



REVIEW

High-Speed Aerodynamics and Dynamic Stability of Aerospace Vehicles: A Review of Aerodynamic Derivatives, Flow Behavior, and Machine-Learning Approaches

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ABSTRACT: This review examines recent advances in the aerodynamic analysis and dynamic stability of high-speed aerospace vehicles, with particular emphasis on surface pressure distributions, aerodynamic stability derivatives, and complex flow behavior under supersonic and hypersonic conditions. The review first outlines the fundamental physical mechanisms governing high-speed aerodynamics and then critically surveys analytical, numerical, computational fluid dynamics, and experimental approaches for predicting aerodynamic characteristics. Particular attention is given to pressure, stiffness, damping, and rolling derivatives, as well as flow behavior in suddenly expanded ducts, which are relevant to the aerodynamic performance and stability of high-speed vehicles. The reviewed studies indicate that Mach number, geometric configuration, angle of attack, and pivot position are among the principal parameters governing aerodynamic forces, flow structures, and dynamic stability. Recent developments in machine learning, including artificial neural networks, surrogate modelling, physics-informed neural networks, and reinforcement learning, have demonstrated considerable potential for reducing computational costs and accelerating aerodynamic prediction and optimization. Despite these advances, several challenges remain. In particular, integrated prediction frameworks that combine high-fidelity simulations, experimental measurements, and data-driven methods remain limited, while comprehensive experimental validation under hypersonic conditions is still scarce. The accurate prediction of aerodynamic stability derivatives using machine-learning approaches also requires further development, particularly when multiple derivatives must be predicted simultaneously across a broad range of operating conditions. By critically assessing the current state of the field, this review identifies key methodological and experimental gaps and highlights promising directions for developing more accurate, efficient, and reliable approaches to the aerodynamic design and dynamic-stability assessment of high-speed aerospace vehicles.

KEYWORDS: Surface pressure; stability derivatives; machine learning; CFD; supersonic flow; hypersonic flow; aerodynamic prediction

1 Introduction

Hypersonic aerodynamics has slowly become a major research focus because it connects to a wide range of applications in high-speed aircraft, atmospheric re-entry bodies, missiles, and orbital transport

systems. Over the past decades, major shifts in theory, analytic work, and computation have improved understanding of these nasty flow events, even if some parts still feel opaque or hard to see. Tsien [1] established similarity laws for hypersonic flows, which created a theoretical framework that scientists use to study gas behavior under extremely high-speed conditions. The research findings helped scientists better understand how high-speed and re-entry vehicles operate through their complex aerodynamics. Carrier [2] and Rossow [3] analyzed the dynamic behavior of oscillating wedges and bodies of revolution through rolling and stiffness-derivative measurements across supersonic and hypersonic flow conditions, focusing on pressure distribution. Lighthill [4] investigated the oscillating airfoil at high Mach numbers, analyzing the surface pressure and pitching at supersonic and low hypersonic speeds. Ashley and Zartarian [5] introduced a simplified aerodynamic method for analyzing aeroelasticity in high-speed flows. The findings established the foundational approach for calculating unsteady airloads in supersonic and hypersonic flight regimes. Sychev [6] examined three-dimensional airflow patterns around thin objects at elevated angles of attack, as these patterns affect both surface pressure measurements and damping-derivative behavior during hypersonic flight. Morgan et al. [7] examined theoretically the characteristics of aeroelastic flutter at high Mach numbers, paying special attention to compressibility effects and supersonic flow on aerodynamic stability. The study gave a theoretical explanation to assess flutter boundaries of aircraft structures in high speed. Zartarian et al. [8] researched unsteady aerodynamic forces and aeroelastic behavior during atmospheric entry, particularly how stiffness and rolling motion affected vehicle stability at hypersonic speeds. Appleton [9] studied the aerodynamic pitching derivatives of wedges, emphasizing stiffness and damping at hypersonic speeds.

Lighthill [4] and Zartarian et al. [8] focused on the surface pressure and pitching motion of wedges. These studies offered insights into stiffness and damping derivatives at high Mach numbers [4,9]. Sychev [6] and Morgan et al. [7] studied unsteady hypersonic flow at elevated angles of attack to examine its influence on stiffness derivatives and three-dimensional aerodynamic behavior. Zartarian et al. [8] examined how stiffness and rolling affect entry movements and how different flow conditions affect the aerodynamic stability of wedge-shaped objects. McInthosh [10] investigated unsteady hypersonic flow to study the aeroelastic characteristics of wedges, thereby developing improved methods for predicting damping and stiffness derivative values. Hayes and Probstein [11] systematized hypersonic flow theory. They reviewed studies on surface pressure, stability, and aerodynamic derivatives for a variety of hypersonic shapes. Hui [12] investigated stability in oscillating wedges and caret wings, linking theoretical predictions to practical design, particularly regarding rolling, damping, and stiffness under supersonic and hypersonic flow conditions. The existing research has provided a clear understanding of the variation of important aerodynamic parameters, including surface pressure, stiffness derivatives, damping, and rolling characteristics, with the geometric configuration in supersonic and hypersonic flow regimes. Further, the present review focuses on flow control and optimization in aerodynamics, particularly for two-dimensional wedge geometries, where geometric parameters play a significant role in stiffness. Overall, the present research contributions provide a robust theoretical and computational understanding of stiffness-derivative prediction for 2D wedges. The findings show that advanced methods, including machine-learning predictive models for estimating stiffness derivatives in supersonic and hypersonic flow conditions, should be used, as these models are vital for developing advanced aircraft designs.

The surface-pressure distribution shapes the aerodynamic forces and moments on a vehicle, which in turn drive stiffness, damping, and the overall rolling-stability derivative picture. On the other hand, the flow structures that form in suddenly expanded ducts, such as shock waves, recirculation areas, and flow separation, significantly alter the pressure field. The stability behavior then follows from that. So

instead of treating surface pressure, stability derivatives, and suddenly expanded flow as isolated subjects, it makes more sense to see them as complementary parts. That way, you get a less patchy, more coherent understanding and better predictions of the aerodynamic performance and stability of fast aerospace vehicles. Collectively, these studies point to a slow evolution in hypersonic aerodynamics, moving from similarity theory toward issues that arise when you start caring about unsteady flow, aeroelasticity, and dynamic stability. Even with the real progress made, many initial investigations focused on simpler wedge configurations or slender bodies. They relied on analytical formulations with idealized flow conditions, so it's not like everything was fully general or guaranteed to carry over cleanly. Also, the literature you can find tends to be pretty scattered across different themes, such as surface-pressure behavior, stability derivatives, unsteady hypersonic flow, and the development of the flow inside suddenly expanded ducts. Yet few studies attempt to stitch these separate threads into a unified review, at least not directly, so the connections remain somewhat hidden. This review provides a comprehensive, somewhat critical assessment of what's available on surface pressure characteristics, stability derivatives, and flow development in sudden-expansion geometries. The emphasis is mostly on two-dimensional wedge configurations under supersonic and hypersonic flow conditions. Beyond summarizing earlier research, the review traces how methodologies evolved, flags what doesn't work well, and highlights where the evidence is still thin or missing. It also introduces new possibilities, including data-driven strategies and machine-learning-based approaches.

2 Review of Literature

This section summarizes existing research, including analytical, experimental, and computational studies on wedge-shaped geometries exposed to supersonic and hypersonic flow conditions. The analysis focuses on five factors: flow expansion behavior, surface pressure distribution, stiffness derivatives, aerodynamic damping, and rolling characteristics, because they all affect aerodynamic stability under flight conditions. The researchers studied these parameters across various Mach number ranges that exhibit different flow physics patterns while maintaining the same geometric shape. The researchers in the examined studies create a model for high-speed flow over wedge configurations by integrating classical aerodynamic theory with their numerical and experimental results. The research establishes the basic framework for developing a computational model that predicts two-dimensional wedge stiffness derivatives under supersonic and hypersonic flow conditions.

2.1 Surface Pressure

The study of surface-pressure prediction has been carried out extensively in both the supersonic and hypersonic regimes. Early supersonic investigations developed basic pressure-distribution characteristics and analytical prediction methods, and later studies expanded these techniques to more complex configurations and higher Mach numbers. This section treats the supersonic studies as methodological foundations and the hypersonic studies as the basis for understanding pressure behavior under the conditions of the present study.

Rossow [3] studied how rotation affects pressure distribution in hypersonic flow by applying the similarity law for bodies of revolution. The study showed that neglecting rotational terms can introduce significant errors in the surface pressure distribution and in drag predictions. Sychev [6] applied small-disturbance theory to study the flow characteristics around streamlined shapes that operated at high incidence angles in high-Mach-number conditions. The study found that aerodynamic characteristics primarily depend on cross-sectional shape, whereas disturbance parameters have minimal impact. Zartarian et al. [8] determined the dynamic air loads that produce surface pressures on pointed configurations during hypersonic flight. The study used two-dimensional piston theory to reduce the problem and applied shock-expansion theory

to analyze conditions at higher Mach numbers. Hui [13] developed a comprehensive theory explaining both supersonic and hypersonic airflow patterns over delta wings when shock waves remain attached. The study revealed a flow pattern comprising two distinct zones of constant supersonic airflow and one subsonic zone exhibiting variable airflow characteristics, with results matching numerical simulations. Pike [14] established a relationship to predict pressure distribution on wings in a supersonic free stream using thin wing surface shape equivalence. The predicted pressure distribution for the caret and delta wings matched both experimental and theoretical results except for areas where shock waves detached from the wings. Hui and Hemdan [15] used thin-shock-layer theory and perturbation methods to study unsteady hypersonic flow past slender delta wings with separated shocks. The research obtained solutions for unsteady pressure distributions while demonstrating that the flow remained dynamically stable. Ghosh and Mistry [16] used extended similitude theory to study how surface pressure behaves on non-planar wedges during hypersonic testing at elevated incidence angles.

The research showed that hypersonic similarity parameters can predict the pressure distribution above oscillating wedges, demonstrating the fundamental strength of similitude theory. Lamar [17] discusses the use of this simple aerodynamic theory and vortex-based flow techniques in designing high-subsonic aircraft. The paper utilizes the NASA Vortex Lattice Method, the Modified Moulthrop Approach, and the suction analogy. It explains how to use these methods to develop wings of various designs. Ghosh [18] studied triangular wing designs that operated at high velocity under steep angles using similarity relationships and strip-theory methods. The study developed a piston theory for unsteady aerodynamic derivatives and found that pitch derivatives remain constant despite variations in the flow.

In contrast, roll derivatives depend on aspect ratio through a linear relationship. Anderson [19] provided a comprehensive study of extreme-speed compressible flow theory with thermal gas effects, including both inviscid and viscous flow conditions at hypersonic speeds and at high temperatures. Hemdan [20] studied the pitching oscillations of two-dimensional thin pointed-nose aerofoils at hypersonic Mach numbers using steady and unsteady flow theories. The analytical solutions obtained for surface pressure and stability derivatives agreed well with existing solutions. Balakumar [21] used high-order numerical methods to investigate supersonic boundary-layer stability on flat plates with blunt leading edges and wedges at $M = 3.5$. The study found that blunt leading edges stabilize the boundary layer by increasing the transition Reynolds number, while blunt wedges provide greater stability than blunt flat plates. Khan and Rathakrishnan [22] analyzed base-region pressure (P_b/P_a) in suddenly expanded flow conditions, which included micro-jet actuation. Fig. 1 shows how the normalized base pressure (P_b/P_a) varies with nozzle pressure ratio (NPR) for both controlled and uncontrolled flow at several area ratios with $L/D = 10$. (a) When the Mach number is 1.25; (b) when the Mach number is 1.30.

Holden and Babinsky [23] examined how micro- and sub-boundary-layer vortex generators affect shock interactions with the boundary layer. The research showed that vortex generators increase boundary-layer momentum while delaying flow separation, but in some cases led to stronger shock waves due to increased boundary-layer energy. Ogawa et al. [24] used three-dimensional bumps to study shock–boundary layer interactions in transonic wing applications. The research demonstrated that specific bump designs reduced the occurrence of λ -shocks while enhancing pressure distribution and reducing drag from counter-rotating vortices. Kalimuthu et al. [25] performed experimental tests to study how a hemispherical forebody with a spike reacted to Mach 6 conditions while trying to reduce drag. Fig. 2 shows a conical compression wave and a shear layer, along with the flow recirculation zone in front of them.

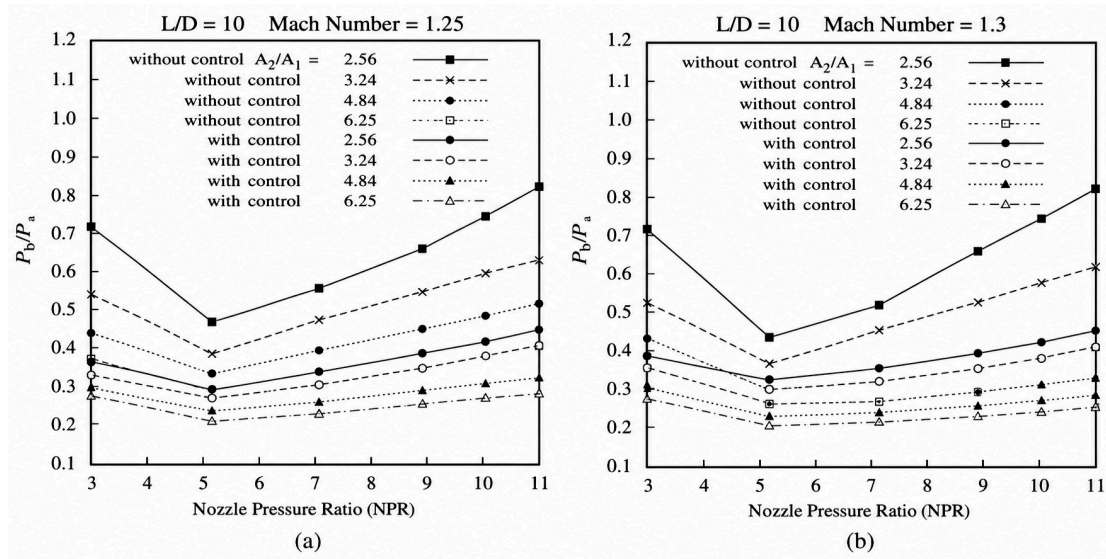


Figure 1: Base-region loading variation with nozzle pressure ratio (NPR) (a) $L/D = 10$, Mach Number = 1.25, (b) $L/D = 10$, Mach Number = 1.3 [22].

