while summarizing the suggested physical models for the dynamic phenomena of blunt bodies. The similitude for planar wedges was studied to investigate the surface distribution of a delta wing with curved leading edges for attached shock situations in supersonic flow conditions using strip and piston theory. A thin strip of the wing,

parallel to the centreline, can be regarded as if the velocity in the Z direction is very small. The strip theory, along with Ghosh's large incidence similitude, yields the 'piston analogy', and pressure P on the surface can be directly related to the equivalent piston Mach number ' M_p '. In this case, both ' M_p ' and flow deflections are allowed to be large. Hence, Lighthill piston theory or Miles' strong shock piston theory cannot be employed, but Ghosh's piston theory will be valid, and for the same pressure ratio is given by,

$$\frac{P}{P_\infty} = 1 + A \left(\frac{M_p}{\cos \phi} \right)^2 + A \left(\frac{M_p}{\cos \phi} \right) \sqrt{\left(B + \left(\frac{M_p}{\cos \phi} \right)^2 \right)} \quad (1)$$

where P_∞ is the free stream pressure,

$$A = \frac{\gamma(\gamma + 1)}{4}, B = \left(\frac{4}{(\gamma + 1)} \right)^2$$

here, γ is the specific heat ratio, and M_p is the local piston Mach number normal to the wedge surface.

The piston Mach number is given by Eq. (2),

$$M_p = M_\infty \sin \alpha + \frac{q(x - x_0)}{a_\infty} \quad (2)$$

where ρ_∞ and a_∞ are the density and velocity of sound in the free stream, respectively.

For mean incidence α_0 for the wing oscillating in pitch with small frequency and amplitude about an axis x_0 . The piston velocity and hence pressure on the windward surface at x remains constant on a spanwise strip of length $2L$. The pressure on the lee surface is assumed zero.

$$m = -2 \int_0^L P(x - x_0) dx \quad (3)$$

The pitching derivative of the delta wing is given by,

$$-Cm_\alpha = \frac{\sin \alpha_0 f(S_1)}{\cos^2 \phi} \left[h^2 - \frac{4}{3}h + \frac{1}{2} \right] \quad (4)$$

where,

$$f(S_1) = \frac{\gamma + 1}{2S_1} \left[2S_1 + (B + 2S_1^2)(B + 2S_1^2)^{\frac{1}{2}} \right] \quad (5)$$

Table 4 shows the comparison of the principal analytical models used in aerodynamics for pressure distribution prediction in high-speed flows, such as Newtonian Theory, Shock Expansion Theory, Piston Theory, and Hypersonic Similitude. The comparison summarizes the application of the flow regime, the important assumptions of each model, the benefits and drawbacks of the models, and their applicability to various high-speed flow conditions. These analytical methods have been extensively used in the literature for aerodynamic analysis. Newtonian theory also applied, to estimate the damping derivative of non-planar wedges under hypersonic flow conditions. Analytical piston theory has also been combined with CFD simulations to investigate the effects of pivot location, Mach number, and angle of incidence on the surface pressure distribution of three-dimensional delta wings. These investigations demonstrate the applicability

of analytical aerodynamic models, including Newtonian and piston theories, for evaluating aerodynamic characteristics across different high-speed flow regimes.

Table 4: Comparison of analytical models used for pressure-distribution prediction.

Model	Flow Regime	Major Assumptions	Advantages	Limitations
Newtonian Theory	Hypersonic	Inviscid flow	Simple	Low accuracy at lower Mach
Shock Expansion Theory	Supersonic	Attached shocks	Good accuracy	Simple geometries
Piston Theory	Supersonic–Hypersonic	Small disturbances	Stability analysis	Limited for separated flows
Hypersonic Similitude	Hypersonic	Similarity assumptions	Rapid prediction	Restricted applicability

Analytical and computational investigations of supersonic flow over planar wedges have examined the effects of Mach number and wedge angle on surface pressure and flow characteristics using analytical formulations and finite-element-based CFD methods. The numerical results were validated using Ghosh piston theory and oblique-shock relations for attached-shock conditions. Similarly, studies of delta-wing aerodynamics and suddenly expanded supersonic flows have employed analytical, experimental, and computational approaches. Collectively, these investigations demonstrate the progressive use of theoretical, numerical, and experimental methods for understanding and predicting aerodynamic characteristics in high-speed flows. The delta wing analyses use piston theory, similitude methods, and CFD modeling techniques to assess the stiffness, damping, and drag properties of attached shock flows. These studies investigate the effects of Mach number, angle of attack, pivot location, and geometric variations on aerodynamic stability coefficients and surface pressure fields. The drag dynamics and stability coefficients are analytically modeled and computationally validated for different supersonic Mach number ranges. Concurrent research efforts on suddenly expanded supersonic flows concentrate on base pressure regulation, wall pressure measurement, and shock/shear-layer interactions in ducts of different L/D ratios. Experimental research studies correctly expanded and under-expanded nozzle flows, emphasizing the importance of micro-jets as active flow control agents. The oblique shock and expansion wave interactions are investigated to determine oscillatory flow phenomena in the duct. These studies together demonstrate the influence of inertia ratio, geometric configuration, and expansion conditions on aerodynamic forces and base pressure properties. Experimental studies have investigated active control of base pressure in suddenly expanded axisymmetric flows using circumferential micro-jets. The effects of nozzle pressure ratio and L/D ratio on base and wall pressure distributions were examined. Other studies employed small orifice jets with DOE and RSM to analyze and optimize flow control in abruptly expanded ducts. Experiments were performed to measure the base pressure with and without the use of micro jets or active control. Mach number (M), nozzle pressure ratio (NPR), area ratio (AR), and length-to-diameter ratio (L/D) were taken as the input variables that control the outputs.

Shaikh and Havaladar [37] discussed passive control measures like ribs, cavities, and boat-tailing, and active control measures like control jets. They emphasized the importance of area ratio and nozzle pressure ratio (NPR) in controlling base pressure.

Studies on high-speed aerodynamics have explored hypersonic similarity, Piston Theory, and oscillating wedge and delta wing dynamics in supersonic and hypersonic flows [38–40]. Previous studies have employed

CFD and theoretical analysis to investigate surface pressure distribution, drag force reduction, and passive control strategies for various geometries including wedges and cones. Similar work has been extended to the damping derivative. Ai et al. [41] studied a $25^\circ/55^\circ$ double-cone in hypersonic flow with a two-temperature model, showing that thermochemical nonequilibrium plays an important role in the behavior of the shock wave and the boundary layer. In a recent study, Huang et al. [42] summarized the state of the art on shock wave/boundary-layer interaction (SWBLI). They found that micro-vortex generators work well in suppressing shock-wave-induced flow separation, but they still emphasized the importance of developing better quantitative assessment methods.

3.5 Hypersonic Flow Regime

Similarity laws and piston-based unstable aerodynamic models serve as the foundation for hypersonic regime techniques, where flow inertia predominates, and sensitivity to Mach number decreases. The reviewed studies address:

- Hypersonic similarity laws developed by Tsien and Hayes.
- Application of piston theory, strip theory, and thin shock-layer theory.
- Prediction of surface pressure, stiffness, damping, and rolling moment for wedges and delta wings.

