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Hypersonic Waveriders: State-of-the-Art of Laminar–Turbulent Transition Prediction and Control

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Abstract

During hypersonic cruise, boundary layers on gliding vehicles are partly laminar and partly turbulent. The extent of turbulent flow on the vehicle determines its performance, such that improving the vehicle handling properties and extending its range is intimately related to knowledge of the origins of turbulence, which is assumed to arise on account of laminar flow instability mechanisms. Physical instability mechanisms, involving exponentially or algebraically growing small-amplitude perturbations in laminar boundary layers, remain under intensive investigation. In a subsequent step, promise of improved overall vehicle performance can be expected from physics-based predictions of laminar-turbulent transition and control of this phenomenon through mitigation of linear instabilities by passive or active means.

This review consolidates the state-of-the-art in transition prediction and control for hypersonic waveriders and hypersonic vehicles in general. We first examine the historical evolution of transition research, then review fundamental instability mechanisms, challenges in prediction, and recent advances in numerical modeling. The implications for prediction and control are discussed, and an outlook is provided for future progress.

Keywords: *Hypersonic Waveriders, Hypersonic flow, Laminar-turbulent transition*

1. Introduction

Hypersonic flight represents one of the most demanding and technologically critical areas of aerospace research. Waverider configurations [1, 2], which leverage shock-attached flow structures to maximize lift-to-drag ratio, are highly susceptible to boundary-layer transition phenomena. The laminar–turbulent transition strongly influences aerodynamic drag, heat transfer, and control authority. Consequently, reliable prediction and, ultimately, control of transition processes remain central to enabling sustained hypersonic cruise.

The study of boundary-layer transition began with early 20th century experiments on incompressible flows, which established the basic framework for laminar-to-turbulent breakdown. With the advent of supersonic and hypersonic flight during and after World War II, the need for a deeper understanding of compressible boundary layers emerged.

Key milestones include:

- Prandtl's [3] early boundary-layer theory, which provided the theoretical foundation for later instability studies.
- Tollmien–Schlichting waves (1929–1940s), experimentally verified by Schubauer and

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Skramstad [4] marking the first successful demonstration of linear instability leading to transition in subsonic flows.

- Van Ingen / Smith and Gamberoni semi-empirical e^Nmethod [5, 6], introduced a practical tool for predicting transition onset based on amplification of disturbances using linear stability theory.

- Mack's theoretical contributions [7, 8], formally identified the families of instabilities in compressible and hypersonic flows. Mack distinguished the first mode (viscous instability) and the second mode (trapped acoustic instability), the latter becoming central in hypersonic transition research.

- Experimental campaigns of the 1970s–1980s, including the seminal work of Stetson, referring to Mach 8–10 sharp-cone and blunt-cone experiments [9-11], provided benchmark data validating Mack's predictions and establishing second-mode instabilities as the dominant mechanism in hypersonic flight. Later on, Schneider [12] surveyed already published flight data for boundary-layer transition at hypersonic speeds, from the open literature, to be used for validation of transition-estimation methods, based on simulation of the physical mechanisms. Experimental work has been later supplemented by more recent experimental studies by Marineau et al., and Moraru [13, 14].

- Three-dimensional instabilities and crossflow research [15-19] expanded the focus to include three-dimensional boundary layers on swept wings of commercial airliners.

- Advances in non-modal / transient growth theory and bypass transition [20-24], who emphasized algebraic growth mechanisms that can lead shear flows to transition in the absence of exponentially growing eigenmodes.

- Maturing of global linear theory [25, 26] that extended classic concepts of linear modal and non-modal instability mechanisms to flows with multiple inhomogeneous spatial directions.

- Accumulated knowledge from some of these efforts has been compiled into empirical transition prediction methods [27] that are currently in use, without much physical justification, also in hypersonic conditions [28].

The historical trajectory shows a gradual progression from simplified semi-empirical tools towards more physics-based models, informed by a synergy of theory, experiment, and computation. Today, with the advent of Navier-Stokes solvers (DNS, LES), and kinetic theory simulations (DSMC), researchers can probe both linear and nonlinear instability mechanisms in unprecedented detail, while flight experiments continue to provide critical validation.