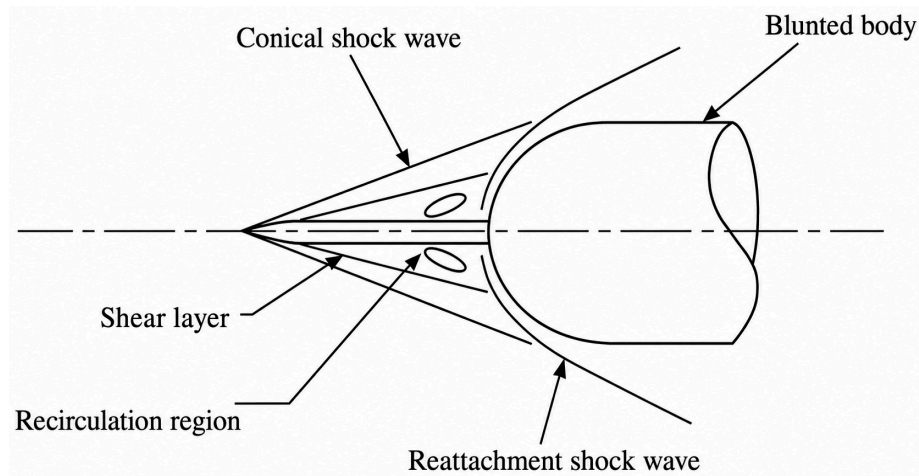


Figure 2: Conical spike [25].

The development of active and passive flow control strategies has greatly improved pressure management in high-speed aerodynamic setups. Kalimuthu et al. [25,26] used both experimental and analytical methods to assess how spikes affect a blunt-nosed body in hypersonic flow at Mach 6, using schlieren visualization and pressure analysis. The study found that the spike generates a conical shock, a separated shear layer, and a recirculation zone, which reduce nose pressure and aerodynamic drag. The study found that longer spikes produce greater pressure reduction by transforming the flow field. (Fig. 3 Schlieren pictures for a canonical spike. Fig. 4 shows that C_p values vary most at the reattachment point at an angle of 50 degrees. In contrast, the pressure decrease depends on the length-to-diameter ratio.

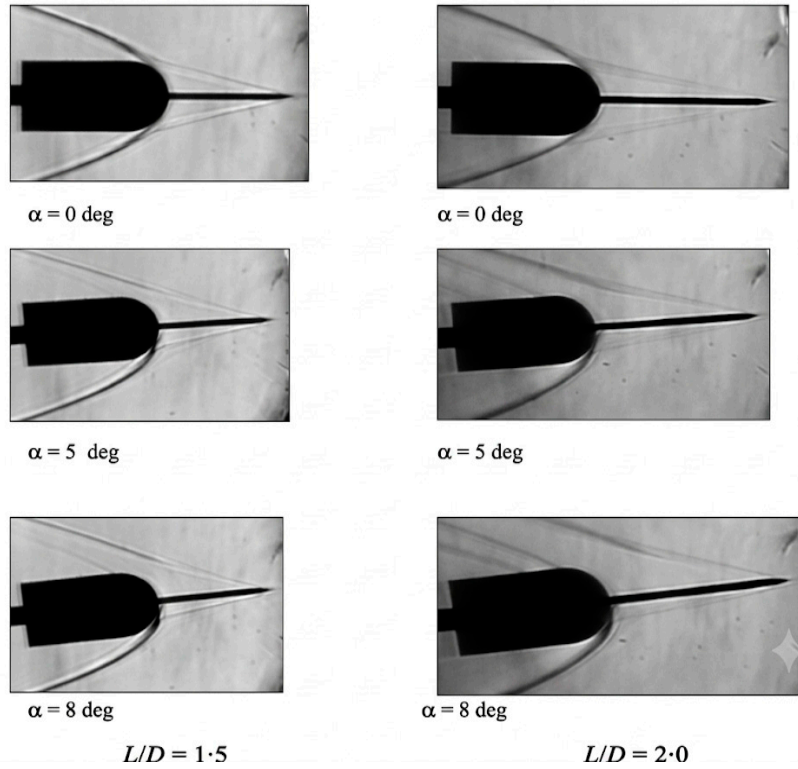


Figure 3: Schlieren pictures for canonical spike [25].

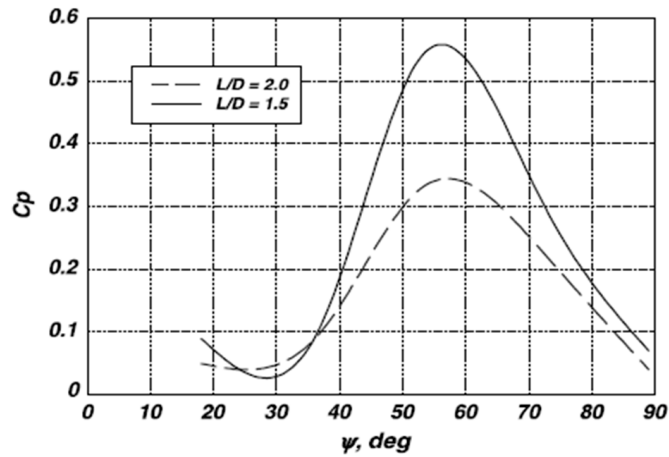


Figure 4: CP distribution over spiked blunt nose at zero incidence [26].

The research study uses surface pressure measurements as its primary method for all stability derivative calculations. The authors used Ghosh's piston theory, which establishes a direct link between wing surface pressure and the corresponding piston Mach number. The pressure ratio at the surface can be expressed as follows:

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

P_∞ is the free-stream pressure, M_p = represents the piston Mach number measured Normal to the wedge surface.

Eq. (2) sets up the constants A and B, which depend on γ . Now, these constants are supposed to work only under the same assumptions as Ghosh's piston theory, which is valid when a shock wave is attached to inviscid supersonic flow, so nothing too fancy is happening here, at least not at this stage.

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

here, γ is the heat capacity ratio.

Babinsky and Harvey [27] explained how compression waves interact with boundary areas during extreme-velocity flows and how this interaction changes surface loading and flow patterns. The results show that it causes separation and instability, which depend on the compressibility level, the viscous effects, and the material's compression strength. Narayanaswamy et al. [28] conducted experiments to investigate SBLI control at Mach 3 using a pulsed-plasma-jet actuator over a compression ramp. The research found that the actuator achieved shock-motion synchronization, reducing low-frequency wall-pressure fluctuations by 30%. Higher actuation frequency further reduced shock oscillation, and upstream injection proved more effective than injection inside the separation bubble for control purposes. The study by Argyris and Lu [29] investigated the performance of small vortex-generating devices, which served as tools for controlling compressive-wave interactions near wall surfaces. The study discovered that MVGs produce streamwise vortices that deliver high-momentum fluid to the wall, thereby preventing shock-induced separation while preserving boundary-layer stability, and revealed complex vortex structures that require further research at different Reynolds numbers. Gaitonde [30] studied SWBLI across three areas: unsteady behavior, heat transfer prediction, and multi-shock interaction analysis. The study found that researchers have extensively studied separation bubble dynamics, while accurately predicting heat transfer remains difficult, even for complex SWBLI. Soni et al. [31] performed numerical simulations to investigate how compressive waves behave when they encounter double-curved cylindrical surfaces that reflect waves. Durbin [32] reviewed some recent developments in turbulence closure modeling.

The research showed that complex shock-reflection patterns, along with bifurcation processes, changed the surface pressure distribution. At the same time, multiple reflection structures affected local pressure changes throughout the high-speed flow. Yin et al. [33] used numerical simulations to investigate how dusty shock waves reflect off double-wedge structures. The study shows that shock-reflection behavior changes significantly due to particle-gas non-equilibrium effects, which are governed by the ratio of the original wedge thickness to the particle relaxation distance. Khan et al. [34] studied supersonic flow over a wedge by using both analytical methods and CFD simulations. The results show that surface pressure increases with higher flow Mach numbers and deflection angle, while viscous effects change the pressure distribution. The pressure ratio (P_2/P_1) shown in Fig. 5 indicates the degree of compression the system undergoes throughout its compression process.

Mortazawy et al. [35] studied the propagation of normal shocks through duct systems with grooved patterns by conducting both experimental tests and simulation studies. The researchers found that groove interaction altered shock behavior and reduced shock strength, resulting in lower pressure changes throughout the duct system, as indicated by their scores and quantitative results. Brahmia et al. [36,37] investigated numerical simulations of shock-wave diffraction over double cylindrical wedges under transonic and supersonic flight conditions. The study found that compressibility and viscous effects, together with the concave surface design, reduced static and dynamic pressure impulses and changed the surface pressure

distribution during shock diffraction. Brunton et al. [38] used PCA/POD and autoencoder-based machine learning methods to analyze surface-pressure data from aerodynamic flows. The research demonstrated that deep autoencoders create more precise flow representations than shallow models and PCA/POD. The comparison shows that deep learning methods yield better latent space representations than traditional reduction methods, as shown in Fig. 6.

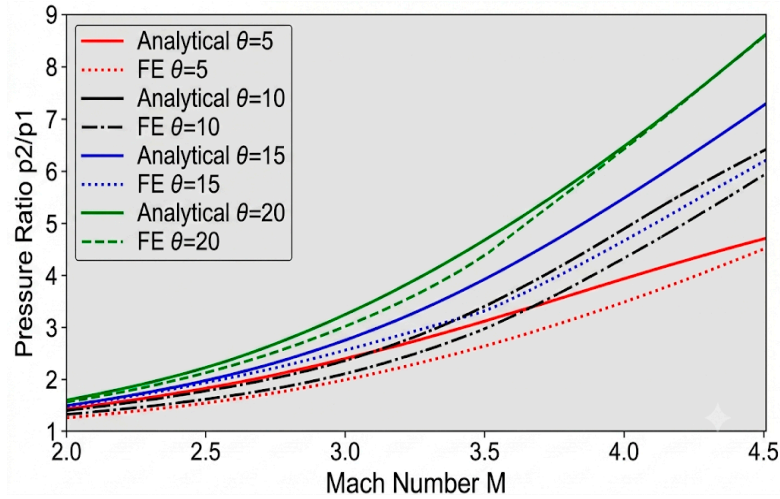


Figure 5: Pressure distribution curves [34].

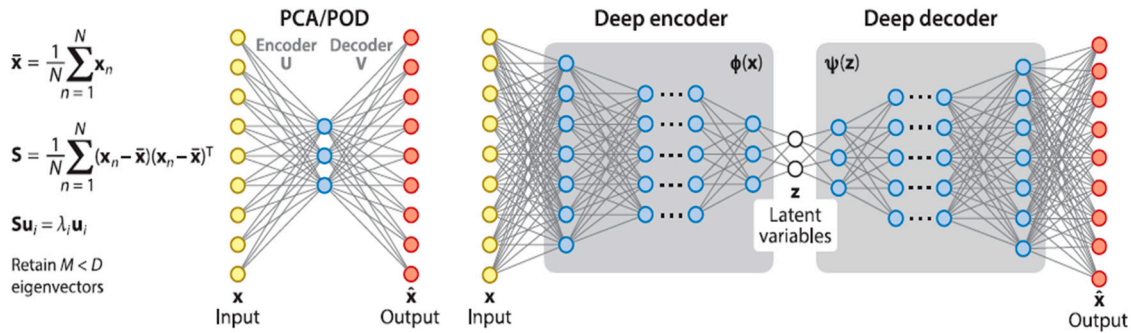


Figure 6: Classical projection and deep representation framework [38].

Huang et al. [39] examined the behavior of SWBLI and control configurations under both confined and external flows. They observed that SWBLI causes flow separation when surface pressure and surface heating increase, but micro-vortex generators enable users to reduce separation and alter the system's wall-pressure pattern. Li et al. [40] developed an optimization framework that leverages deep learning techniques to improve surrogate-based methods for high-dimensional aerofoil design using DCGAN and CNN architectures. The model generated aerofoil shapes that remained physically valid, exhibited smooth transitions, and improved the surface pressure distribution. EGO-based optimization with GAN and CNN produces aerofoils with smooth C_p curves and reduced shock formation, resulting in lower aerodynamic drag, as shown in Fig. 7.

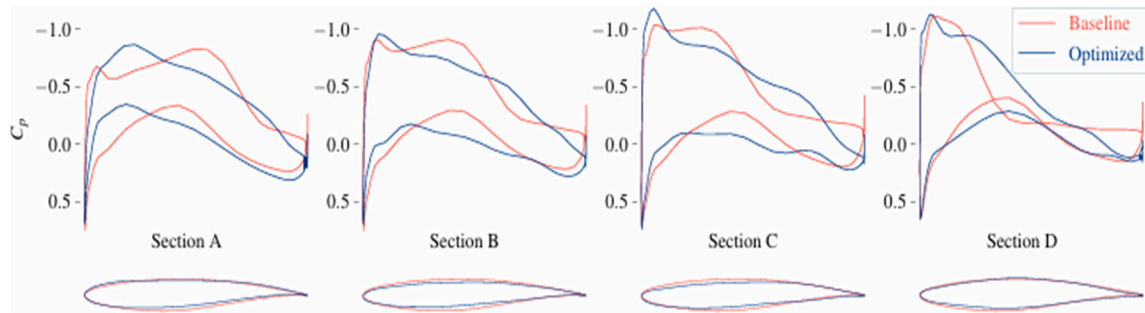


Figure 7: Airfoils optimized by EGO with GAN and CNN [40].

Chen et al. [41] developed deep learning based methods for the prediction of aerodynamic coefficients of airfoils. Jana and Kaushik [42] conducted an experiment to understand the evolution of wall static pressure in the presence of strong interaction between shock waves and the boundary layer. The study found that pressure reached its maximum at the shock-impact point, then stabilized in the separation area before gradually recovering in the reattachment zone. The results in Fig. 8 demonstrate that shock interaction leads to surface separation, with pressure changes occurring at different points along the surface.