Hemdan [43] examines small pitching oscillations of thin, pointed-nose two-dimensional hypersonic airfoils at small angles of attack. Employing recently developed steady and unsteady hypersonic approximations, a first integral is obtained to eliminate density and reduce the governing equations to linear PDEs. A double perturbation expansion in small surface curvature and reduced frequency is used to obtain polynomial solutions. Closed-form expressions for unsteady surface pressure and stability derivatives of non-symmetric curved airfoils are formulated. Tarpley and Lewis [44] analyzed an attached shock wave over tangent wedge geometry and derived an analytical expression for the longitudinal and lateral stability derivatives using linear piston theory. A coupled unsteady hypersonic/supersonic panel method integrated by Chen and Liu [45] into ZAERO is an extension of linear potential theory that incorporates rotationality correction, equivalent Mach number transformation, and a local pulsating cone analogy to simulate complex high-speed geometries. This method allows for both steady and unsteady aerodynamic and aeroelastic analyses to be performed in a single framework. The stability and receptivity properties of the three-dimensional hypersonic boundary layer flow on a 7° half-angle cone at an angle of attack were computationally analyzed by Balakumar and Owens [46] employing high-order WENO and TVD Runge-Kutta schemes to solve the full Navier-Stokes equations. The work focused on the stationary crossflow vortices created by surface roughness and the dominant wavenumbers and second-mode instabilities in the Mach 6 flow conditions.

The combined analytical and CFD approach [47] also used to investigate the stiffness and damping derivatives of a similitude delta wing represented by a two-dimensional oscillating wedge under hypersonic flow conditions. Ghosh's similitude and Lighthill's piston theory were employed to derive the aerodynamic derivatives, followed by CFD validation for various Mach numbers. The pressure, velocity, and temperature distributions over the wedge were also evaluated.

Shamitha et al. [48] applied the analytical and numerical approach to investigate the surface pressure on an oscillating 2D wedge at hypersonic Mach numbers using Ghosh's piston theory along with strip theory and compares the results with CFD simulations. The research investigates the effect of attached shock conditions $M_2 \geq 2.5$, a range of Mach numbers from 5.5 to 15, and a range of wedge angles from 5° to 25° using a Taguchi L25 design. The study in [49,50] explored the characteristics of surface and

base pressure distribution in high-speed compressible flows in two-dimensional configurations and in suddenly expanded ducts. It also examines the effects of critical flow parameters, including Mach number, nozzle pressure ratio, Reynolds number, and expansion ratio, on the aerodynamic pressures. An active flow control method, micro-jet injection, is applied to modify the recirculation area to enhance the pressures. Experimental measurements are carried out to examine the effects of shock boundary layer interaction and the sensitivity of the pressures to varying flow conditions. Kalimuthu et al. [51,52] experimentally investigate the drag reduction mechanisms of a hemispherical blunt body with forward-facing spike configurations under hypersonic flow conditions at a Mach number of 6. Various spike configurations, including conical spikes, hemispherical aero disks, and flat-faced aero disks, with a length/diameter ratio of 1.5 and 2.0, are considered to investigate the effect of the spikes on the structure of the shock wave and the separated flow field. Schlieren visualization techniques are used to record the bow shocks, conical shocks, shear layers, and reattachment. Six-component balance techniques record the drag, lift, and pitching moment. Emphasis is given to the effect of the spikes on the recirculation region upstream of the blunt body, which affects the stagnation pressure. Special emphasis is given to the effectiveness of the spikes at different angles of attack ranging from 0° to 8° . The study [53] focuses on the experimental investigation of the aerodynamic drag reduction of hemispherical blunt bodies with forward-facing spike configurations under hypersonic flow conditions at Mach 6. Different spike geometrical configurations and the length-to-diameter ratio are experimentally tested to investigate their impact on the bow shock, recirculation zones, and reattachment points of the separated flow. The research focuses on understanding the effect of spike configuration on the stagnation pressure distribution. Meng et al. [54] carried out a fluid thermal coupling analysis on a double cone missile and examined the application of a spike and a combination of a spike with a multi-jet approach to decrease the drag and the thermal heating at hypersonic flight regimes. Recent studies have focused on fluid-thermal coupling, high-temperature gas effects, shock-layer chemistry, and drag-reduction tactics for hypersonic vehicles. Meanwhile, advanced CFD methods that incorporate thermochemical nonequilibrium models have meaningfully improved how well they forecast pressure distribution and aerodynamic heat load at Mach numbers beyond 10. More recent investigations even showed that combined spike-jet arrangements can be effective at reducing both drag and thermal loads during hypersonic flight. Overall, it looks like there's a move away from just aerodynamic work toward a more multidisciplinary hypersonic vehicle design, where fluid behavior, thermal effects, and structural interactions have to be handled together. The research conducted by Javed Shaikh et al. [55–59] on high-speed aerodynamics utilizes numerical simulations and analytical models to study surface pressure and stability derivatives of wedges and cones during the supersonic and hypersonic regimes. In this research, the parameters are based on Ghosh's two-dimensional piston theory, an analytical method used to compare the results with the outcomes of the Computational Fluid Dynamics analysis and regression method. The computational fluid dynamics (CFD) simulation of the wedge geometry is performed by employing a two-dimensional planar model of hypersonic flow characteristics as per the analytical study. The sharp wedge geometry shown in Fig. 2 is taken into consideration, where the wedge angle θ ranges from 5° to 25° . The computation domain is extended appropriately, where the inlet section is placed at five times the wedge length upstream, the outlet section is placed at eight to ten times the wedge length downstream, and the top surface is placed at a distance far away from the wedge surface to avoid interference effects at the boundaries. The hypersonic freestream flow conditions are specified by employing various Mach number values of $M = 5, 7, 9, 10, 15$ together with specified freestream pressure and temperature values. The compressible Navier-Stokes equations are solved using a density-based solver with second-order upwind discretization under steady-state conditions. A structured quadrilateral mesh is created for the computational domain, with

the grid lines aligned in the flow direction to capture the oblique shock structure properly. Special care is taken while creating the mesh by focusing on refinement in critical areas of the domain. A highly refined mesh is created near the leading edge of the wedge, as there are high gradients of pressure and velocity caused by the formation of shock waves. A dense mesh distribution also resolves the shock region. For the wedge surface, inflation layers are created to resolve the boundary layer, comprising various layers of prisms with a specific growth rate (usually between 1.1 and 1.2). The first cell height is chosen properly to keep $y^+ < 1$, as required to predict the effects of the boundary layer correctly. A relatively coarser mesh is created away from the critical areas of the domain, as it helps optimize the computation efficiency without losing accuracy.