One particularly disturbing "known unknown" [29] in this context is the fact that, as the flight altitude increases toward the lower mesosphere, uncertainty in the flight Reynolds number increases to unacceptable levels, e.g., uncertainties of O(35%) in Reynolds number determination was reported in the ROTEX-T flight experiments of Thiele et al. [30] for flight altitudes between 35 and 60km. At high altitudes, even highly accurate CFD tools may become irrelevant when restricted to classical mechanisms such as the second mode, crossflow, or Görtler vortices. In these regimes, simulations risk being numerical exercises with little physical meaning, while empirical transition criteria developed for simplified geometries often provide only crude approximations or even misleading results.

In an attempt to quantify laminar basic flows relevant to relatively low Reynolds number hypersonic glider flight, kinetic theory methods have been applied to vehicle sub-components [31, 32] and entire vehicle models [33, 34] at low altitude/low Mach number and high altitude/high Mach number environments, respectively. Quantitative, but not qualitative differences in linear eigenspectra of hypersonic flat-plate boundary layers have been documented when perturbations originate in the laminar boundary layer; however, low frequencies inherent to the shock layer [35], only accessible to fully resolved (by kinetic theory) shocks, give rise to a newly-discovered high-frequency laminar boundary layer linear perturbation mechanism [36]. The present contribution will elaborate on the above discussion and the implications of the recent findings for physics-based laminar-turbulent transition criteria on realistic hypersonic gliding vehicles.

2. Instability Mechanisms in Hypersonic Boundary Layers

The study of instability mechanisms in high-speed boundary layers has a long tradition, beginning with Mack's pioneering analyses of acoustic and vorticity-driven instabilities [7, 8]. These foundational works introduced the classification of instability modes that continue to serve as the framework for hypersonic transition research. In hypersonic regimes, multiple families of instabilities are now recognized, each of which can dominate under different flow and geometric conditions.

First and second Mack modes: The so-called first mode represents viscous instabilities akin to Tollmien–Schlichting waves at lower Mach numbers, while the second mode corresponds to a trapped acoustic wave within the boundary layer. The second mode is characterized by high frequencies and strong amplification, and has been shown to dominate transition at high Mach numbers, particularly in flows over sharp cones, blunt cones, and flat plates [9-11, 37- 40]. Recent direct numerical simulations (DNS) and experiments have further revealed the role of mode competition, where nonlinear coupling between first and second modes can alter transition onset.

Crossflow instabilities: These three-dimensional instabilities arise due to velocity gradients along swept surfaces, particularly in flows with significant spanwise pressure gradients. They have been identified as critical in waverider and swept-wing configurations, where crossflow vortices develop due to the combination of streamwise and spanwise velocity components, and can dominate the transition process [17-19]. Crossflow instabilities may interact with acoustic disturbances and surface roughness, making their prediction highly sensitive to environmental conditions.

Görtler vortices: Curvature-induced centrifugal instabilities appear over concave surfaces and can accelerate transition by creating streamwise-aligned vortical structures that promote secondary instabilities [15, 41]. In hypersonic applications, Görtler vortices are of particular interest for engine intakes and compression ramps, where wall curvature effects become significant [42].

Shock–boundary layer interactions: More recently, the coupling between shock dynamics and boundary-layer instabilities has emerged as a critical pathway to transition. High-frequency perturbations inherent to shock layers can excite second-mode waves [36], while unsteady shock motion may amplify low-frequency modes, giving rise to complex instability pathways [35]. Such mechanisms are especially important in hypersonic inlets, where repeated shock–boundary layer interactions occur.

The work of Sivasubramanian and Fasel [43] used DNS to study the laminar-turbulent transition process in a sharp cone's boundary layer at Mach 6, focusing on the fundamental breakdown mechanism. They demonstrated that fundamental breakdown is a dominant path to transition under such conditions, verified by the development of streamwise "hot" streaks on the surface of the cone. The DNS simulation successfully captured key transition phenomena, such as aligned vortical structures and peak heat flux, matching very well the corresponding experimental data.

The coexistence of these instabilities and their nonlinear interactions create a transition environment that defies simplistic prediction. Nonlinear mode coupling, resonance phenomena, and receptivity to environmental disturbances—including acoustic noise, surface roughness, and thermal effects—play decisive roles [40]. Furthermore, high-enthalpy effects such as vibrational nonequilibrium and real-gas phenomena can alter instability growth rates, highlighting the importance of combined theoretical, computational, and experimental approaches [44, 45].