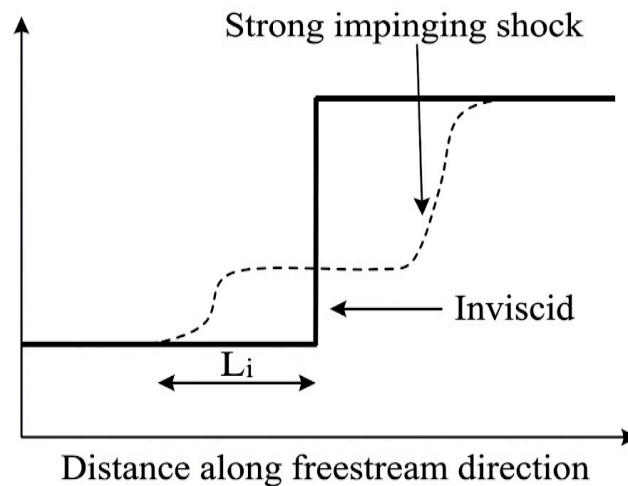


Figure 8: Wall static pressure measurement [42].

Li et al. [43] developed a deep learning-based fully convolutional neural network (FCNN) to predict wall surface pressure distributions over bluff bodies with varying geometries. Their approach reproduced the CFD-generated pressure fields quite well, with small deviations mostly in the lower-pressure regions associated with flow separation. Fig. 9a–h shows a side-by-side comparison of the predicted results with the CFD pressure distributions for several bluff body forms and aspect ratios. Overall, the FCNN captures the main pressure patterns and serves as a quicker, computationally efficient alternative for estimating aerodynamic performance. Fig. 9 compares deep learning and CFD predictions of wall pressure across a handful of bluff-body shapes. (a) Circular cylinder, (b) Elliptical cylinder, (c) Hexagonal cylinder ($R = 0.3$), (d) Elliptical body ($R = 0.1$), (e) Square cylinder, (f) Rectangular cylinder, (g) Diamond-shaped cylinder, and (h) Rhombus-shaped cylinder.

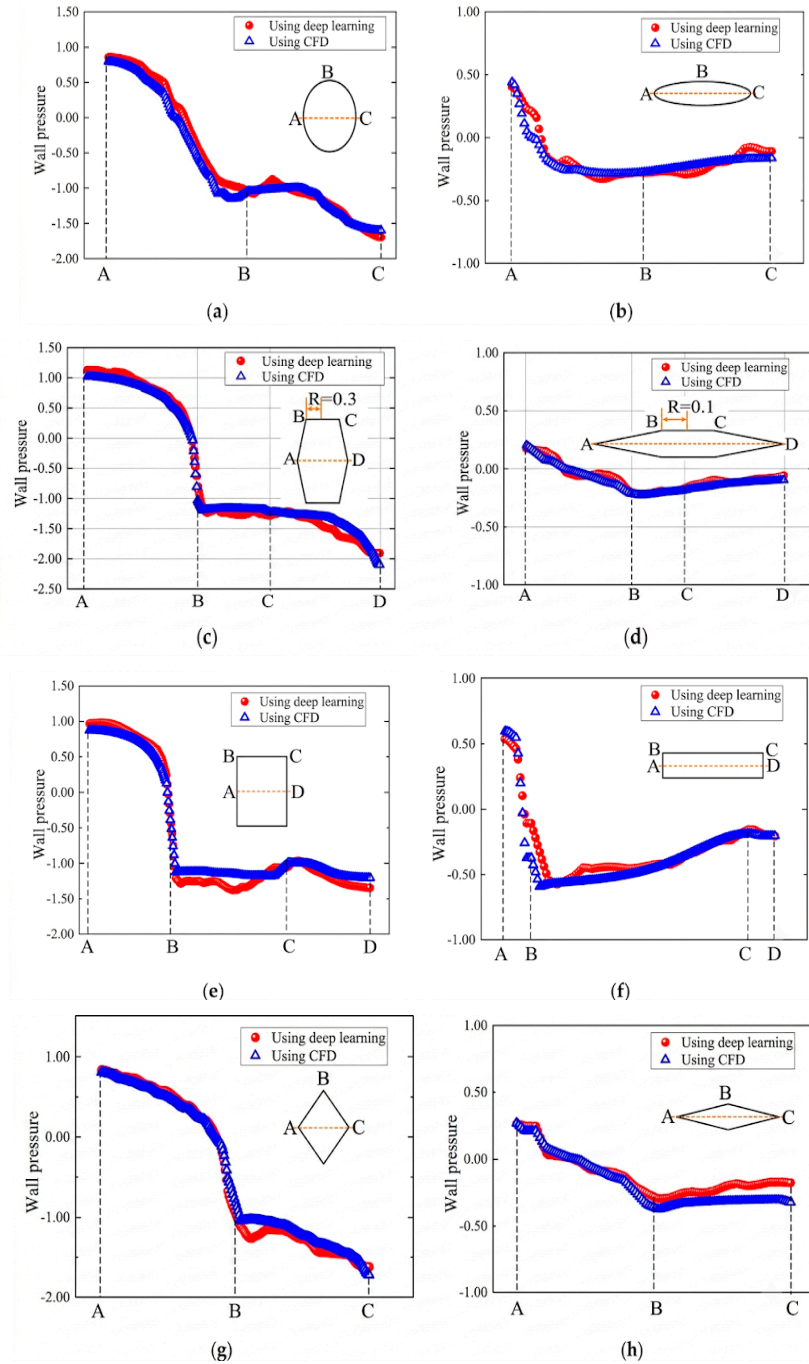


Figure 9: The prediction versus wall pressure for various bluff body shapes and aspect ratios (a–h) [43].

Zhao et al. [44] applied Physics-Informed Neural Networks (PINNs) to supersonic compressible flow, demonstrating their capability to solve the governing Euler and Taylor–Maccoll equations and capture shock-wave structures. Shah et al. [45] conducted a computational fluid dynamics study using oblique shock theory to evaluate the performance of conical and ogival missile nose cones at Mach 2.0. The researchers found that different shapes produced distinct pressure and temperature fields, leading to distinct aerodynamic forces. The ogival shape exhibited lower pressure rise and reduced aerodynamic resistance, indicating better supersonic performance. Wang et al. [46] investigated how shock waves interact with turbulent

boundary layers in a symmetric double-fin setup at Mach 2.8. The study showed that shock waves induced flow detachment and altered wall-pressure patterns, whereas micro-ramp vortex generators enhanced momentum transfer between fluids and prevented flow separation. Chen et al. [47] used reinforcement learning methods to create better aerodynamic designs that control transonic buffet conditions. The study demonstrated that shock-wave-boundary-layer interaction produces unsteady flow patterns and surface pressure fluctuations. At the same time, the optimized aerofoil design improves the lift-to-drag ratio and extends the buffet onset time, thereby enhancing aerodynamic stability. Dussauge et al. [48] applied a reinforcement learning approach to optimize the shape of the airfoil. Lou et al. [49] investigated the aerodynamic optimization of an airfoil based on deep reinforcement learning. Ray and De [50] studied the effect of leading-edge bluntness on a double-wedge at hypersonic speeds. The researchers found that increased bluntness led to bow shock and separation regions, thereby improving shock–boundary-layer interactions and moving the separation point upstream. Aft-wedge angles between 45° and 60° produce intense pressure variations that change the surface pressure distribution pattern.

Dash et al. [51] used ANSYS Fluent simulations to investigate the aerodynamic performance of bi-conic nose cones with dimpled surfaces at subsonic, transonic, and supersonic flight conditions. The study found that dimples modify the boundary layer, reducing flow separation and improving surface pressure distribution, while dimple spacing, depth, and eccentricity significantly affect pressure profiles and aerodynamic efficiency. Liu et al. [52] used deep reinforcement learning to optimize supercritical aerofoils by controlling surface pressure. The study showed that geometric changes could delay shock formation and improve buffet-onset lift, while maintaining higher lift-to-drag ratios during cruise, resulting in better aerodynamic performance. Sawant et al. [53] compared reinforcement learning agents for optimizing airfoil shapes. The pressure distribution patterns over delta wings in supersonic flow exhibit complex behavior due to three factors: changes in operational flow speed, different angles of attack, and wing rotation. According to Ghosh's piston theory, the compression side of the wing shows a surface pressure ratio, P_2/P_1 , from Eq. (3), which is used to determine the surface pressure ratio at the pivot location or nearby. The overall formulation works for attached-shock supersonic flow; it also assumes inviscid, compressible flow and largely ignores viscous effects.

$$\frac{P}{P_\infty} = 1 + EM_p^2 + EM_p\sqrt{1 + FM_p^2} \quad (3)$$

where, M_p is the local Mach number at the pivot, and constants E and F depend on the air's specific heat ratio.

$$E = \frac{\gamma + 1}{4} \text{ and } F = \left(\frac{4}{\gamma + 1} \right)^2$$

Shetty et al. [54] conducted CFD simulations to examine the distribution of surface pressure over a delta wing at supersonic Mach numbers ranging from 1.3 to 3.8, while varying the sweep angle from 5° to 25°. In other words, the results show that both Mach number and overall geometry strongly affect the pressure map, and the numerical outputs agree well with piston-theory solutions. This also helps confirm that the analytical strategy is trustworthy, especially for attached-shock flow conditions, even if the physics is a bit delicate. Fig. 10 shows how the dimensionless pressure ratio (P_2/P_1) varies as the pivot location shifts slightly across several Mach numbers. Usually, the pressure ratio increases with the Mach number, reflecting stronger shock compression. Still, the overall effect of pivot position seems relatively moderate compared to that, not really super dramatic or anything.

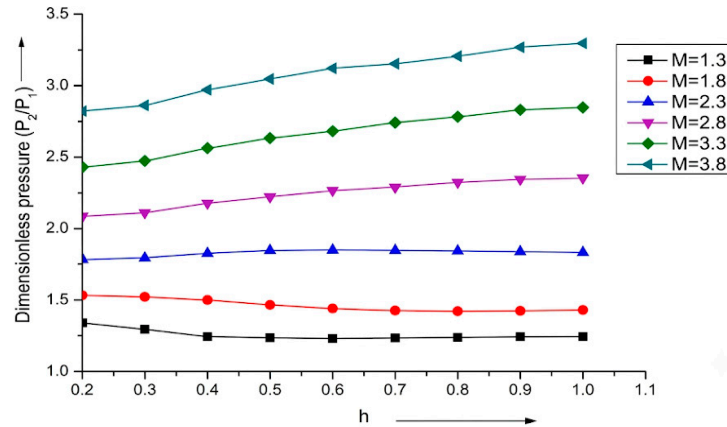


Figure 10: Pressure ratio vs. pivot position (h) [54].

Shaikh et al. [55–58] used CFD methods to study pressure distribution on 2D wedge and cone shapes under both supersonic and hypersonic flow conditions. They used analytical methods and CFD in a unified manner. In all runs, it was clear that as the Mach number rises and the cone angle increases, shock compression strengthens. This leads to higher surface pressure and also a thinner shock region. The consistency between the analytical results and the CFD simulations also supports the reliability of the analytical method for tracing the pressure distribution in attached-shock flow. Fig. 11 compares the analytical and CFD predictions of the non-dimensional pressure ratio at Mach 5 for the various semi-cone angles. Both results align closely, validating the analytical model. At the same time, as the cone angle increases, the pressure rises more gradually, suggesting stronger shock compression and stronger aerodynamic loading. Fig. 12 shows the static-pressure contours around the cone, demonstrating that as the Mach number rises, the shock layer becomes thinner and the pressure over the cone surface increases. The flow becomes more compressible, and the aerodynamic load increases at supersonic speeds.

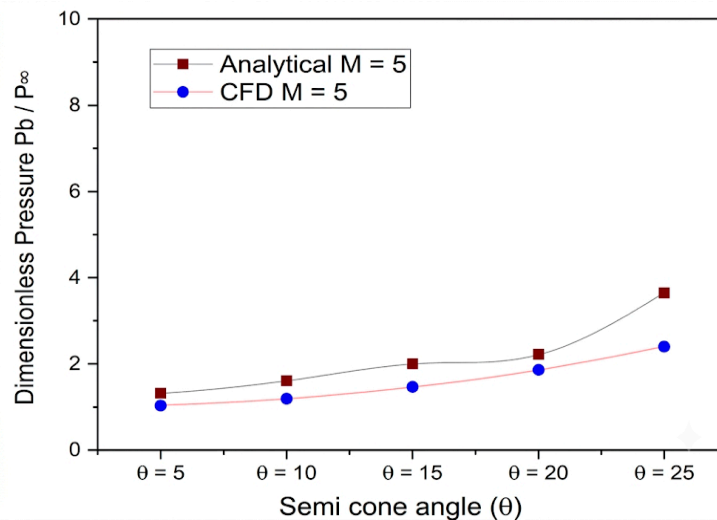


Figure 11: Analytical and CFD comparison of non-dimensional pressure variation at M = 5 [57].

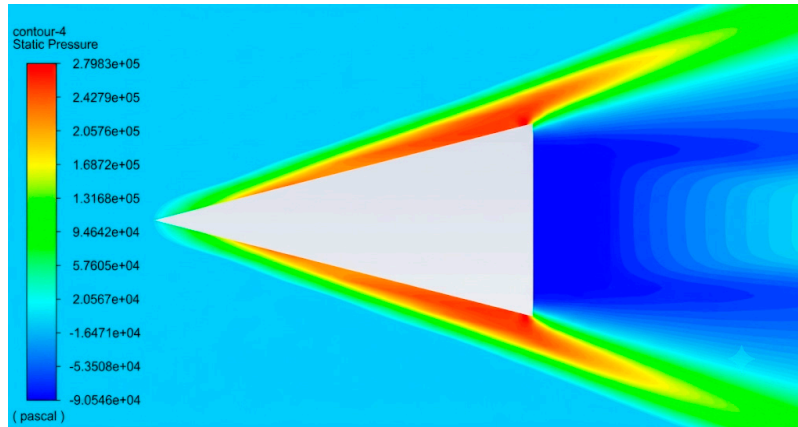


Figure 12: Static pressure contours of varying Mach number for a semi-cone angle of 15° [57].