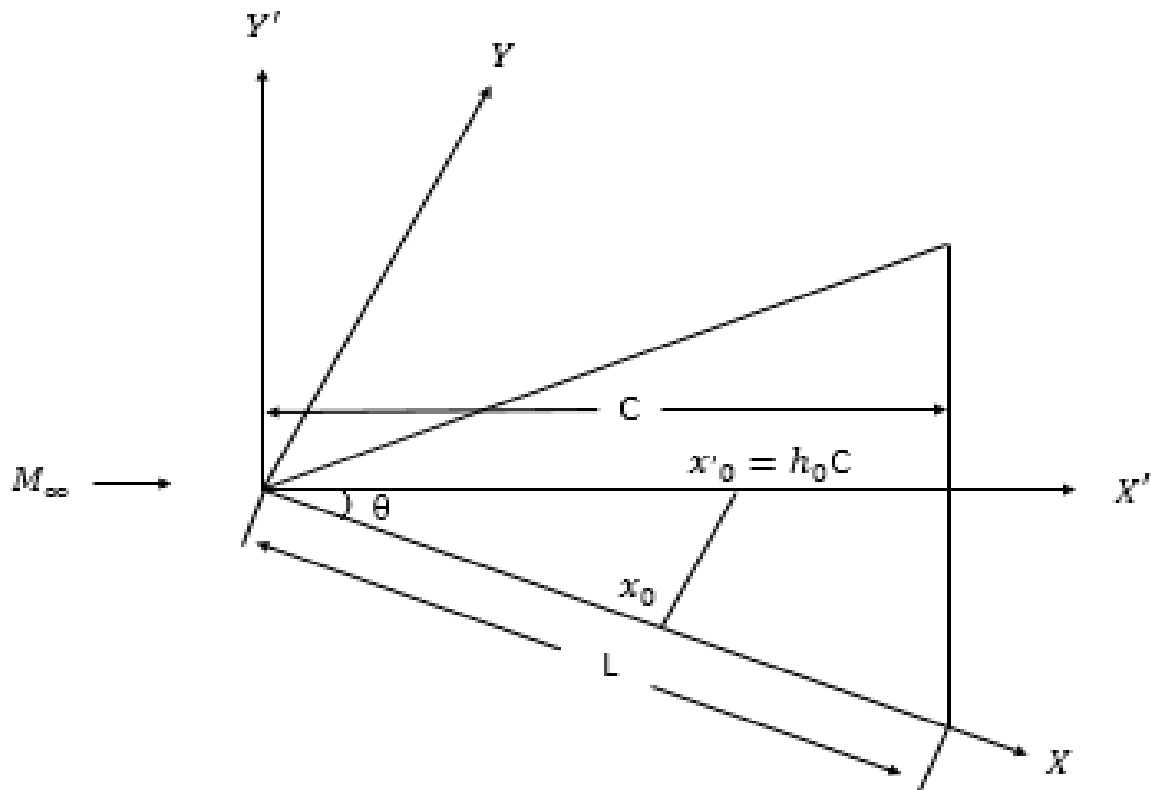


Figure 2: Geometry of plane wedge transfer of pivot position from x_0 to x'_0 [55].

3.6 Related Applications of Pressure Distribution and Flow Control

Although the primary focus of this review is on wedges, cones, and delta wings, related studies involving base-pressure control, duct flows, and aerodynamic drag-reduction techniques are briefly discussed because they provide valuable insight into pressure-field modification, flow separation, shock interaction, and flow-control mechanisms relevant to high-speed aerodynamic configurations. Baidya et al. [60] investigated the near wake of a circular cylinder in Reynolds and Mach number regimes. The instantaneous streamwise velocity deficit determines the near wake of a circular cylinder due to flow separation and the recirculation region. At the same time, the swirl (vorticity) field represents the development of coherent vortical structures, the interaction of which with the velocity field determines the dynamics of the near wake and the onset of vortex shedding, as shown in Fig. 3.

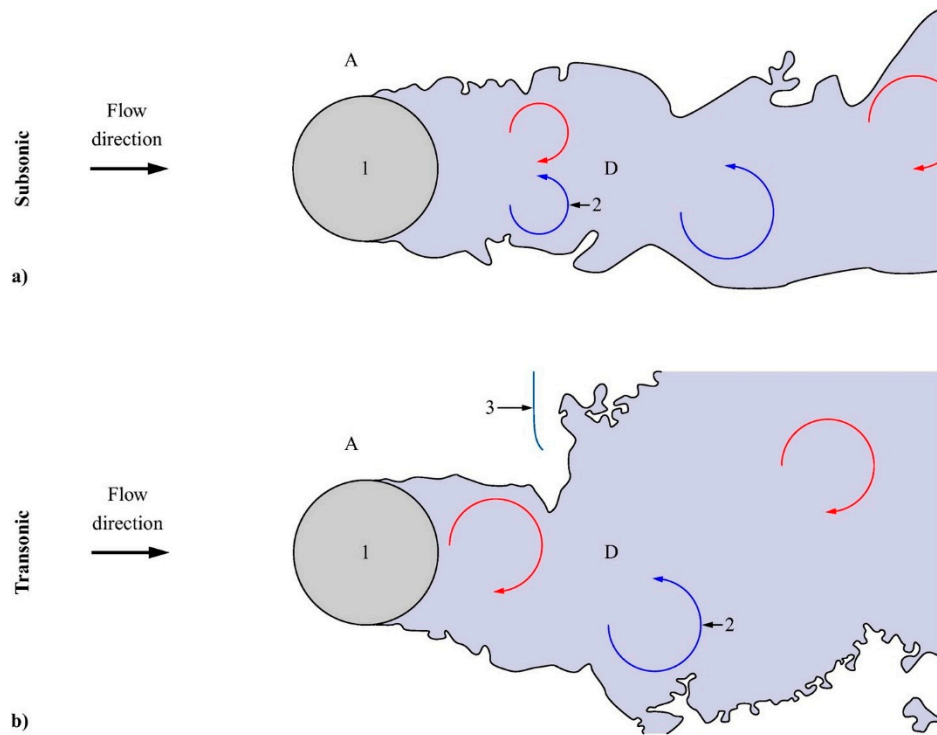


Figure 3: Schematic of the cylinder near-field flow features in (a) subsonic, (b) transonic [60].

Baidya et al. [60] presented mean flow and turbulent kinetic energy fields using the particle image velocimetry technique for Mach numbers varying from 0.3 to 2. They considered a transonic wind tunnel with a testing section measuring $1800 \times 300 \times 675 \text{ mm}^3$, as shown in Fig. 4. A cylinder, which is 20 mm in diameter D with aspect ratio 15:1, is used for wake formation. The Mach number is examined by setting the inflow between 100 and 500 m/s, with upstream chamber pressure varied from 150 to 250 kPa for subsonic runs.

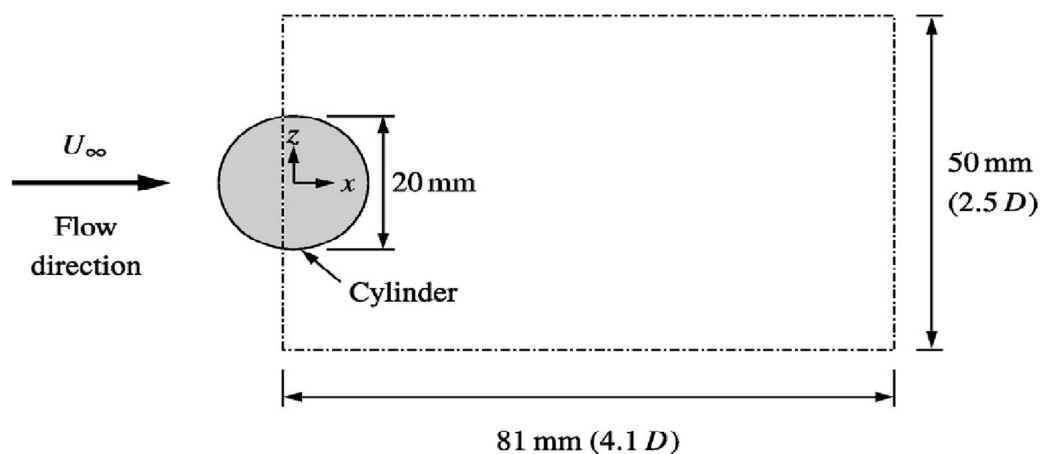


Figure 4: Experimental setup for wake enclosure [60].