As hypersonic vehicle design advances, understanding and predicting the competition between instability mechanisms remains central to developing reliable transition models. Future research directions emphasize high-fidelity DNS, uncertainty quantification, and advanced experimental diagnostics such as ultrafast schlieren and laser-induced fluorescence, which continue to shed light on the intricate physics of hypersonic boundary-layer transition.

3. Challenges in Transition Prediction at High Altitudes

Accurate prediction becomes increasingly challenging in the rarefied regimes of the upper stratosphere and mesosphere. The uncertainty in Reynolds number, which governs the onset and growth of instabilities, is particularly problematic. The ROTEX-T flight experiments [30] demonstrated uncertainties on the order of 35% for Reynolds number estimates, between 35–60 km, undermining the applicability of conventional transition prediction tools.

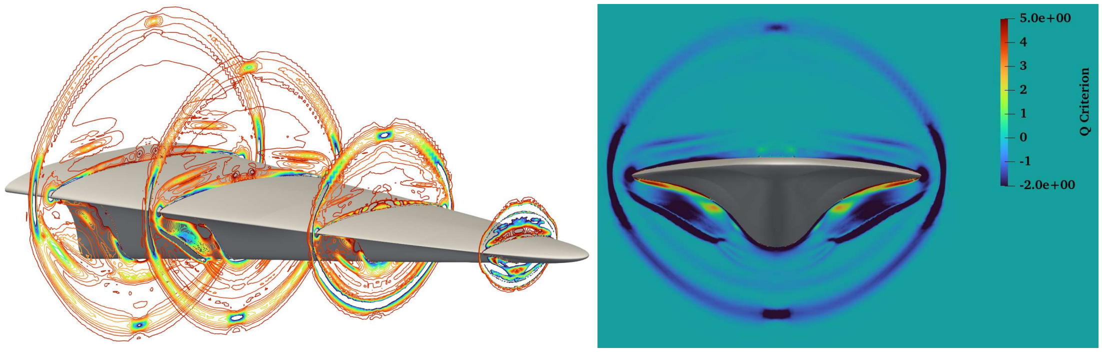

Fig 1. Q-criterion contours around a waverider at 30km altitude, Mach 6, 0.0 a.o.a. The simulation was carried out using SU2 solver. The contour at the right corresponds to a plane 1.6m downstream the nose of the vehicle.

Such uncertainties are compounded by the fact that the mean free path in these regimes approaches the characteristic scales of boundary-layer thickness, creating a breakdown of continuum assumptions that underlie classical CFD. For example, Boyd & Schwartzentruber [46] highlight the limitations of Navier–Stokes solvers under transitional Knudsen numbers, necessitating kinetic treatments. Moreover, experimental data from missions and more recent HIFiRE campaigns [47] illustrate strong variability in transition onset that cannot be reconciled with existing empirical models.

Empirical and semi-empirical transition criteria of van Ingen [5], often derived from simplified geometries, are ill-suited to capture the full spectrum of instability mechanisms present in realistic hypersonic vehicles. Classical e^N methods, although effective at lower Mach numbers, struggle when multiple competing instability families (second mode, crossflow, Görtler vortices, and shock-induced perturbations) interact nonlinearly [38, 39]. Furthermore, surface roughness, ablation, enthalpy, and real-gas chemistry can shift transition onset significantly [48], adding to predictive uncertainty.

Uncertainty quantification (UQ) frameworks are therefore becoming increasingly important. Approaches such as Input-Output Analysis [49] and Bayesian calibration of transition models [50] have been proposed to incorporate variability in flight parameters and measurement uncertainty into predictive models. The inadequacy of traditional methods highlights the urgent need for physics-based approaches that explicitly incorporate both linear and nonlinear instability dynamics under uncertainty, while accounting for rarefied gas effects, surface conditions, and shock–boundary layer interactions.

4. Advances in Physics-Based Modeling

Advancements in computational fluid dynamics (CFD) have enabled increasingly detailed studies of instability development. Direct numerical simulation (DNS) has been instrumental in uncovering nonlinear breakdown pathways of second-mode instabilities [45, 51]. However, CFD based on continuum assumptions is limited in rarefied regimes.