Overall, the reviewed studies indicate that the surface-pressure distribution in high-speed flows is primarily governed by Mach number, geometry (e.g., the angle of a wedge/cone), and axial position. Analytical results and CFD investigations appear to agree, both showing an increase in surface pressure with increasing Mach number and geometric inclination. Yes, they've made better progress in predicting things since then, and they've made their computer simulation run more efficiently, but, well, there's not a lot of experimental validation of this sort under hypersonic conditions. Many integrated data-driven prediction frameworks exist. Finally, these results indicate that accurately predicting surface pressure is crucial to the aerodynamic analysis and design of high-speed aerospace vehicles.

Flow separation control is, in some respects, very important for understanding the surface pressure distribution and overall aerodynamic performance. In practice, flow separation is often delayed or even quenched by active and passive flow-control techniques, such as micro-jets, blowing, suction, vortex generators, and boundary-layer control devices. Key factors that determine their effectiveness include Mach number, Reynolds number, angle of attack, actuation frequency, and jet momentum coefficient. Good flow separation control can increase pressure recovery, decrease drag, improve aerodynamic efficiency, and enhance vehicle stability. Table 1 summarizes the surface pressure studies.

Table 1: Summary of surface pressure studies.

Reference	Method	Mach Range	Geometry	Key Findings
[56]	Numerical (DOE)	1.5–3.0	2D Wedge	Surface pressure increases with both the Mach number and the wedge angle.
[59]	Analytical + CFD	Supersonic	2D Wedge	Good agreement between analytical and CFD results.
[60]	CFD	Supersonic-Hypersonic	2D Wedge	Pressure distribution strongly depends on Mach number.
[61]	Analytical	Hypersonic	2D Wedge	Cone angle significantly affects pressure distribution.
[62]	CFD	Supersonic	2D Wedge	Numerical results validate pressure trends.

2.2 Aerodynamic Derivatives

Investigation of aerodynamic derivatives has also advanced from supersonic to hypersonic flow regimes. Experimental testing at supersonic Mach numbers led to the development of analytical and computational methods to calculate stiffness, damping, and stability derivatives, which were then extended to hypersonic Mach numbers. These studies are applicable to the present review because they show the changes in aerodynamic prediction at high speed; hypersonic studies provide the specific physical context for the present research.

2.2.1 Stiffness Derivatives

Stiffness derivatives are critical parameters for static stability analysis of aerodynamic configurations. This section reviews the roles of geometry and flow regime in stiffness characteristics, with particular emphasis on wedge-like configurations. Appleton [9] studied hypersonic wedge pitching using oscillation tests. The findings showed that stiffness derivatives matched piston theory predictions, while changes in wedge geometry affected aerodynamic stability. Hui [12,63] applied perturbation theory to study the behavior of oscillating wedges and flat plates in both supersonic and hypersonic flow conditions. The study found that stiffness derivatives depend on Mach number and incidence but not on aspect ratio, whereas high angles of attack lead to pitching instability, demonstrating the role of stiffness in maintaining stability. Khan et al. [34] used CFD and piston theory to investigate supersonic wedge flow. The study found that the Mach number and geometric factors determine the aerodynamic response and stiffness properties, which stabilize at high Mach numbers. Fig. 13 shows that static pressure varies with Mach number, indicating stiffness derivative behavior.

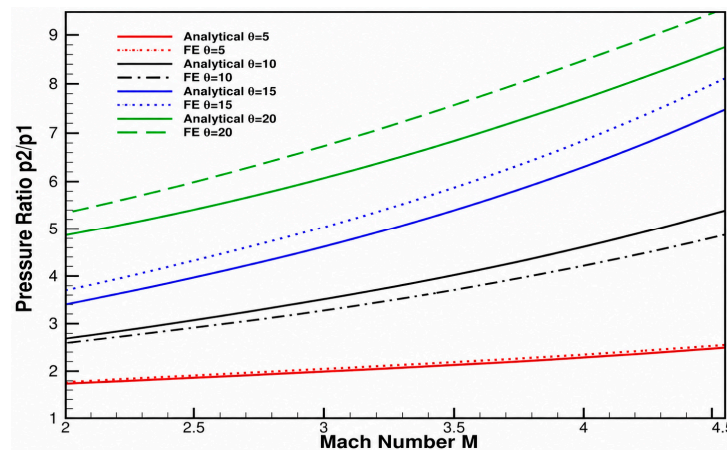


Figure 13: Pressure variation with Mach number [34].

Orlik-Ruckemann [64] demonstrated that high-Mach-number dynamic stability derivatives require precise measurement. Wind-tunnel facilities showed limited measurement capabilities, necessitating the development of improved methods to assess stiffness properties. Liu and Hui [65] used perturbation methods to study how oscillating delta wings develop aerodynamic stability under high-speed flow conditions that maintain attached shock structures. The study showed that the dynamic stability of such configurations depends on the system's stiffness derivatives, Khan and Crasta [66].

The researchers used analytical techniques to investigate how a supersonic delta wing with curved leading edges exhibited oscillatory movements. The two testing conditions, including the pivot position and angle of incidence, showed their effects on the stiffness derivative values, as indicated by the study results. The results in Fig. 14 demonstrate that the stiffness derivative varies directly with the pivot position, and Liu and Hui's theory accurately predicts these results. This trend occurs because, as the pivot position moves downstream, the aerodynamic restoring moment about the reference location decreases, resulting in a lower stiffness derivative. The results obtained are closely aligned with classical theories. In aerodynamic design, it's essentially the same idea: carefully consider the location of the pivot point; otherwise, in a high-speed vehicle, one will have no longitudinal static stability when things get sensitive at high speed.

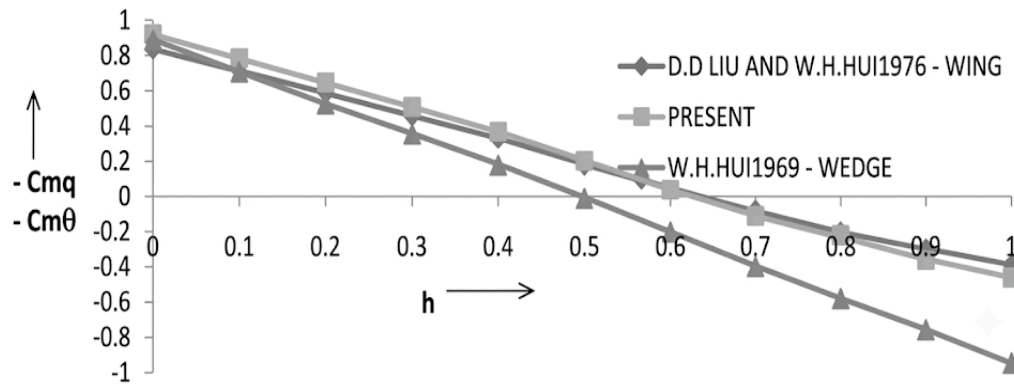


Figure 14: Variation of stiffness derivative with pivot position at $M = 4$, $\alpha_0 = 15^\circ$, $\gamma = 1.4$ [66].

Experimental investigations have also helped validate aerodynamic stability derivatives for practical aircraft shapes. Anton and Botez [67] studied the stability derivatives of delta-wing aircraft using wind-tunnel data collected for their investigation of the X-31 aircraft. The research found that $C_{m\alpha}$, C_{mq} , and C_{lp} indicate aircraft stability. They also forecast oscillation patterns. Table 2 and Fig. 15 show that these derivatives influence short-period and phugoid motions.

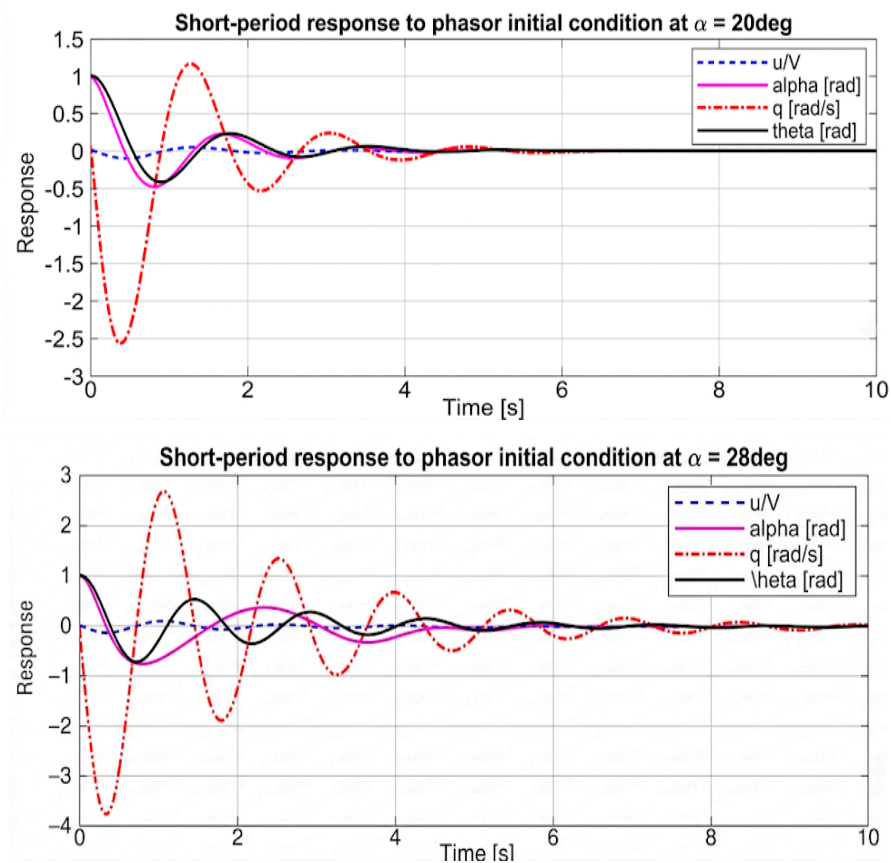


Figure 15: Cont.

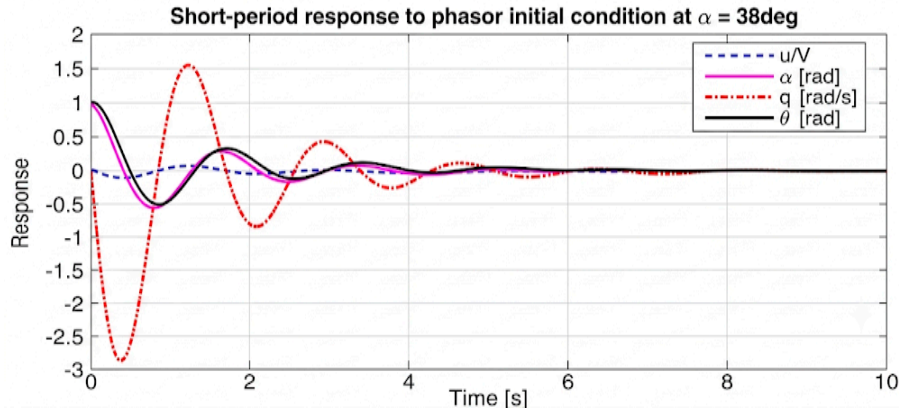


Figure 15: Short-period motion response with phasor initial condition [67].

Table 2: Constant short-period approximation parameters.

Parameter	$\alpha = 20^\circ$	$\alpha = 28^\circ$	$\alpha = 38^\circ$
α/δ_0 (rad/rad)	-0.2018	2.3857	1.0657
q/δ_0 (rad/rad · s)	1.1459	1.3313	1.0308

Recent investigations have further advanced the analysis of stiffness derivatives by combining analytical methods with CFD simulations to understand aerodynamic stability in high-speed flows. Firouz-Abadi and Alavi [68] studied supersonic fin performance using structural–aerodynamic coupling methods and piston theory. The results showed that increasing fin thickness, along with higher incidence angles, decreased the divergence Mach number, indicating reduced stability. Mader and Martins [69] developed a time-spectral CFD and adjoint-based methodology for computing static, dynamic, and transient aircraft stability derivatives and their gradients.

Recent studies further investigated the stiffness derivative in hypersonic flow for delta and ogive shapes. The stiffness and stability derivatives of delta-wing and hypersonic-wing configurations have been studied for different Mach numbers, pivot positions, and flow unsteadiness. The results show that the aerodynamic derivatives tend to decrease with increasing Mach number and trailing-edge hinge shift, and that unsteady flow effects and flow deflection can also cause nonlinear variations in stability characteristics. Under hypersonic conditions, the specific heat ratio and flow-deflection angle greatly affect the stiffness derivatives for ogive configurations. The changes in the overall stability characteristics are observed by the increase in pitching moments as it approaches the nose pivot and a decrease in the same near the intermediate pivot, whereas a more pronounced increase is seen in the stability derivative near the trailing-edge region.

Mi and Zhan [70] and He et al. [71] evaluate the stiffness derivative ($-C_m\alpha$) of a two-dimensional wedge in supersonic airflow, which contributes to the stability assessment of aerospace vehicles. The study examines a flow regime that extends from Mach number 2.2 to 4.0 with wedge angles of inclination (θ) from 2° to 20° and positions (h) measured from the start to the end of the chordwise distance. Fig. 16 shows the geometry of a 2D wedge. In the analytical investigation, Ghosh’s piston theory is applied, which extends Lighthill’s [4] piston analogy for supersonic flows with attached shocks.