Fig. 5a–f shows instantaneous streamwise velocity and flow fields, respectively, for various Mach numbers of 0.3, 0.8, and 2. The wake for the subsonic inflow cases was found to be physically greater by an order of magnitude compared to the supersonic cases for a given cylinder diameter D . For the subsonic

cases, the eddies are convected almost parallel to the streamwise direction, and hence the eddies formed from the top and bottom surfaces are separated in the transverse direction. Hence, the eddies are physically closer in the transverse direction in the supersonic case than in the subsonic case, leading to a much more restricted wake in the supersonic case.

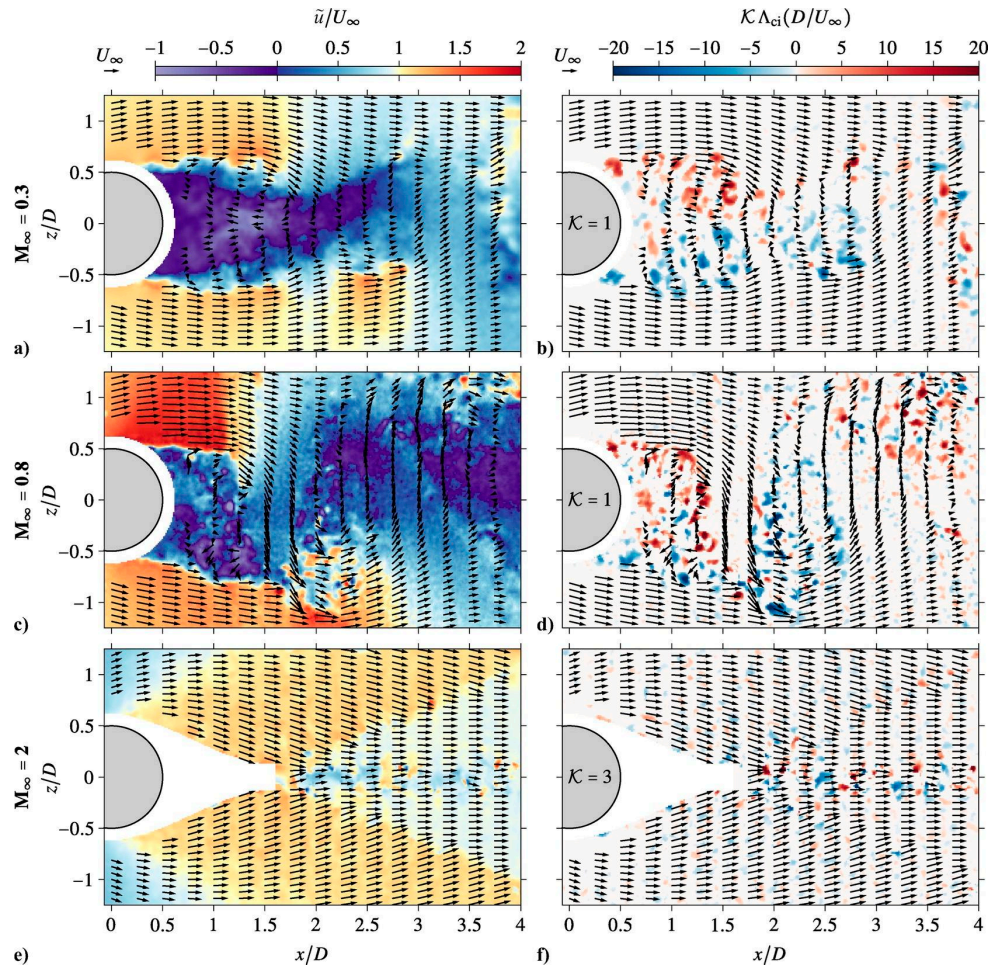


Figure 5: Instantaneous streamwise velocity contours illustrating wake development and vortex evolution at different Mach numbers [60].

The flow from nozzles expanding suddenly into circular pipes with and without cavities was experimentally studied by Rathakrishnan et al. [49] for a Mach number range of 0.6 to 2.75. The investigation reveals that introducing secondary circulation through cavities reduces the oscillatory nature of the flow more in the subsonic region than in the supersonic region. Rathakrishnan's study [50] focused on the problem of sudden expansion flows that appear in such devices as combustors, diffusers, and propulsion ducts. In such devices, the base pressure must be controlled. Previous studies focused on passive control using a cavity and found that secondary recirculation helped reduce oscillations and enhance pressure recovery. However, the Mach numbers in the existing studies were limited to subsonic. In the study reported here, passive control using an annular rib was carried out to promote secondary vortex formation and to investigate the effect from low subsonic to sonic Mach numbers. Zuhair [61] analyzed the effect of trailing-edge geometry on the aerodynamic characteristics of low-speed BWB UAVs, which have been relatively less investigated than full-scale subsonic/transonic BWB transport aircraft. Earlier works primarily concerned platform geometry

variables like leading-edge sweep, aspect ratio, and transonic phenomena for transport BWBs, whereas only limited parametric information is available for small UAV BWBs flying at low Reynolds numbers. To fill this research gap, the researcher carried out a CFD parametric analysis of four different BWB designs with the same leading-edge sweep and wetted surface, but with different trailing edge sweep geometries. The computations were carried out at $Re = 500,000$ and angles of attack ranging from 4° to 22° , using validated RANS models, primarily the Transition SST turbulence model. Flow separation, recirculation and formation of vortices downstream of the sudden expansion are the most important factors affecting base drag in these flows. Active and passive flow-control techniques such as micro-jets, cavities and ribs have been examined to modify base and wall pressure in both subsonic and supersonic regimes. Additionally, the geometric parameters area ratio, L/D ratio, cavity aspect ratio and rib height play an important role in determining the pressure distribution and oscillatory flow behaviour. Khan et al. [62] offered a detailed review of passive control methods for base pressure and base drag control. The article reviewed different passive control devices such as cavities, ribs, dimples, splitter plates, aerospikes, and boat-tailing devices used for subsonic to supersonic flow conditions. The article focused on the effect of Mach number, nozzle pressure ratio (NPR), area ratio, and recirculation zone dynamics on base pressure. The article reviewed different internal and external flow control methods and their importance in aerodynamics related to missiles, rockets, launch vehicles, and bluff bodies. Khan et al. [63] carried out a numerical study on the role of a single annular rib as a passive control technique to promote base pressure in a suddenly expanded duct with a sonic Mach number, published in CFD Letters. The authors used ANSYS Fluent with the $k-\epsilon$ model to simulate the behavior of compressible flows for different rib ratios (3:1 to 3:3) and positions (1D to 4D). The impact of NPR (1.5–5) and area ratio on the recirculation zone and reattachment length was also investigated. The study aimed to optimize rib geometry and position for passive control of base pressure. The research focused on the behavior of compressible flows at various Mach numbers, particularly on the recirculation zone development and its interaction with the shear layers that follow the expansion. The pressure distribution on the wall and variations in base pressure were explored to determine the effect of geometric and flow variables. The objective of the research was to determine the conditions that can be used to enhance the base pressure without using active control techniques.