Kinetic theory approaches, particularly those employing the Boltzmann equation and direct simulation Monte Carlo (DSMC) [52], like SPARTA kernel [53, 54], have gained traction for modeling hypersonic flows.

Component-level analysis: In the work of De Tullio et al. [55] the linear instability and breakdown to turbulence, induced by an isolated roughness element in a boundary layer at supersonic flow, over an isothermal flat plate with laminar adiabatic wall temperature, have been analysed by means of DNS, coupled with spatial BiGlobal and three-dimensional parabolized (PSE-3D) stability analyses.

In the work of Paredes et al. [56] the spatial BiGlobal analysis technique was implemented to study the modal instabilities amplified in the hypersonic flow over the HIFiRE-5 elliptic cone geometry. The analysis was performed using an in-house-developed multi-dimensional stability code, which has been verified against DNS results.

Unsteadiness of axisymmetric shock-dominated hypersonic laminar separated flow over a double cone was studied by Tumulku et al. [57] using a combination of time accurate DSMC calculations, linear global instability analysis, and momentum potential theory.

Sawant et al. [31] and Klothakis et al. [32] used kinetic theory (DSMC codes) to study instabilities in simplified geometries, revealing modifications to classical eigenmode structures. Non-modal linear stability analysis results for hypersonic flow over an elliptic cone, with an aspect ratio of two at zero angle of attack, was performed by Quintanilha et al. [58], using the non-modal analysis framework of the massively parallel global instability analysis code LiGHT.

Whole-vehicle studies: Klothakis and Nikolos [59-61] extended kinetic modeling to simple hypersonic configurations and hypersonic waverider configurations at varying flight regimes, bridging the continuum–rarefied transition. Cutrone et al. [62] evaluated RANS-based models for the prediction of laminar-turbulent transition over the BOLT flight configuration that was tested in the CUBRC LENS-II wind tunnel test facility. Comparisons were made between simulation results from several transition models and CFD codes.

Shock-driven perturbations: Sawant et al. (2022) [35] and Cerminara et al. [36] uncovered low and high frequency modes respectively originating in shock layers, adding a new dimension to the instability spectrum. These findings underscore that while traditional instability mechanisms remain relevant, high-altitude flight introduces qualitatively new pathways that must be incorporated into transition models.

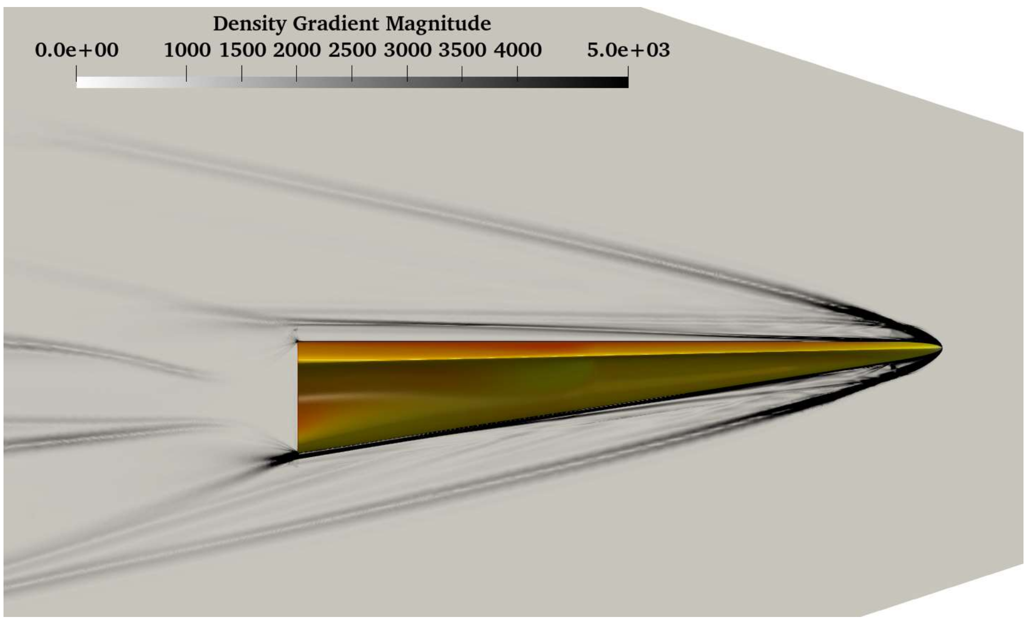

Fig 2. Density Schlieren contour of the test case presented in Fig. 1.