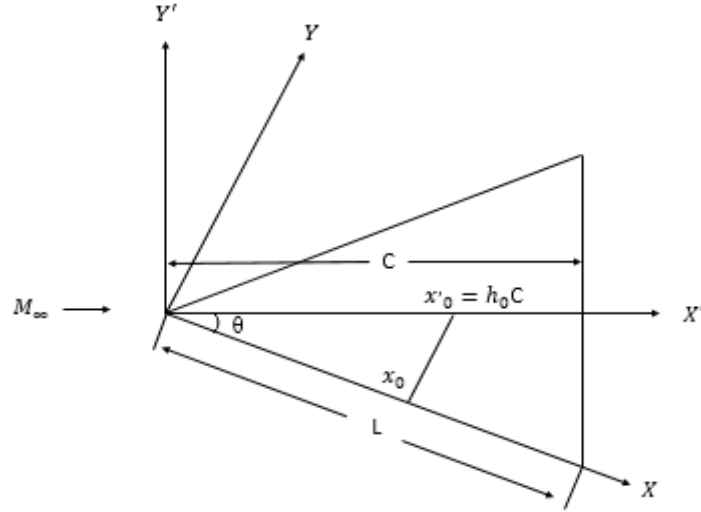


Figure 16: Geometry of 2D wedge [70].

The stiffness derivative in pitch is expressed as:

$$-Cm_\alpha = \left[\frac{\gamma + 1}{M_\infty \cos \alpha_0 \cos \varphi} \right] F(S_1^1) \left[\frac{1}{2} - h \cos^2 \alpha_0 \right] \quad (4)$$

where,

$$F(S_1^1) = 2S_1^1 + \frac{F + 2(S_1^1)^2}{\sqrt{F + (S_1^1)^2}} \quad (5)$$

and γ is the specific heat ratio.

Eq. (5) defines the function $F(S_1)$, which is used in the stiffness derivative formulation shown back in Eq. (4). This function also considers how local flow parameters actually affect the aerodynamic stiffness coefficient, not just in a general way, but more specifically. It is evaluated, more or less, under the same assumptions as Eq. (4), namely, attached shock, in viscid, compressible supersonic flow, when you consider slender wedge configurations. Recent studies have further improved stiffness-derivative analysis by combining analytical methods with statistical design methods, especially for high-speed aerodynamic cases. Mi and Zhan [70] and He et al. [71] examined the stiffness behaviors of two-dimensional wedge geometries under both supersonic and hypersonic flows and employed the Design of Experiments (DOE) method. They showed that the Mach number, wedge angle, and pivot position all significantly affect the variation in the stiffness derivative and the associated aerodynamic restoring moment. The analytical results are consistent with the DOE-based findings across a broad span of operating conditions. Overall, this confirms the method's reliability. Fig. 17a–c compares the analytical and current stiffness derivative results for various Mach numbers. In every instance, the stiffness derivative continues to drop as the pivot location moves farther downstream, indicating a smaller aerodynamic restoring moment. The excellent agreement between the analytical and the present results validates the proposed methodology for forecasting the static stability behaviors of wedge configurations across a wider supersonic flow range. The observed reduction in the stiffness derivative as the downstream pivot moves farther along is mostly due to a decrease in the aerodynamic restoring moment.

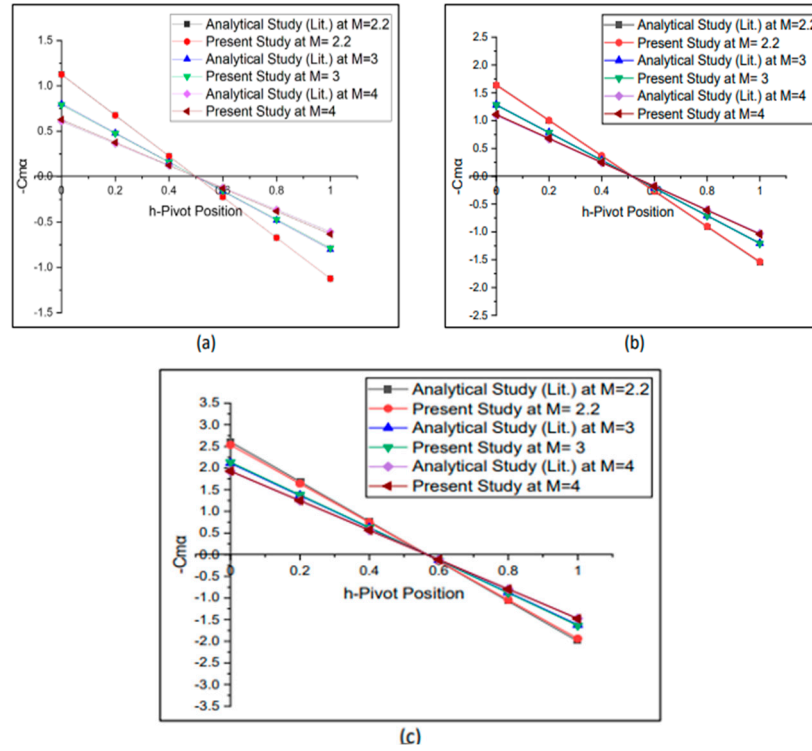


Figure 17: Variation of stiffness derivative ($-Cm\alpha$) with pivot location (h) (a–c) [70].

Overall, the reviewed studies indicate that the parameters Mach number, wedge angle, and pivot position strongly influence the stiffness derivatives. Although analytical, numerical, and experimental methodologies differ, the results are consistent. As the pivot position moves downstream, it reduces the aerodynamic restoring moment and affects static stability. These findings provide a theoretical basis for determining damping derivatives in oscillatory high-speed flows.

2.2.2 Damping Derivative

Aerodynamic damping plays a significant role in interpreting unsteady flow characteristics. This section briefly reviews previous studies on the influence of damping on oscillatory or time-dependent flow. The research examines the damping derivative to determine how wings lose energy during pitch oscillations. Orlik-Ruckemann [64] demonstrated the need to obtain aerodynamic damping measurements at elevated incidence angles. The study found that wind-tunnel equipment constraints prevent researchers from obtaining the precise damping-derivative values needed for high-Mach-number testing. Hui [13,63] analyzed the unsteady aerodynamic characteristics of a delta planform with a low aspect ratio and a flat plate, both oscillating around various axes. The results show that oscillatory motion and shock interactions significantly affect stability, and at high angles of attack, the system may exhibit negative aerodynamic damping, leading to instability. Ghosh and Mistry [16] studied oscillating non-planar wedges in high-incidence hypersonic flow using piston theory. The study demonstrates that damping behavior depends on three factors: flow incidence, wedge geometry, and shock effects during small-amplitude oscillations. Hemdan [20]. The researchers investigated the hypersonic behavior of two-dimensional airfoil designs by studying their vibration patterns at low incidence angles through unsteady flow theory. The researchers developed unsteady pressure and stability derivative equations as part of their reduced-frequency expansion. The study includes pitch-rate-dependent terms, indicating that the damping derivatives were analytically

evaluated, and the results match those of all existing studies. Khan and Crasta [66] studied two methods for assessing aircraft damping derivatives under high-incidence conditions: the steady-state approximation method and the dynamic response assessment method. The results showed that shock detachment and separation led to different outcomes, while damping derivative values depended on both the pivot position and the system's geometric design. Fig. 18 shows that damping varies with pivot location for wing and wedge shapes.

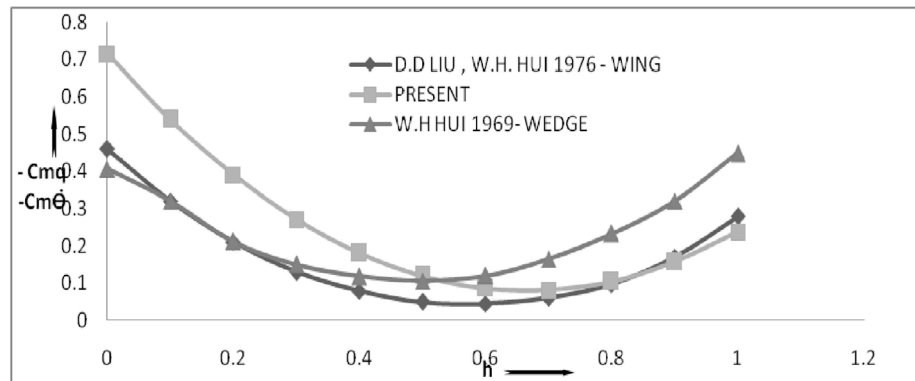


Figure 18: Variation of damping derivative with pivot position for $M = 4$, $\alpha_0 = 15^\circ$, $\gamma = 1.4$ [66].

Anton and Botez [67] studied the stability derivatives of a delta wing using wind tunnel experiments. They showed that the damping derivative controls dynamic stability. Fig. 19 shows that aerodynamic forces and moments behave differently at different pitch rates, reducing oscillatory motion and improving stability control.

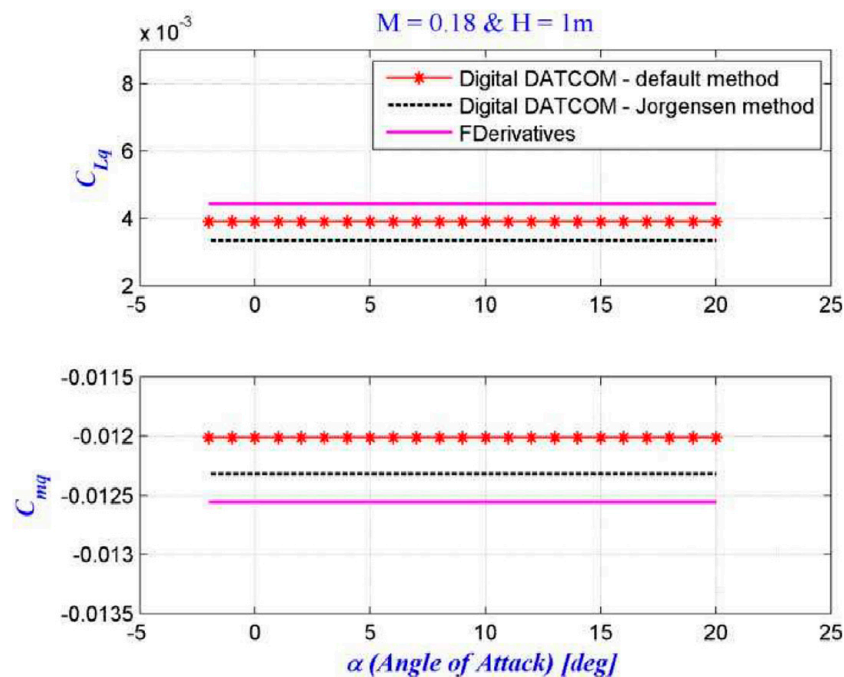


Figure 19: Variation of lift and pitching moment (C_{Lq} , C_{mq}) vs. the angle of attack [67].

Mader and Martins [69] studied supersonic wedge flow using both CFD simulations and analytical techniques. The study found that temperature and pressure variations affected damping stability, while higher Mach numbers intensified compressibility effects. According to Fig. 20, the temperature distribution affects damping behavior by influencing boundary-layer development.

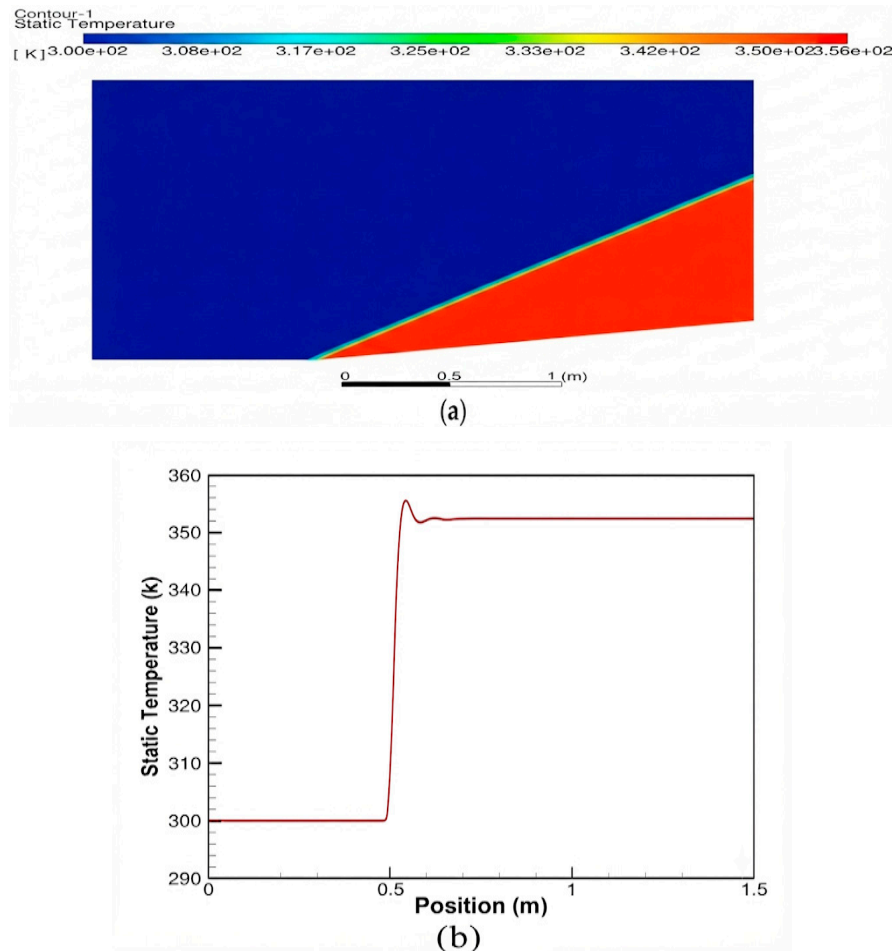


Figure 20: Temperature distribution: (a) contour, (b) plot [69].

2.2.3 Rolling Moment Derivatives

Rolling characteristics and their derivatives play an important role in the dynamic stability of high-speed vehicles. This section presents the effect of geometry and Mach number on rolling characteristics. The research investigated the roll-damping derivative to determine how delta wings maintain their rolling stability. Ghosh [18] developed a piston-theory model based on strip theory to assess the unsteady rolling derivatives of oscillating delta wings in hypersonic flight. The study demonstrated that the roll-damping derivative is linearly related to aspect ratio, indicating that wing geometry plays a crucial role in determining rolling dynamic stability and enabling quick predictions. Liu et al. [52] developed a deep reinforcement learning method that optimized supercritical airfoils to improve lift performance and aerodynamic stability through a state-based learning system. Khan and Crasta [66] used a similitude analysis to examine the roll-damping derivatives. The study found that roll damping decreases between Mach 0 and Mach 1, remains constant at high speeds, and increases with aspect ratio to enhance rolling stability. The relationship between roll damping and aspect ratio, together with incidence angle, shows different values in Fig. 21.