4 Results and Discussion

4.1 Sonic and Subsonic Flow Regime

Aerodynamic stability derivatives were evaluated by Anton et al. [24] using the Digital DATCOM code and were validated with the experimental low-speed wind tunnel data from the German Dutch Wind Tunnel (DNW-NWB). The methods used to validate this paper's proposed method were based on handling qualities. Ronch [25] compared estimated damping derivatives for forced pitch oscillations at large amplitudes using wind tunnel data and found that there was reasonable agreement between the estimates and the experiments at large angles of attack. The analysis by Rom [26] demonstrates that, for high angles of incidence, the aerodynamic characteristics are dominated by organized structures of vortices, which can have a significant effect on lift and stability derivatives. The findings conclude that, for accurate predictions of maneuverability characteristics for modern aerospace vehicles, the effects of the interaction between separated regions and the lifting surfaces must be taken into consideration. The study by Mohamed et al. [27] investigates the low-speed aerodynamic behavior of non-slender delta wings at low angles of attack, focusing on vortex formation and flow separation characteristics. Results indicate that leading-edge vortices and wing geometry parameters significantly influence aerodynamic performance. The findings provide useful insights for aerodynamic optimization and stability enhancement in low-speed

aircraft applications. Mader [28] computed aircraft stability derivatives and verified and validated using Euler and Reynolds-averaged Navier Stokes equations CFD solver.

The effectiveness of making modifications on airfoil surfaces is analyzed by Barua et al. [29] numerically and found that instead of oscillation of the shock wave for small regions, it moves entirely over the surface of the airfoil. Mi. and Zhan [30] presented a highlight of the development of mathematical techniques used to compute dynamic stability derivatives of aircraft, discussing the compromise between accuracy of results and speed of calculations. Time domain computational fluid dynamics (CFD) is still the best combination of versatility and accuracy but is expensive to run. Frequency domain methods provide a good balance between speed and accuracy for repetitive or periodic types of motion. Future research should continue to refine methods that have improved robustness for nonlinear fluid flow, explore extending the frequency domain approach to more general types of rotational motion, and look at integrating accurate CFD methods with lower-order modeling methods for design purposes. Baidya et al. [60] compared the swirl and velocity at two points to determine the scale of the eddies. The data reveal that the smaller eddies, formed near the top and bottom surfaces, interact with each other and produce larger secondary eddies. The larger eddies are responsible for the overall swirling motion and the large-scale behavior of the flow. In the case of Mach numbers less than 0.8, the velocity fluctuations play an important role in the separate shear layers. The fluctuations travel along the surface of the cylinder and form a closed-loop flow pattern. Rathakrishnan et al. [49] show that the cavities are capable of reducing the pressure oscillation in the expanded duct for subsonic Mach numbers. The combination of the primary vortex and the secondary disturbances caused by the cavities leads to an increase in the base pressure. The influence of the aspect ratio of the cavity on the base pressure and the pressure distribution in the expanded duct is significant. Rathakrishnan [50] reports that annular ribs significantly impacted base pressure, such as when the minimum base pressure was found with a 3:1 aspect ratio near L/D ratios of 4, corresponding to a specific pressure ratio. Moreover, larger L/D ratios indicate lower sensitivity of the base pressure, while some ribs indicate increased base pressure with L/D . Zuhair [61] showed that the configurations with fixed trailing edge sweepback (especially configuration a, then c) had the highest aerodynamic efficiency with $(C_L/C_D)_{\max} \approx 16.9$ and ≈ 16 at $\alpha \approx 4^\circ$. The configurations with positive or variable trailing edge sweep (b and d) had lower efficiency (≈ 14 to 14.5) because of separation and higher pressure drag, but they reduced wingtip vortices. The baseline case validation was done at $M \approx 0.106$ (36.58 m/s), thus ensuring that the simulation is purely in the low subsonic Mach number regime as shown in Fig. 6.

Ribs are more effective than cavities, which can cause resonance for particular flow conditions, in terms of the passive flow-control techniques. The former (active flow-control methods) can provide better flow control performance, but are in general more complex and more energy consuming. The results of these observations emphasize the importance of studying passive control and time-dependent pressure oscillations in supersonic flows in more detail. Ambareen et al. [62] concluded that passive control devices are effective in increasing base pressure and reducing drag, especially when favorable pressure gradient conditions are met. An optimal level of under-expansion ($P_e/P_a \approx 1.5$) was also determined for maximum base pressure enhancement, and the results decreased at high area ratios. This work proves passive control as a viable and energy-efficient alternative to active flow control techniques. The findings [63] revealed that the addition of ribs significantly enhanced the base pressure over the smooth duct, especially when the 3:3 aspect ratio rib was placed at 3D and 4D positions. The enhancement of base pressure was found to be more prominent for NPR numbers greater than 2 during sonic flow. This research work concludes that a single properly located rib can be highly effective in stabilizing the shear layer and enhancing the base pressure without any extra energy input.

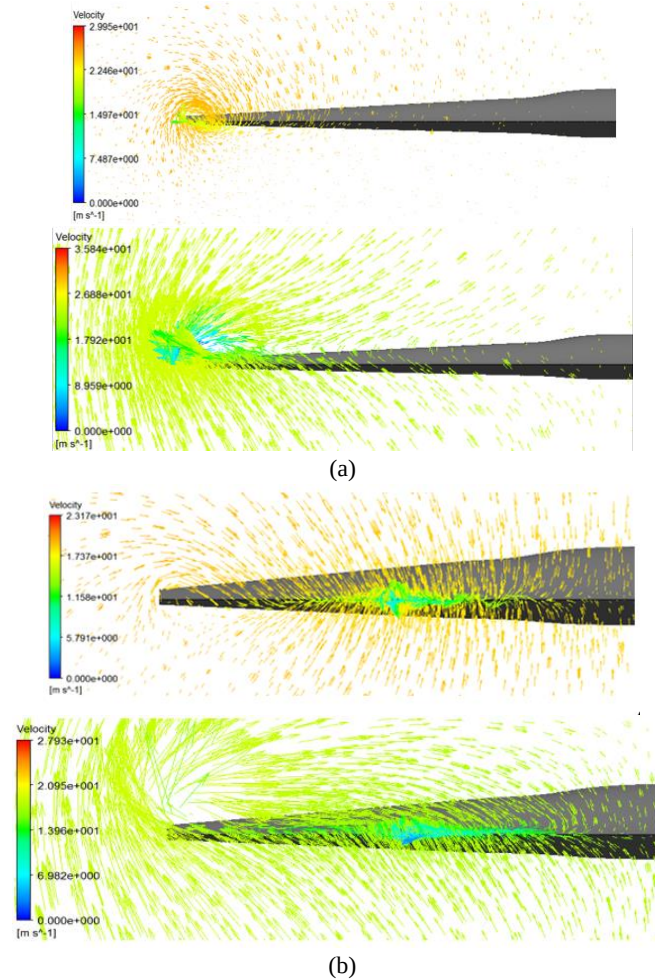


Figure 6: Wingtip vortex velocity vector field at $\alpha = 0^\circ$ (top) and 22° (bottom) [61].