5. Advances in Control Strategies

The ability to delay the onset of laminar-to-turbulent transition is a critical enabler for efficient hypersonic flight, directly mitigating the severe aerothermal loads and skin-friction drag associated with turbulent boundary layers [63]. A diverse portfolio of control strategies, broadly categorized as passive and active [64] has been developed to manipulate the growth of boundary layer instabilities. Passive methods rely on fixed geometric or material properties, whereas active methods require energy input for real-time flow manipulation.

Among passive techniques, ultrasonically absorptive coatings (UACs) put forward in the work of Fedorov and co-workers [65, 66], have demonstrated significant efficacy [67]. These porous surfaces are engineered to damp the dominant second-mode instability by absorbing its acoustic energy, analogous to an acoustic muffler [68]. Extensive research confirms that UACs, including those made from dual-use thermal protection materials like Carbon-Carbon (C/C) composites, can strongly stabilize the second mode, albeit with a marginal destabilization of the first mode—a generally acceptable trade-off in the hypersonic regime [65]. Geometric modifications are also fundamental to passive control, particularly for waveriders. Leading-edge bluntness, essential for thermal management, critically alters the entropy layer and can exacerbate cross-flow instabilities inherent to swept-wing designs [69]. Micro-vortex generators (MVGs) can counteract such effects by introducing streamwise vortices that energize the boundary layer, enhancing its resistance to separation [70]. A more novel approach involves using spanwise strips of materials with differing thermal properties to passively generate a non-uniform surface temperature distribution, creating stable streamwise streaks that suppress the growth of second-mode waves [71].

Active control strategies offer greater adaptability by enabling real-time boundary layer manipulation. Precision thermal control, specifically localized surface cooling, has emerged as a powerful technique. In contrast to global cooling which destabilizes the second mode, a cooling strip placed strategically upstream of an instability's neutral point can significantly damp disturbances and delay transition [72]. This effect stems from a localized alteration of the boundary layer profile that disrupts the energy transfer mechanism fueling second-mode growth [73]. Recent simulations combining local cooling with acoustic metasurfaces predict a remarkable reduction in disturbance amplitude by a factor of over 270 [74]. Plasma-based flow control, particularly using Dielectric Barrier Discharge (DBD) actuators, is another promising active method [75]. With no moving parts and a rapid response time, DBD actuators generate a body force or localized heating to energize the near-wall flow or create compression waves that interfere with instabilities [76]. Other active techniques include mass flow control, where suction stabilizes the boundary layer by removing low-momentum fluid, while controlled blowing can deliberately trip it at a desired location [77], such as ahead of a scramjet inlet [78]. Frontier concepts envision adaptive surfaces using smart materials to achieve in-flight shape morphing or even active wave cancellation, though these remain at a low Technology Readiness Level for hypersonic applications [79, 80].