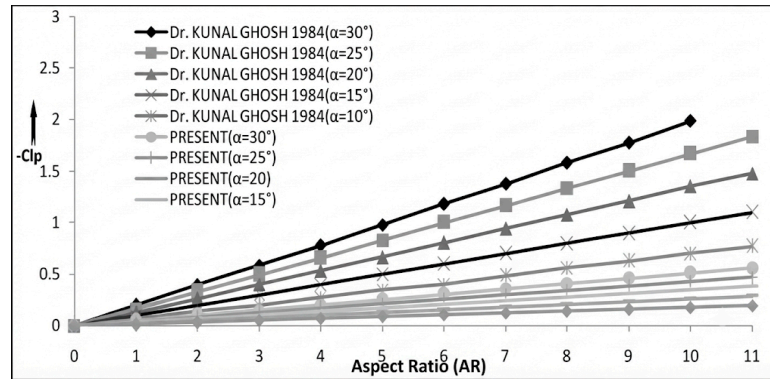


Figure 21: Variation of roll damping derivative with aspect ratio of delta wings at $M = 10$ [66].

Anton and Botez [67] measured the rolling-stability derivatives Cl_p and Cl_r for a delta-wing aircraft using authentic aerodynamic data. The researchers found that roll-rate derivatives significantly impacted lateral stability and control performance across all tested angles of attack. Fig. 22 shows that changes in roll rate and angle of attack lead to different yawing-side force and rolling-moment effects, which, in turn, affect the stability of high-angle-of-attack maneuvers.

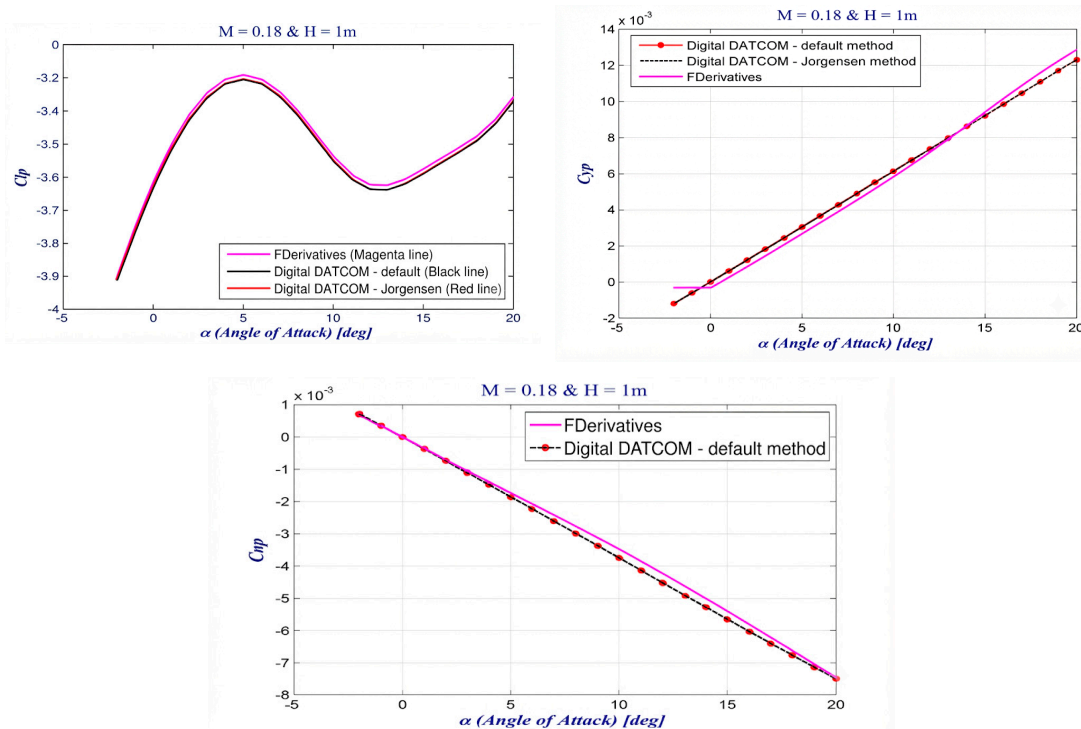


Figure 22: Effect of angle of attack on yawing, side-force, and rolling moment derivatives [67].

Mi and Zhan [70] reviewed numerical approaches for predicting aircraft dynamic stability derivatives, including analytical, semi-empirical, time-domain CFD, and frequency-domain methods. He et al. [71] studied roll-moment control through active flow management, using pneumatic jets to test their UCAS delta-wing design. The researchers discovered that jet operation could reduce roll oscillations and improve stability by controlling the nonlinear hysteresis arising from vortex effects. Pneumatic jets in Fig. 23 demonstrate their ability to manage roll moment while decreasing roll-rate changes at various angles of

attack. In Fig. 23, the lift coefficient (C_L) under various oscillation and actuation setups: (a) lift coefficient variation at $\alpha = 20^\circ$, $f = 1.0$ Hz, and $f_{act} = 1.0$ Hz; (b) lift coefficient variation at $\alpha = 10^\circ$, $f = 2.0$ Hz, and $f_{act} = 2.0$ Hz.

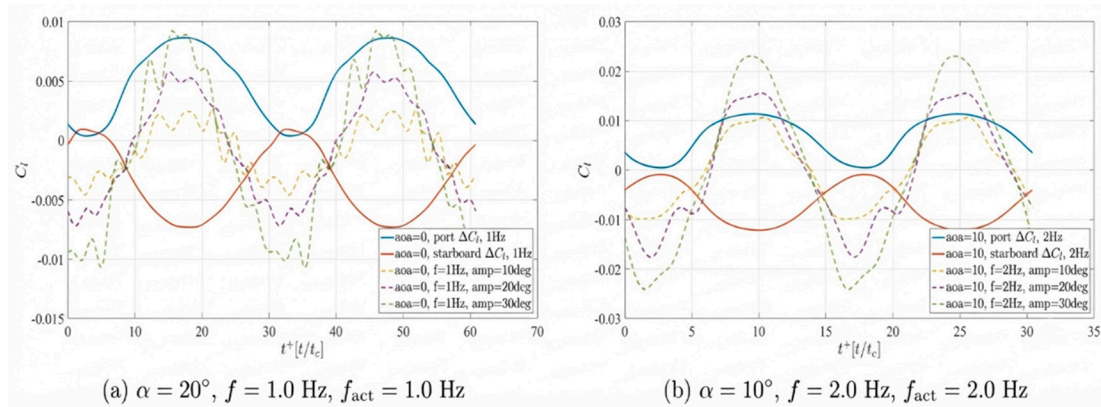


Figure 23: Control authority on roll moment coefficient (a,b) [71].

Overall, the reviewed studies demonstrate that the rolling derivative is significantly influenced by wing geometry, aspect ratio, angle of attack, Mach number, and active flow control approaches. The results indicate that these parameters significantly influence the lateral dynamic stability characteristics of high-speed aerospace configurations, both analytically and experimentally. Examples include increased roll stability in supersonic and hypersonic vehicles, which can achieve better overall dynamic performance by implementing effective aerodynamic design and flow-control strategies.

2.3 Suddenly Expanded Flow

Suddenly expanded flow is a high-speed-flow problem involving shock interaction, separation, recompression, and base-pressure development, and it is strongly nonlinear. While some investigations have been performed at supersonic conditions, they provide insight into the physical and computational aspects of shock-generated separation and pressure behavior relevant to high-speed aerodynamic applications. The concepts illustrated in the hypersonic studies that follow are applicable, but limited, at higher Mach numbers.

Flow development in a duct with a sudden expansion has received considerable attention in high-speed flow due to its significant influence on pressure recovery, base pressure, flow separation, and drag. Understanding the aerodynamic performance and stability of high-speed vehicles is closely linked to the pressure distribution in the expanded region; thus, the flow mechanisms governing this region must be understood for both theoretical analysis and engineering applications. These investigations are especially relevant to the design and optimization of aerospace propulsion systems, nozzles, and high-speed aerodynamic configurations, where flow behavior significantly impacts overall performance and efficiency. This section presents an extensive survey of analytical, experimental, and numerical investigations of suddenly expanded flows, highlighting the most relevant contributions to understanding fundamental flow physics and their application in the design of high-speed aerospace systems.

Khan et al. [72] experimentally studied micro-jet active flow control in suddenly expanded axisymmetric ducts over Mach numbers 1.25–3.0. The researchers found that micro-jets control base pressure effectively while maintaining wall pressure patterns. System performance depended on three factors: flow velocity, geometric expansion proportion, and length-to-diameter configuration. The testing conditions establish a specific L/D ratio that achieves peak control efficiency for all experimental conditions. Fig. 24 shows the

experimental setup for pressure control at the duct base in a flow passage with a sudden area expansion. The setup includes micro-jet injection points and pressure measurement locations.

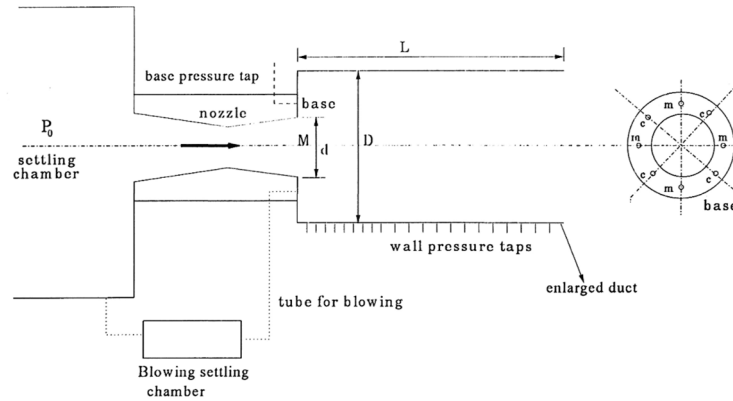


Figure 24: Experimental arrangement for active control of suddenly expanded flow [72].

The study by Khan and Rathakrishnan [73] tested base pressure control using 1 mm micro-jets, which they placed at 90-degree angles to the channel axis, in tests of suddenly expanded axisymmetric channels. The study demonstrated that micro-jets improve base-pressure results while maintaining wall-pressure patterns, with superior performance at higher Mach numbers. Fig. 25 shows how base pressure changes with different flow speeds. The results indicate that micro-jet application enhances pressure recovery performance at increased speeds. Fig. 25 shows the variation in normalized base pressure (P_b/P_a) with Mach number for both controlled and uncontrolled flows at different area ratios. In particular, Fig. 25a relates to an (L/D) ratio of 10 and Fig. 25b to an (L/D) ratio of 8. Both configurations show a trend of higher normalized base pressure than in the uncontrolled case, validating the micro-jet actuation mechanism's ability to reduce base pressure loss, especially at higher Mach numbers.

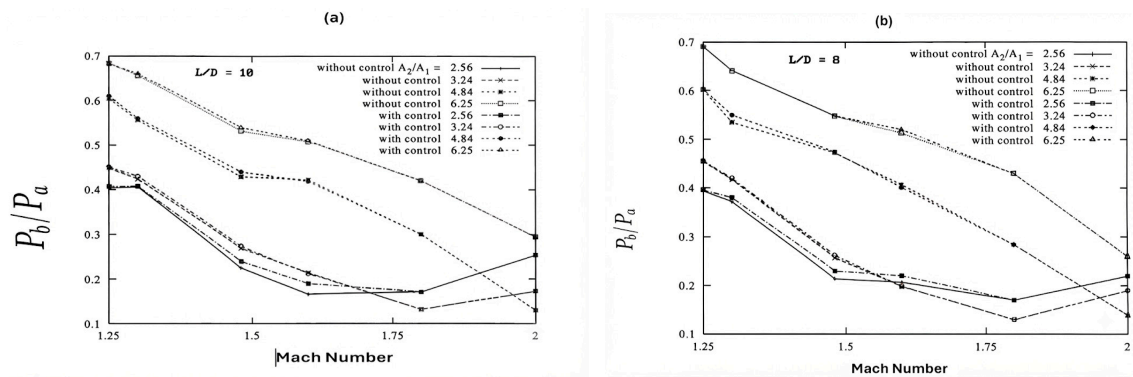


Figure 25: Variation of normalized base pressure with Mach number (a) $L/D = 10$, (b) $L/D = 8$ [73].

Micro-jet-based active flow control is an effective approach for modifying base pressure in suddenly expanded flows. Introducing micro-jets can enhance base pressure while preserving the general wall-pressure distribution, although effectiveness depends on Mach number and geometric parameters. DOE and RSM techniques provide systematic methods for evaluating the effects of flow and geometric parameters on base pressure and recirculation-zone behavior, enabling their prediction and optimization in supersonic sudden-expansion flows. Ray and De [50] conducted a numerical investigation to determine how leading-edge bluntness affects double-wedge structures in hypersonic flow experiments. The researchers found that

increasing bluntness altered shock interactions, leading to detached shocks, larger separation bubbles, and stronger shock–boundary-layer interactions that sometimes exhibited unsteady behavior across different wedge angles.

The reviewed literature showed that the Mach number, duct geometry, area expansion ratio, and active flow control technique are the main factors governing the base pressure and flow characteristics of suddenly expanded ducts. Experimental and numerical studies have consistently shown that these parameters significantly affect pressure recovery, flow separation, recirculation, and overall aerodynamic performance. In particular, micro-jet actuation has been shown to improve base pressure recovery and maintain a stable wall pressure distribution, making it an effective active flow control technique.

2.4 Machine Learning Techniques in High-Speed Aerodynamic Prediction

Machine-learning-based aerodynamic prediction has evolved across a wide variety of flows, including supersonic and hypersonic flows. Examples include supersonic studies, where data-driven models approximate non-linear aerodynamic quantities, and recent hypersonic applications, where models predict aerothermal quantities in complex high-speed flows. In this regard, the reviewed machine-learning studies are examined with respect to methodological developments and their application to predictions in hypersonic aerodynamics.