4.2 Supersonic Flow Regime

Ghosh [31] developed a constant-density solution that yielded simplified expressions for shock angle and surface pressure on cones. An axisymmetric shock-expansion theory was developed to account for the effect of ogive nose curvature and viscous boundary-layer displacement thickness. In addition, hypersonic expressions for the pitching moment derivatives of oscillating cones and ogives were generalized to be applicable in the supersonic flow domain. Balakumar [32] shows that the effect of leading edge bluntness is strong on the supersonic boundary layer, and this effect is stronger on wedges than on flat plates. The transition Reynolds numbers are found to be increased by bluntness by a large amount, by factors of about 3.5 for flat plates and more than 7 times for wedges compared to the similarity solution. Also, the receptivity coefficients are found to be reduced with increasing bluntness. Khan and Crasta [35] show that the leading-edge bluntness has a strong stabilizing effect on supersonic boundary layers, and this effect is stronger for wedges than for flat plates. The survey by Kazemba et al. [36] identified trends common across different configurations and stressed the growing database of experimental and computational results. It concluded that better predictive tools and physical insights are required to improve the reliability of dynamic stability analysis for blunt bodies in supersonic flow.

Analysis of the results [47] reveals that the surface pressure, density, and temperature rise with Mach number and wedge angle, while the downstream Mach number falls across the shock. Fig. 7 shows the

findings of temperature effects on different parameters of the wedge flow. It is evident from these findings that there exists a gradual rise in temperature with an increase in the Mach number. The CFD solutions agree well with the analytical solutions for the attached shock conditions. Theoretical studies of high-speed aerodynamic derivatives indicate that the damping derivative is strongly influenced by the pivot position and angle of incidence. In general, an increase in the angle of incidence produces a significant increase in damping, while the corresponding shift of the center of pressure can enhance the static stability of the configuration. Surface pressure in high-speed flow is also strongly dependent on Mach number and angle of incidence because of changes in shock-wave strength and flow compression. The influence of pivot position on pressure distribution is generally moderate, although local pressure variations may occur depending on the flow conditions and surface location.

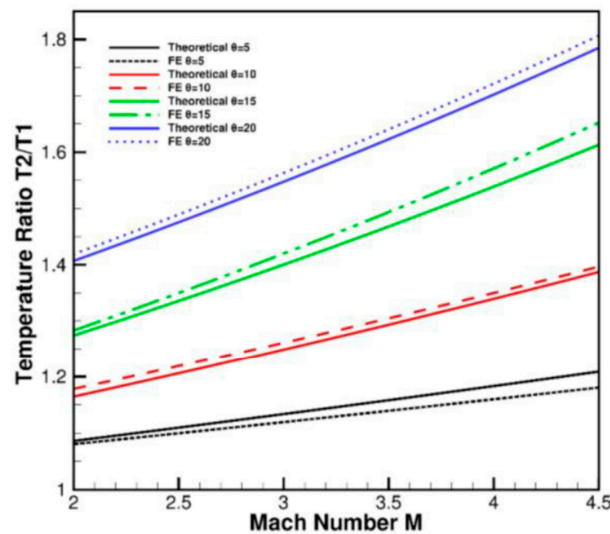


Figure 7: Temperature effect on mach number [47].

Mach number and angle of attack have a significant effect on the aerodynamic stability derivatives, drag and surface pressure coefficients of delta wings. The location of the pivot and the geometric parameters are also of significant influence on the stiffness and damping properties, with some configurations offering better aerodynamic stability. For the case of suddenly expanded flows, the flow field is dominated by shock–expansion effects, which also help to create oscillations in the wall pressure. Using micro-jets for active control, a modification of base pressure can be carried out while maintaining the general character of the wall-pressure distribution. The aerodynamic stability and base-flow characteristics of overall high-speed are very sensitive to Mach number, expansion ratio and geometric variations. Experimental results have also shown that, by using micro-jet actuation, a significant enhancement of the base-pressure rise can be achieved, and that the values of base-pressure responses under controlled and uncontrolled conditions can be statistically predicted by using a nonlinear regression model and ANOVA.

Shaikh and Havaladar [37] conclude that active control measures are more effective than passive control measures for the purpose of increasing base pressure. Control jets are found to be very effective in increasing base pressure without affecting the flow field.

The results of the cavity [64] suggest that the maximum effectiveness of the cavities in increasing base pressure is achieved at certain intermediate values of NPRs (e.g., NPR 6), and the effectiveness reduces at low or high NPR due to changes in the reattachment point of the flow with respect to the cavity. The results demonstrate a strong level of consistency between the computational/regression analysis and the

results obtained through analysis, with the regression models being able to capture the trends in the surface pressure/temperature distribution and damping derivatives effectively [38,39]. The Mach number has a large influence on temperature rise and pressure ratios, and the semi-cone angle and position are also important parameters in the variation of pressure along the slant length of the cone.

4.3 Hypersonic Flow Regime

Explicit expressions for the stiffness and damping derivatives are derived and assessed by Hemdan [43]. The results for symmetric wedges at zero incidence were found to be in good agreement with available analytical and experimental data. Tarpley [44] obtained good agreement with the analytical work done by Hui. The stability derivatives of a Mach 6 wave-rider are calculated, and it is found to have negative pitch and yaw stiffness. Agreement within 8% is obtained at a Mach number of 7.9 and a Reynolds number of 2.7×10^6 . Validation of the results has been done by Chen et al. [45] against CFL3D solutions, AP98 data, and experimental data, and it has been found that the results are in good agreement with a considerably reduced computational time of 2–3 min per case. The technique is accurate, versatile, and useful for aerodynamic, stability derivative, aeroelastic, and aeroservoelastic problems. The results [46] show that the strongest amplified waves occur in particular azimuthal sectors, for second-mode frequencies between 400–900 kHz, and transition is predicted earlier along the cone sides than along the windward or leeward rays. The crossflow vortices were found to originate near the nose and move towards the leeward ray, with no perturbations on the windward side. Similitude theory is a simplified analytical tool that can be used to relate the aerodynamic characteristics of geometrically similar configurations when subjected to high speed flow. It can be used in conjunction with the strip theory or piston theory to calculate surface pressure and aerodynamic loads in attached shock supersonic flow cases for planar wedges and delta-wing configurations. These are effective ways of simplifying the flow in three dimensions to tractable analytical relationships and are also applicable to preliminary aerodynamic analysis and prediction of the pressure distributions. The stiffness derivative shows good agreement with oblique shock theory, with an error of less than 10% at $M = 17$. At the same time, significant deviations exist in the case of damping derivative at high deflection angles [65] as shown in Fig. 8. Stiffness increases with the angle of incidence and reduces linearly with the pivot position. In contrast, pressure and thermal loads increase significantly at high Mach numbers.