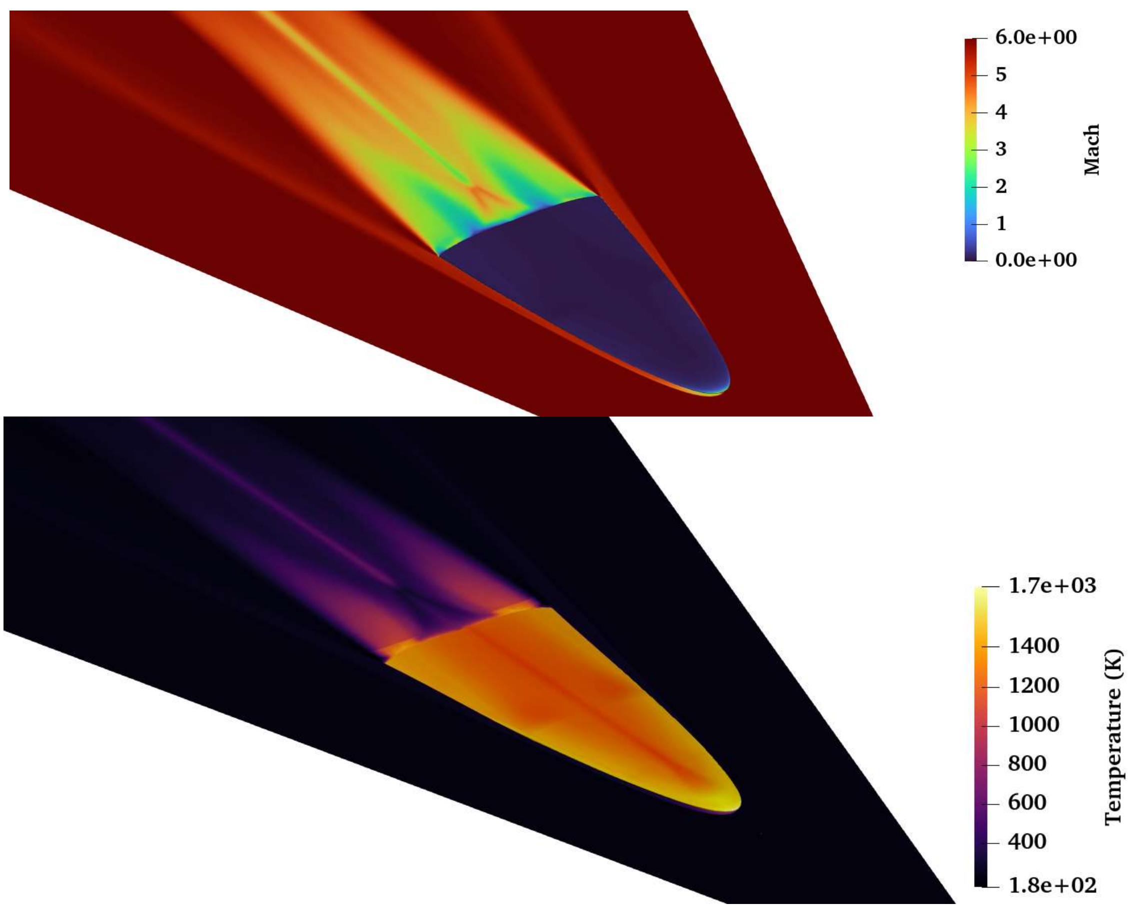

Fig 3. Mach number (top), and temperature contours, of the test case presented in Fig. 1.

6. Conclusions

The future of hypersonic transition research will be shaped by three converging trends: (a) kinetic-level modeling to resolve rarefied effects, (b) uncertainty quantification for reliable prediction under stochastic conditions, and (c) experimental validation, both in ground facilities and in flight, to bridge the gap between theory and practice. Progress will depend on coordinated international efforts to standardize methodologies and share data across computational and experimental domains.

Laminar–turbulent transition remains one of the most critical uncertainties in hypersonic waverider design. While classical instabilities such as the second Mack mode remain central, new findings on shock-induced perturbations expand the instability landscape. Traditional empirical criteria are insufficient under high-altitude uncertainty; instead, physics-based and probabilistic approaches are required. Advances in kinetic theory modeling, uncertainty quantification methods, and systematic control strategies offer the most promising path toward reliable hypersonic cruise capability. However, significant challenges remain in bridging the gap between fundamental research and practical implementation. A coordinated effort in simulation methodologies, and flight testing is required to establish reliable benchmarks for future waverider designs.