2.4.1 Evolution of Machine Learning in Aerodynamic Prediction

Aerodynamic research has evolved significantly, particularly with the growth of computational and experimental datasets and the increasing use of Artificial Intelligence (AI) and Machine Learning (ML). Early ML applications modeled the relationship between aerodynamic inputs and outputs to approximate non-linear relationships. As computational costs increase dramatically for higher-resolution CFD, its applications have become more widely adopted and have evolved into surrogate modeling, rapid aerodynamic prediction, design optimization, flow-field reconstruction, and flow control. Over the last decade, more recently developed approaches like artificial neural networks (ANNs), deep-learning models, physics-informed neural networks (PINNs), and reinforcement learning (RL) have been adopted to expand the application of AI to complex high-speed flows. Downstream numerical solutions from conventional methods are more expensive in supersonic and hypersonic aerodynamics, where phenomena such as shock waves, high pressure gradients, boundary layer interactions, and thermal effects are key.

2.4.2 AI-Assisted CFD and Surrogate Modeling

One of the key assets of ML in aerodynamics research is its ability to integrate data-driven models with high-fidelity CFD. It requires generating experimental or CFD simulation data to prepare the training set, and the ML model defines the nonlinear relationship between flow parameters, geometric parameters, and aerodynamic responses. Lastly, the resulting surrogate model can predict results quickly, without needing to run another CFD simulation for each new operating condition. This results in significant efficiency gains in performing parametric studies, sensitivity analysis, design-space exploration, and optimization [59,74–76]. This potential is further illustrated in recent hypersonic research through the development of a deep-learning-based assimilation of wall-pressure measurements over a Mach 6 cone that can decrease the computational cost of the high-dimensional data assimilation problem [62]. These developments reflect the application of AI with high-fidelity CFD to make CFD more useful for repeated, high-computation-demand analyses.

2.4.3 ANN and Deep-Learning Approaches

Artificial Neural Networks (ANNs) are widely used for aerodynamic prediction because they can represent nonlinear relationships among multiple input parameters and aerodynamic responses. ANN-based models have predicted various aerodynamic coefficients, surface-pressure distributions, and other flow quantities using CFD and experimental data [75]. Their main benefit is that, after training, they offer a quick assessment of aerodynamic responses and can significantly shorten the computational time required for repeated numerical simulations. Deeper neural-network architectures have further enhanced the ability of data-driven models to capture complex, high-dimensional aerodynamic relationships. Recent examples of hypersonic flow illustrate the use of deep-learning models in applications beyond traditional forward prediction, such as assimilating sparse wall-pressure measurements into computational flow models [62]. Therefore, the progress from usual ANN prediction to deep learning-based flow reconstruction is an important step forward in high-speed aerodynamic modeling.

2.4.4 AI for Aerodynamic Optimization and Intelligent Design

AI has increasingly evolved from aerodynamic prediction to intelligent design and optimization. Surrogate models, which can replace computationally intensive CFD evaluations in the optimization procedure, can efficiently investigate a greater number of aerodynamic configurations [75,76]. This is especially useful for hypersonic vehicles, where performance must be assessed across a wide range of flight conditions. Recent research on hypersonic inlet design shows a growing shift toward intelligent optimization and data-driven design techniques, leveraging existing high-fidelity CFD and experimental databases to enhance design efficiency [77]. This shows that AI is currently used not only to forecast aerodynamic performance but also to select and optimize high-speed aerodynamic configurations.

2.4.5 Physics-Informed Neural Networks and Intelligent Flow Control

In further development, Su et al. [60] presented a deep reinforcement learning based inverse design approach for designing 3-D morphing wings that reached about 98% of the desired aerodynamic performance in different operating conditions. The AI-based approach is applied in Physics-Informed Neural Networks, which combine governing equations and boundary conditions during the learning process [61]. PINN is completely independent of large labeled datasets, unlike conventional data-driven models. This will enable a pathway to combine the flexibility of machine learning with computational fluid dynamics. Consequently, reinforcement learning has introduced adaptive decision-making into aerodynamic design and control [78]. Supersonic and hypersonic flow control are evolving, with active and passive methods being developed to control shockwaves, boundary-layer transition, separation, drag, noise, and thermal effects, as reviewed recently [79].

2.4.6 Transformative Impact and Research Gap

Overall, AI has revolutionized high-speed aerodynamic research through fast prediction, optimization, data assimilation and flow control. ML and ANN models reduce the computational cost of repeated CFD simulations, and PINNs and RL provide better physical consistency and adaptive optimization. In recent years, AI has shown its usefulness for assimilation of wall pressures in hypersonic flow [62] and for optimizing hypersonic inlets [77] and hypersonic flow control [79]. However, few efforts have combined CFD with neural networks to simultaneously predict surface pressure and temperature in hypersonic cone flow. This gap motivates the present CFD–neural-network approach for efficient hypersonic aerothermal prediction. Table 3 compares recent machine learning approaches for aerodynamic prediction.

Table 3: Comparison of recent machine learning approaches for aerodynamic prediction.

Technique	Application	Main Advantage	Limitation
ANN	Pressure prediction	Fast prediction	Large dataset required
Surrogate Mode	Aerodynamic optimization	Reduces CFD cost	Approximation error
PINN	CFD and flow prediction	Physics-based learning	High training cost
RL	Morphing wing optimization	Adaptive optimization	Computationally intensive

2.5 Critical Synthesis of Research Evolution and Research Gap

The reviewed literature in Sections 2.1–2.4 includes both supersonic and hypersonic regimes, and the review theme mainly focused on surface pressure, calculation of aerodynamic derivatives, high-speed flows with sudden expansion, and machine learning-based aerodynamic prediction. The supersonic studies largely reflect the early development of analytical, experimental, CFD, and data-driven approaches, while the hypersonic studies offer the most direct context for the pressure and temperature prediction problem addressed in this work. Therefore, the chronological progression of the reviewed research should be understood as the evolution of high-speed aerodynamic methodologies, rather than as a comparison between supersonic and hypersonic flow regimes. The research has been further studied to critically synthesize the above studies in terms of methodological development, major studies, limitations, and motivations for further research directions. This evolution is summarised by linking together the main research themes discussed in the previous sections in Table 4. The cited studies have not been independent; rather, each has addressed challenges inherent in previous research and advanced one of the research fronts currently transitioning to CFD-assisted data-driven prediction.

Table 4: Chronological evolution, advancements, limitations, and research motivation in high-speed aerodynamic research.

Research Theme	Flow-Regime Context	Research Advancement	Limitations/Challenges	Future Research Direction
Surface Pressure	Supersonic and Hypersonic	Evolution from analytical/experimental to CFD-based pressure prediction	Simplified assumptions and high CFD cost	Rapid CFD–ML pressure prediction
Aerodynamic Derivatives	Supersonic and Hypersonic	Development from analytical stability models to CFD-based derivative prediction	Complex unsteady flow and computational cost	ML-based stability prediction
Suddenly expanded flow	Predominantly supersonic; extended to high-speed applications	Improved understanding of shock interaction, separation and base pressure	Strong nonlinearities and flow complexity	Advanced CFD and data-driven modelling
Machine learning in high-speed aerodynamics	Supersonic and Hypersonic	ANN, deep learning and surrogate-based prediction	Dependence on training data and generalization	CFD-integrated ML for multi-parameter prediction
Future research direction	Hypersonic Based	Integration of CFD and ML approaches	Validation and generalization remain challenging	Prediction of aerodynamic flow properties

The studies examined have shown that research in high-speed aerodynamics has been an ongoing process of overcoming past research methodologies. Most early research on surface pressure was analytical and experimental, yielding basic physical knowledge and valuable engineering estimates. However, increasing interaction among shocks, viscous effects, geometric configuration, and thermal properties led to the use of CFD for more detailed prediction of the flow field. Simultaneously, aerodynamic derivative studies continued by examining dynamic stability and damping properties, and studies of suddenly expanded flows examined complex shock structures, separation, base pressure behavior, and flow control mechanisms. These advances made more and more simulations necessary across wider ranges of parameters, with some of the simulations becoming very involved. These advances led to a growing need for increasingly complex simulations over wider ranges of parameters. Thus, using machine learning methods to build computationally efficient predictive/surrogate models from numerical or experimental databases became a promising idea.

Overall, the reviewed studies show that progress in high-speed aerodynamic research has shifted from analytical and experimental methods to CFD-based approaches and, more recently, data-driven prediction. Supersonic investigations have been fundamental to developing underlying methodologies for predicting surface pressure, aerodynamic derivatives, shock-induced flow phenomena, and machine-learning applications; subsequent hypersonic investigations have extended these methods to higher Mach numbers and aerothermal conditions. However, previous work suggests that applying high-fidelity computational fluid dynamics (CFD) and neural-network (NN) methods to simultaneously predict surface pressure and temperature along external hypersonic cone configurations with systematically varied flow and geometric parameters remains limited. This motivates the present investigation.

3 Summary and Discussion

3.1 Surface Pressure

The reviewed studies consistently indicate that surface pressure is primarily influenced by Mach number, aerodynamic shape, angle of attack, and the flow setup [55–58,69]. As the Mach number or wedge/cone angle increases, stronger oblique shock waves produce greater compression, leading to higher surface pressure and increased aerodynamic loading [55–58]. Furthermore, geometric modifications such as spikes, aerodisks, optimized aerofoil configurations, and cone geometries significantly influence shock-wave structures and recirculation regions, improving surface pressure distributions and aerodynamic performance [25,39,40,45–47]. These findings emphasize the critical role of aerodynamic configuration and flow conditions in determining pressure characteristics and optimizing the performance of high-speed aerospace vehicles. Kalimuthu et al. [25] demonstrated that the flow structure and drag characteristics of a system are dependent on the specific spike design and the length-to-diameter ratio that has been implemented. The conical spikes create shock-separation patterns, whereas the aero disks produce more extensive recirculation zones that decrease forebody pressure and enhance drag reduction. Fig. 26 shows the C_p changes as a function of L/D ratio and angle of attack for the aero disk.

The surface pressure of a cone in hypersonic flow is highly affected by the Mach number, the cone angle, and the (x/L) ratio [57]. Pressure increases with higher Mach numbers (5–7) and a larger angle range (5° – 10°). The CFD results show a strong correlation with existing analytical data, thereby validating the method [57].

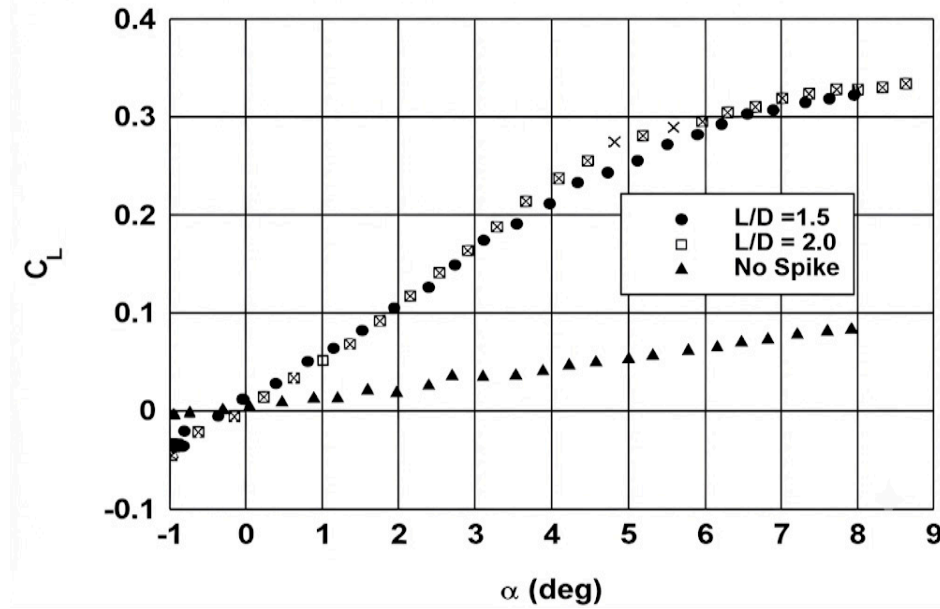


Figure 26: Effect of L/D ratio on lift coefficient for flat-faced aero disk [25].

3.2 Aerodynamic Derivatives

3.2.1 Stiffness Derivative

The reviewed studies show that the aerodynamic stiffness derivative is highly influenced by Mach number, pivot position, incidence angle, and the overall geometric configuration [66,70,71]. As the Mach number increases, the stiffness derivative decreases due to compressibility effects and the stabilizing influence of high-speed flow, thereby reducing the sensitivity of the pitching response. At the same time, changes in the pivot position, wedge angle, and other geometric parameters can strongly affect the pitching moment and static stability by modifying the surface pressure distribution and aerodynamic loading [66,70,71]. The close agreement between the analytical results based on piston theory and recent numerical investigations indicates the reliability of this approach for investigating the stiffness derivative in attached-shock high-speed flow conditions [66,70,71]. The decrease in the stiffness derivative as the Mach number increases is mostly due to compressibility effects, which reduce the aerodynamic restoring moment at higher speeds. The figure shows that both Mach number and pivot location are more sensitive to longitudinal static stability. Taken together, these points provide useful guidance for selecting appropriate geometric and stability parameters during the aerodynamic design of supersonic and hypersonic vehicles.

The research by Mi et al. [70,71] shows that the Ghosh formulation based on piston movement achieves precise estimation of aerodynamic stability parameters through its analytical findings. The study indicates that higher flow speed reduces the stability coefficient, while increasing the flow inclination angle enhances it. The method uses flow speed (M), flow inclination angle (θ), and pivot position (h) to calculate aerodynamic stability, which provides quick and dependable outcomes for attached-shock conditions.

3.2.2 Damping Derivative

Research by Anton and Botez [67] showed that stability derivatives yield accurate wind-tunnel results for aerodynamic forces and moments across the 2° to 20° testing range, outperforming Digital DATCOM in accuracy. The analysis demonstrates that higher angles of attack reduce stability because the system exhibits reduced damping and delayed stall recovery. Fig. 27 shows the dynamic behavior of a stable airplane

when it gets a step input at the elevator. As the angle of attack increases from 20° to 38° , short-period oscillations become longer in duration and less damped, reducing stability and lowering damping ratios.