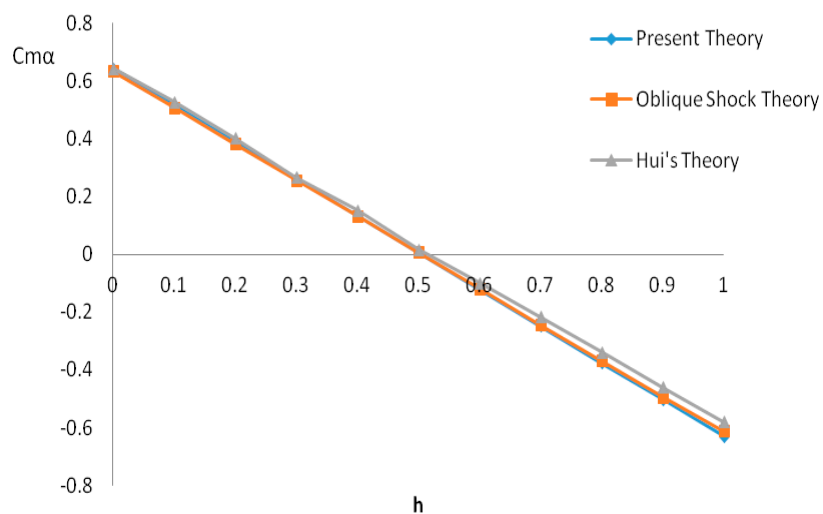


Figure 8: Comparison graph of stiffness derivative vs. pivot position for $M = 17$ [65].

The stiffness derivative reduces with increasing pivot position and semi-vertex angle, with considerable change occurring when it varies from 5° to 10° , while further increase results in marginal change; 3-D effects are of major importance. As Mach number is increased, stiffness and damping derivatives reduce marginally and finally obey the Mach number independence principle ($M \geq 10$). The damping derivative shows a 33% rise with increasing angle θ from 5° to 10° ; the center of pressure lies at $h = 0.7-0.8$ with increasing Mach number. The results indicate that the stiffness derivatives are highly dependent upon the Mach number and the semi-vertex angle for lower values of the Mach number. The effect of the Mach number is significant for higher values of the Mach number. It was found that for a location of the hinge closer to the center of pressure (i.e., $h = 0.6$), the variation of the Mach number has a negligible effect on the stiffness derivatives. The effect of the angle of the ogive was found to be significant for stability. The stiffness derivatives are found to be negative for a hinge location further downstream (i.e., $h = 0.8$), indicating a negative static margin. The effect of the hinge position and the ogive angle was found to be more dominant in determining the static stability than the effect of the Mach number for the range of the hypersonic regime. The analytical and CFD solutions show good agreement [48], with the maximum deviation being 10% as shown in Fig. 9. This validates the proposed theoretical model.

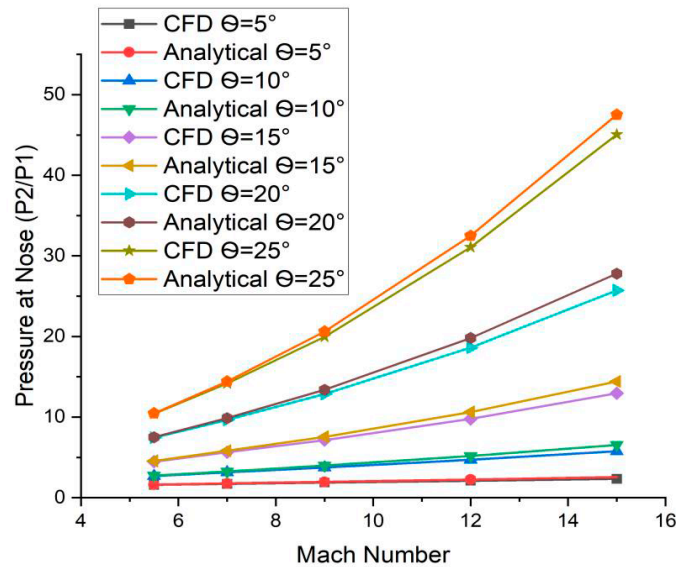


Figure 9: Variations of dimensionless static pressure of the wedge vs. Mach numbers [48].

Dimensionless static pressure at the nose of the wedge increases significantly with an increase in Mach number as well as the wedge angle, attaining values above 44 for $M \approx 15$ and $\theta \approx 25^\circ$. The results [48] have indicated that base and surface pressure distribution is highly dependent on Mach number and geometric parameters. Micro-jet control is found to be effective in enhancing base pressure without affecting the wall pressure distribution, thus improving flow stability. The results have further confirmed that selection of flow and geometric parameters is of great importance in optimizing aerodynamic performance. Flow visualization over all the tests confirmed that the attachment of the spike generates a large separated recirculation region ahead of the blunt nose [51,52], which acts to protect the nose from direct stagnation pressure and thus significantly reduces the drag. The aero disk configuration, especially at $L/D = 2$, shows greater capability for drag reduction compared to the conical spike. Maximum values of 75–78% reduction was recorded at zero angle of attack. However, the reduction in drag decreases with increasing angle of attack, whereas the lift coefficient shows a marked increase (almost 300%) with a corresponding large increase in pitching

moment. Kalimuthu et al. [53] demonstrates that the attachment of spikes results in a large separated recirculation region ahead of the blunt nose, resulting in large reductions in stagnation pressure and drag. Larger ratios of length-to-diameter and aerodisk-type geometries show larger drag reductions at zero angle of attack, while increasing the angle of attack reduces the drag reduction effectiveness and results in large increases in lift and pitching moment due to asymmetry effects. The results of Meng, et al. [54] have shown that increasing the jet pressure ratio reduces the peak pressure and heat flux by 58.21% and 46.43%, respectively. At the same time, the length of the spikes has a non-monotonic effect on the structure of the flows, and the drag and heat depend on the angle of the reattachment shock wave.

Overall, in all the studies [55–59], static pressure and aerodynamic derivatives, such as stiffness and damping, have been found to increase with a higher angle of incidence or wedge angle, and the magnitude of the aerodynamic derivatives has been found to reduce with an increase in the Mach number. Fig. 10 shows contours for static pressure against Mach number. Numerical results from CFD and regression analysis have shown good correlation with the analytical results, which have verified the dominance of the Mach number, the geometry of the body, and the position of the pivot in the pressure distribution and stability.

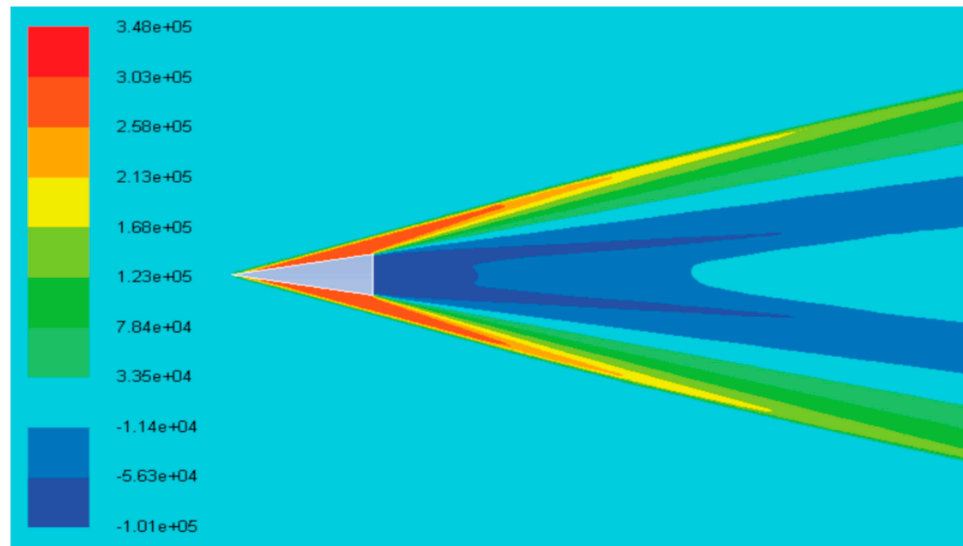


Figure 10: Contour of static pressure for Mach number $M = 6$ and angle of incidence $\theta = 10^\circ$ [56].