References

1. Maikapar, G. I.: On the wave drag of non-axisymmetric bodies at supersonic speeds. Journal of Applied Mathematics and Mechanics 23(2), 528-531 (1959)
2. Nonweiler, T. R. F.: Delta wings of shape amenable to exact shock wave theory. J. R. Aerosp. Soc. 67, 39 (1963)
3. Prandtl, L.: Über Flüssigkeitsbewegung bei sehr kleiner Reibung. Verhandlungen des III. Internationalen Mathematiker-Kongresses, Heidelberg (1904)
4. Schubauer, G. B., Skramstad, H.K.: Laminar Boundary-Layer Oscillations and Stability of Laminar Flow. Journal of the Aeronautical Sciences 14(2), 69-78 (1947)
5. van Ingen, J. L.: A suggested semi-empirical method for the calculation of the boundary layer transition region. Technische Hogeschool Vliegtuigbouwkunde, Report V.T.H.-74, Delft, Nederland (1956)
6. Smith, A. M. O., Gamberoni, N.: Transition, Pressure Gradient and Stability Theory. Report No. ES 26388, Douglas Aircraft Co., El Segundo, CA (1956)
7. Mack, L. M.: Boundary-Layer Stability Theory. Jet Propulsion Laboratory, Pasadena, CA, Document No. 900-277, Rev. A. (1969)
8. Mack, L. M.: Boundary-layer linear stability theory. In Special Course on Stability and Transition of Laminar Flow. AGARD Rep, 709 (1984)
9. Stetson, K. F.: Hypersonic Boundary Layer Transition Experiments. U.S. Air Force Wright Aeronautical Labs. Technical Report AFWAL-TR-80-3062 (1980)
10. Stetson, K. F., Thompson, E. R., Donaldson, J. C., Siler, L. G.: Laminar boundary layer stability experiments on a cone at Mach 8. Part I: Sharp cone. 16th AIAA Fluid and Plasma Dynamics Conference, July 12-14, Danvers, Massachusetts, USA (1983)
11. Stetson, K. F.: Nosetip Bluntness Effects on Cone Frustum Boundary Layer Transition in Hypersonic Flow. 16th AIAA Fluid and Plasma Dynamics Conference, July 12-14, Danvers, Massachusetts, USA, AIAA Paper 1983-1763 (1983)
12. Schneider, S. P.: Flight data for boundary-layer transition at hypersonic and supersonic speeds. Journal of Spacecraft and Rockets 36(1) (1999)
13. Marineau, E. C., Moraru, C. G., Lewis, D. R., Norris, J. D., Lafferty, J. F., Wagnild, R. M., Smith, J. A.: Mach 10 Boundary-Layer Transition Experiments on Sharp and Blunted Cones. 19th AIAA International Space Planes and Hypersonic Systems and Technologies Conference, AIAA Paper 2014-3108 (2014)
14. Moraru, C. G.: Hypersonic Boundary-Layer Transition Measurements at Mach 10 on a Large Seven Degree Cone at Angle of Attack. M.Sc. Thesis, Purdue Univ., West Lafayette, IN, (2015)
15. Saric, W. S.: Görtler vortices. Annu. Rev. Fluid Mech. 26, 379–409 (1994)

16. Bippes, H.: Basic experiments on transition in three-dimensional boundary layers dominated by crossflow instability. Progress in Aerospace Sciences 35(4), 363-412 (1999)

17. Saric, W. S., Reed, H. L., White, E. B.: Stability and transition of three-dimensional boundary layers. Annual Review of Fluid Mechanics 35, 413–440 (2002)

18. Saric, W. S., Reed, H. L.: Supersonic laminar flow control on swept wings using distributed roughness. AIAA Pap. No. 2002-0147 (2002)

19. Saric, W. S., Reed, H. L., White, E. B.: Stability and transition of three-dimensional boundary layers. Annu. Rev. Fluid Mech. 35, 413–40 (2003). doi: 10.1146/annurev.fluid.35.101101.161045

20. Trefethen, L. N., Trefethen, A., Reddy, S. C., Driscol, T. A.: Hydrodynamic stability without eigenvalues. Science 261(5121), 578-584 (1993)

21. Reddy, S. C., Schmid, P. J., Henningson, D.S.: Pseudospectra of the Orr-Sommerfeld operator. SIAM J. of Appl. Math. 53(1), 15-47 (1993)

22. Luchini, P.: Reynolds-number-independent instability of the boundary layer over a flat surface. J. Fluid Mech. 327, 101 – 115 (1996)

23. Reshotko, E.: Transient Growth: A Factor in Bypass Transition. Physics of Fluids 13(5), 1067–1075 (2001). doi:10.1063/1.1358308

24. Fedorov A. V., Tumin, A. M.: Initial-value problem for hypersonic boundary-layer flows. AIAA J. 41(3), 379–389 (2003)

25. Theofilis, V.: Advances in global linear instability analysis of nonparallel and three-dimensional flows. Progress in Aerospace Sciences 39, 249-315 (2003)

26. Theofilis, V.: Global linear instability. Annu. Rev. Fluid Mech. 43, 319–52 (2011)

27. Bowcutt, K. G.: Optimization of hypersonic waveriders derived from cone flows, including viscous effects. PhD Thesis, Univ. of Maryland (1986)

28. Chuanzhen, L., Qiang, L., Peng, B., Weijiang, Z.: Planform-customized waverider design integrating with vortex effect. Aerosp. Sci. Technol. 86, 438-443 (2019)