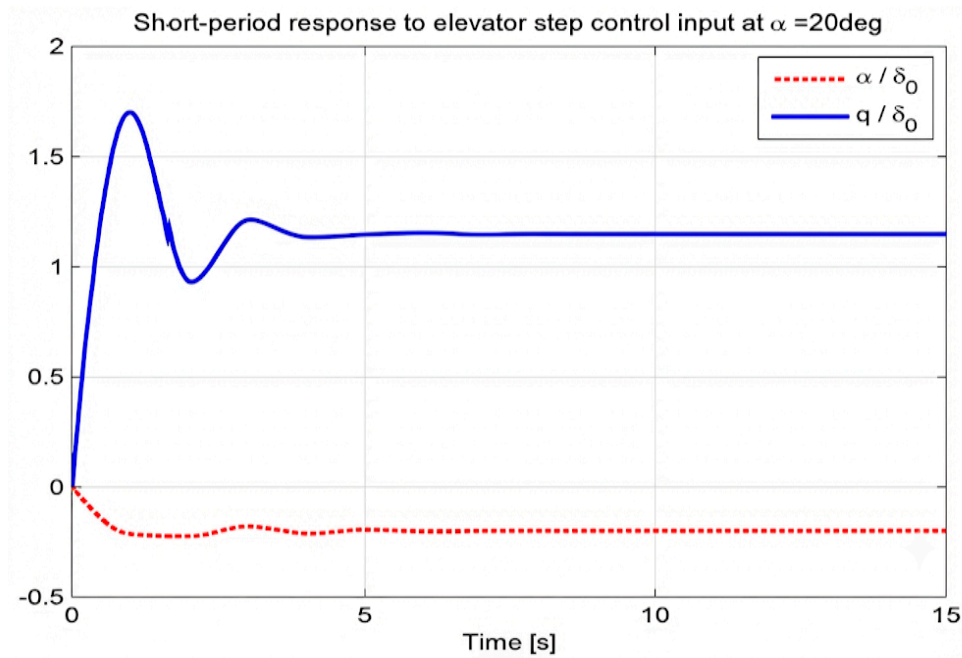


Figure 27: Response to elevator step input with α and q negative for a stable aircraft [67].

Khan et al. [72,73] show that their regression model results match the analytical aerodynamic method, which predicts the damping properties of a 2D wedge. The system's damping behavior depends mainly on three factors, namely Mach number, wedge geometry angle, and pivot position, since it exhibits constant aerodynamic behavior at high-speed flow conditions.

3.2.3 Rolling

Anton and Botez [67] validated the FDerivatives code through a case study of an X-31 tailless delta-wing aircraft, using actual aerodynamic test results. The model accurately predicted lift and drag coefficients across the linear incidence-angle range, with excellent correlation to the measured data. Fig. 28 shows that lift increases with higher incidence angles in a nearly linear pattern, which matches results from the aerodynamic testing facility. The data in Fig. 29 show that drag forces increase with increasing incidence angle. The model provides accurate predictions over the 0° – 20° range, demonstrating improved capability for forecasting aerodynamic performance.

The study demonstrates that the recommended deep reinforcement learning optimization framework successfully acquires aerodynamic design techniques through its interaction with the environment. The action network functions as a developed optimization system that effectively directs the aerofoil shape enhancement procedure. The method achieves high-precision solutions and performs well in both benchmark and supercritical aerofoil design cases, with a success rate exceeding 90% in the optimization space. The system maintains essential aerodynamic limits, including buffet-onset lift and cruise lift-drag ratio, thereby demonstrating its ability to generalize and maintain performance across different situations [52].

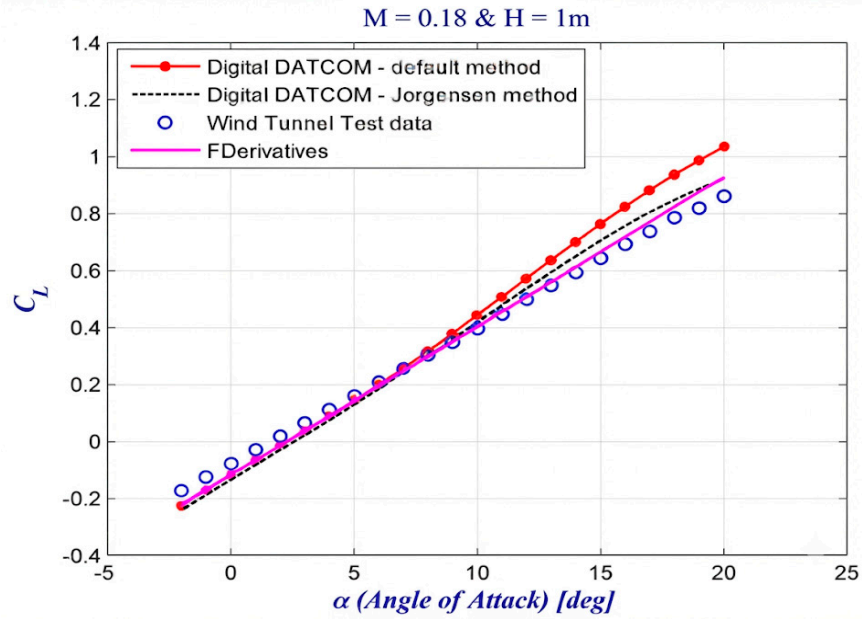


Figure 28: Effect of angle of attack on lift coefficient [67].

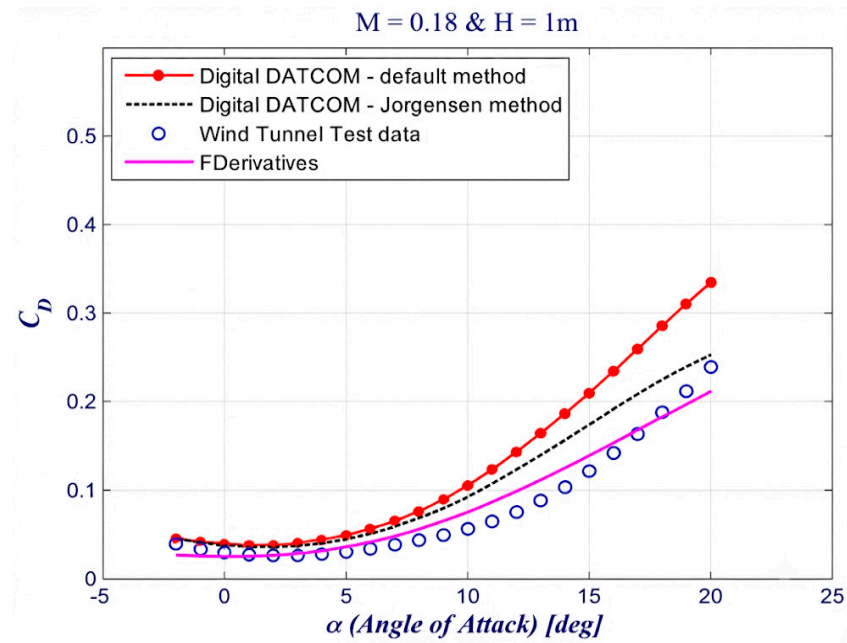


Figure 29: Effect of angle of attack on drag coefficient [67].

3.3 Suddenly Expanded Flow

The study by Khan and Rathakrishnan [72] demonstrated that active flow control can effectively manipulate the shock structure and flow characteristics of suddenly underexpanded flow. Khan and Rathakrishnan [73] found that micro-jets can control base pressure in supersonic sudden-expansion flows by altering their performance, which depends on both Mach number and duct geometry, including the expansion ratio and the length-to-diameter ratio. The researchers showed that micro-jets increase base pressure at high NPR levels while maintaining wall-pressure stability through flow control, which depends

on the L/D ratio. Fig. 30 demonstrates that base pressure increases with NPR, while micro-jets amplify this effect by maintaining a constant wall pressure and controlling the recirculating flow [80]. Atue and Bruce [79] showed that reduced-order models can be used for fast prediction of supersonic and hypersonic bodies, which are computationally efficient alternatives to high fidelity simulation. For bluff bodies, Li et al. [81] developed a fully-convolutional neural network (FCNN) based on consistent shape description to predict the aerostatic performance, and showed the ability of deep learning to rapidly and accurately predict the aerostatic performance of different bluffs.

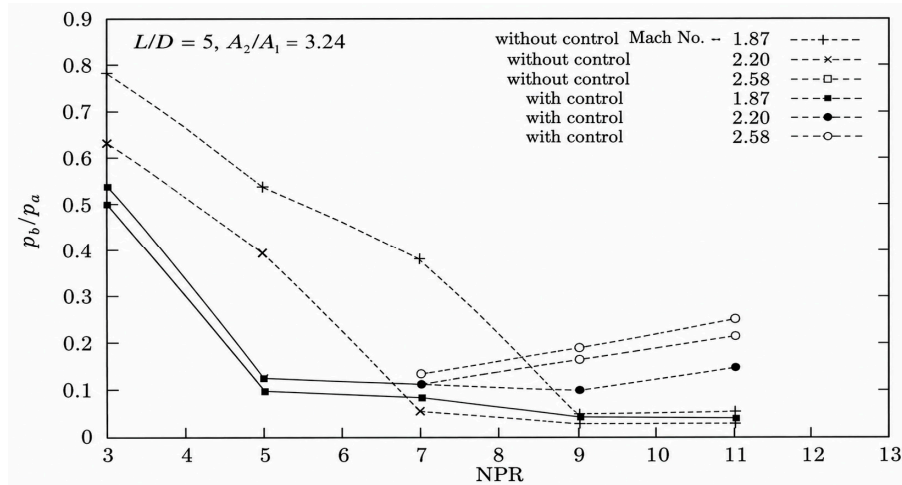


Figure 30: Base pressure variation with NPR [80].

4 Research Gap

Although significant progress has been made in high-speed aerodynamics, several key research areas remain unaddressed. While most current studies focus separately on surface pressure distribution, aerodynamic stability derivatives, and suddenly expanded flows, a comprehensive approach that simultaneously predicts all of these aerodynamic properties remain missing [69,71,77]. Additionally, few experimental validation datasets are available at hypersonic Mach numbers, which are expensive to test, and hypersonic facilities are not readily available for testing [55–58]. Machine learning methods for aerodynamic prediction and optimization have proven highly promising. However, simultaneous estimation of stiffness, damping, and rolling stability derivatives remains in its infancy [47,52,59–62,75–78,81]. Furthermore, existing studies on active and passive flow control have mostly focused on improving pressure recovery and suppressing shock-wave effects. In contrast, the simultaneous effects of active and passive flow control on aerodynamic stability and dynamic flight characteristics have received relatively little attention [72,73]. Solving these challenges with an integrated computational, experimental, and data-driven approach will help develop more accurate and efficient methodologies for analyzing and designing high-speed aerospace vehicles.

5 Future Directions

Future research should develop integrated aerodynamic prediction frameworks that combine analytical methods, computational fluid dynamics (CFD), experimental tests, and machine learning tools to achieve a comprehensive understanding of aerodynamic behavior at high velocities. Further research should focus on advanced machine learning approaches, such as Physics-Informed Neural Networks (PINNs), surrogate models, and hybrid CFD–ML frameworks, to obtain accurate surface pressure distribution predictions and aerodynamic stability derivatives at much lower computational cost and analysis time. Also, extensive

experimental research under realistic hypersonic flow conditions can enhance the reliability and robustness of analytical and numerical models. Further research on the simultaneous application of active and passive flow control techniques to surface pressure distribution, aerodynamic stability derivatives, and dynamic flight characteristics should also be pursued to better understand the combined effects of these techniques on overall vehicle performance for future applications. Finally, computationally efficient reduced-order models for fast aerodynamic design optimization and real-time engineering applications are a promising future path for analyzing and designing the next generation of high-speed aerospace vehicles.

6 Conclusion

This review presents a comprehensive overview of recent developments in surface pressure, stability derivatives, machine learning methods, and suddenly expanded flows at supersonic and hypersonic Mach numbers. This review finds that aerodynamic characteristics are primarily governed by Mach number, shape/geometry, angle of attack, and pivot position, which significantly affect surface pressure, stiffness derivative, damping derivative, and rolling derivative. The other literature suggests that analytical approaches, CFD simulations, and experimental investigations are consistent and reliable when the flow is ideal. Furthermore, active and passive flow control methods were found to be effective in improving pressure recovery and flow separation and in stabilizing the flow in suddenly expanded flows. In the recent study, machine learning models, Artificial Neural Networks (ANNs), surrogate models, Physics-Informed Neural Networks (PINNs), and Reinforcement Learning (RL) are promising for improving aerodynamic prediction and design optimization, with significant reductions in computational cost and analysis time. These data-driven methods can efficiently replace repeated high-fidelity CFD simulations, especially for large-scale parametric studies or optimization problems. Furthermore, testing the model in realistic hypersonic flow conditions remains limited, as testing facilities are costly and few in number. Aerodynamic stability and dynamic flight characteristics of the combined effects of active and passive flow control techniques should also be investigated further. Moreover, more widespread use of physics-informed and hybrid machine learning models is required to enhance the robustness, interpretability, and generalizability of aerodynamic prediction models. Solving these research challenges will enable the creation of accurate, efficient, and reliable aerodynamic prediction methods. These developments will play a significant role in the analysis, optimization, and design of future supersonic and hypersonic aerospace vehicles, enabling improved aerodynamic performance, enhanced flight stability, and faster engineering design.

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Nomenclature

M	Mach Number
M _p	Piston Mach Number
P_{∞}	Free Stream Pressure
P _a	Atmospheric P
ρ_{∞}	Air Density
a_{∞}	Velocity of sound in air
C _p	Pressure Coefficient
γ	Specific heat ratio
P/P_{∞}	Non-dimensional Pressure Ratio
L/D	Length-to-diameter Ratio
NPR	Nozzle Pressure Ratio
C _m α	Stiffness Derivative
C _m q	Damping Derivative

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