4.4 Shock Wave–Boundary Layer Interaction

Shock-wave/boundary-layer interaction is important for understanding surface pressure patterns in supersonic and hypersonic flows. The interaction of Mach number, Reynolds number, boundary-layer state, wall temperature, pressure gradient, shock strength, and geometric configuration influences shock-wave/boundary-layer interaction (SWBLI). Recent studies in the review suggest that shock-wave compression increases with increasing Mach number, which can further increase SWBLI. The effect of Reynolds number, however, depends on the flow conditions and the nature of the boundary layers and therefore cannot be generalized. Recent review by Huang et al. [42] have emphasized that the prediction and control of SWBLI require consideration of these coupled parameters, while passive flow-control devices such as micro-vortex generators have shown considerable effectiveness in mitigating shock-induced flow separation and improving aerodynamic performance.

4.5 Critical Synthesis of Analytical, Computational, and Experimental Approaches

The reviewed literature shows that analytical, computational, and experimental approaches each matter a lot for understanding surface pressure distribution over wedges, cones, and delta wings. But their usefulness changes a fair bit depending on the flow regime, the geometry, and the level of prediction accuracy needed. On the analytical side, there are things like Newtonian theory, piston theory, hypersonic similitude, shock-expansion theory, and strip theory. These analytical methods are simple to use, require very little computation, and give rapid estimates of surface pressure distribution and aerodynamic stability derivatives, and can be valuable in preliminary aerodynamic analysis and physical interpretation. Their application, however, is restricted by making certain assumptions, such as attached shock waves, inviscid flow, slender geometries, and small disturbances. Their predictive accuracy, therefore, decreases when the flow is viscous, shock-wave/boundary-layer interactions, flow separation, and complex 3D flow configurations are present. Computational Fluid Dynamics (CFD) has become the tool that most people reach for, because it can reproduce complex shock structures, viscous effects, and nonlinear flow behavior. CFD papers tend to agree well with both analytical results and experimental data, in both supersonic and hypersonic regimes. The accuracy of CFD predictions, however, is highly sensitive to mesh quality, turbulence models, numerical schemes, and boundary conditions. Furthermore, if the problem is high fidelity, e.g., real gas effects, unsteady flow effects, or complex three-dimensional cases, the computational resources and simulation time are considerable. In this context, experimental studies are still essential to confirm analytical and numerical predictions and to guarantee the correctness and reliability of aerodynamic analyses under realistic high-speed flow conditions. Wind-tunnel testing gives direct measurements of pressure distributions, shock locations, aerodynamic forces, and stability characteristics. But wind tunnels can be costly and slow, and facility constraints are real, especially at very high Mach numbers. In those cases, aerodynamic heating becomes a major factor, and real-gas effects start to matter more.

The studies analyzed indicate that analytical modeling, computational fluid dynamics (CFD), and experimental validation are increasingly being integrated, reflecting a trend toward this approach. While analytical methods are still useful in the early design stage and for physical understanding, CFD has become the key tool in the detailed aerodynamic study. Experimental investigations still serve as a criterion to validate analytical and numerical predictions and ensure the accuracy and reliability of high-speed aerodynamic analyses. As we advance, research should aim for unified predictive frameworks that can include viscous effects, shock-wave/boundary-layer interaction, real-gas phenomena, and fluid-thermal-structural coupling, all inside one consistent methodology. Table 5 shows a comparison of analytical, computational, and experimental approaches used for predicting pressure distribution.

Table 5: Comparison of analytical, computational, and experimental approaches used for pressure-distribution prediction.

Method	Major Assumptions	Advantages	Limitations	Suitable Flow Regime
Newtonian Theory	Inviscid, hypersonic flow	Simple, fast	Poor for low Mach numbers	Hypersonic
Piston Theory	Small disturbances, attached shock	Stability analysis	Limited for separated flows	Supersonic–Hypersonic
Shock-Expansion Theory	Attached shocks	Accurate for simple geometries	Limited for complex geometries	Supersonic
CFD (RANS)	Turbulence modeling required	Detailed flow prediction	Model dependent	All regimes

Table 5: *Cont.*

Method	Major Assumptions	Advantages	Limitations	Suitable Flow Regime
CFD (LES/DES)	High computational cost	High accuracy	Expensive	Supersonic–Hypersonic
Experimental Methods	Physical testing	Validation benchmark	Costly and facility dependent	All regimes

5 Conclusion

This review examined the development of analytical, computational, and experimental approaches for investigating surface pressure distribution in high-speed aerodynamic configurations. The literature suggests that pressure distribution characteristics are mostly governed by Mach number, angle of attack, geometric parameters, shock-wave structure, viscous effects, and flow-regime transitions. Even so, wedges, cones, and delta wings remain the main canonical configurations used to study high-speed aerodynamic phenomena. At the same time, related work on flow-control techniques and pressure-field modification provides practical insight into the mechanisms that influence aerodynamic performance and stability.

Analytical methods such as Newtonian theory, shock-expansion theory, hypersonic similitude, and piston theory remain useful and efficient for predicting high-speed aerodynamic flows in a preliminary stage and offer physical understanding. Their applications, however, are conditioned on some assumptions, such as those on the geometry, flow conditions, and shock attachment. Computational fluid dynamics (CFD), on the other hand, has become the main method for detailed aerodynamic analysis, as it can well represent the complex shock-wave structure, viscous effects, shock–boundary-layer interaction, and 3D flow phenomena. Still, solution quality tends to be rather sensitive to turbulence modeling, grid resolution, numerical schemes, and boundary conditions, in ways that are easy to underestimate at first. Experiments remain important too, mainly to validate theoretical and computational results, especially in regimes with shock-wave/boundary-layer interaction, flow separation, and high-temperature effects, even when setups are hard to run.

The comparative assessment of the reviewed studies shows a growing tendency toward integrated analytical–computational–experimental methodologies for predicting pressure distributions. Despite major progress, important issues are still open. For example, accurate modeling of shock-wave/boundary-layer interaction, real-gas effects, fluid–thermal–structural coupling, uncertainty quantification, and high-fidelity prediction of unsteady aerodynamic loads. So future research should lean on advanced numerical methods, high-resolution experimental diagnostics, data-driven modeling approaches, and multidisciplinary design frameworks to raise predictive capability and support the development of next-generation high-speed aerospace vehicles.

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Nomenclature

M	Mach Number
Mp	Piston Mach Number
P_∞	Free Stream Pressure
Pa	Atmospheric P
ρ_∞	Air Density
a_∞	Velocity of sound in air
Cp	Pressure Coefficient
γ	Specific heat ratio
P/P_∞	Non-dimensional Pressure Ratio
L/D	Length-to-diameter Ratio
NPR	Nozzle Pressure Ratio
Cm_α	Stiffness Derivative
Cm_q	Damping Derivative

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