29. Bertin, J. J., Cummings, R. M.: Critical hypersonic aerothermodynamic phenomena. Annu. Rev. Fluid Mech. 38, 129–157 (2006)

30. Thiele, T., Gülhan, A., Olivier, H.: Instrumentation and Aerothermal Postflight Analysis of the Rocket Technology Flight Experiment ROTEX-T. Journal of Spacecraft and Rockets 55(5) (2018). https://doi.org/10.2514/1.A34129

31. Sawant, S. S., Theofilis, V., Levin, D. A.: On the synchronisation of three-dimensional shock layer and laminar separation bubble instabilities in hypersonic flow over a double wedge. J. Fluid Mech. 941, A7 (2022). doi:10.1017/jfm.2022.276

32. Klothakis, A., Quintanilha Jr., H., Sawant, S. S., Protopapadakis, E., Theofilis, V., Levin, D. A.: Linear stability analysis of hypersonic boundary layers computed by a kinetic approach: a semi-infinite flat plate at $4.5 \leq M\infty \leq 9$. Theor. Comput. Fluid Dyn. 36, 117–139 (2022). https://doi.org/10.1007/s00162-021-00601-y

33. Lappas, V., Klothakis, A., Nikolos, I., Theofilis, V.: On the Design of Miniature Reentry Vehicles for Mesosphere Exploration. Part I: Theoretical Considerations. AIAA SCITECH 2024 Forum, 8-12 January, Orlando, FL, AIAA 2024-1160 (2024). https://doi.org/10.2514/6.2024-1160

34. Klothakis, A., Nikolos, I. K., Theofilis, V.: DSMC simulation of a non-axisymmetric Hypersonic Vehicle at 90km altitude. 33rd International Symposium on Rarefied Gas Dynamics (RGD33) Conference, Göttingen, Germany (2024) (in press)

35. Sawant, S. S., Levin, D. A., Theofilis, V.: Analytical prediction of low-frequency fluctuations inside a one-dimensional shock. Theoretical and Computational Fluid Dynamics 36, 25-40

(2022).

36. Cerminara, A., Levin, D. A., Theofilis, V.: Susceptibility of shock-transitional-boundary-layer interaction to shock oscillations in hypersonic flow. AIAA SCITECH 2024 Forum, 8-12 January, Orlando, FL, AIAA Pap. No. 2024-0290 (2024). https://doi.org/10.2514/6.2024-0290
37. Smith, F. T.: On the first-mode instability in subsonic, supersonic or hypersonic boundary layers. J. Fluid Mech. 198, 127-153 (1989)
38. Schneider, S. P.: Effects of High-Speed Tunnel Noise on Laminar-Turbulent Transition. Journal of Spacecraft and Rockets 38(3), 323–333 (2001). doi:10.2514/2.3705
39. Fedorov, A. V.: Receptivity of a High-Speed Boundary Layer to Acoustic Disturbances. Journal of Fluid Mechanics 491, 101–129 (2003). doi:10.1017/S0022112003005263
40. Fedorov, A., Tumin, A.: High-Speed Boundary-Layer Instability: Old Terminology and a New Framework. AIAA Journal 49(8), 1647–1657 (2011). doi:10.2514/1.J050835
41. Hall, P.: The linear development of Görtler vortices in growing boundary layers. Journal of Fluid Mechanics 130, 41-58 (1983). https://doi.org/10.1017/S0022112083000968
42. Li, F., Choudhari, M., Chang, C.-L., Wu, M., Greene, P. T.: Development and Breakdown of Görtler Vortices in High Speed Boundary Layers. 48th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition, 04-07 January, Orlando, Florida, Pap. No. AIAA 2010-705 (2010). https://doi.org/10.2514/6.2010-705
43. Sivasubramanian, J., Fasel, H. F.: Direct numerical simulation of transition in a sharp cone boundary layer at Mach 6: fundamental breakdown. Journal of Fluid Mechanics 768, 175-218 (2015)
44. Zhong, X., Wang, X.: Direct Numerical Simulation on the Receptivity, Instability, and Transition of Hypersonic Boundary Layers. Annual Review of Fluid Mechanics 44, 527-561 (2012)
45. Laurence, S. J., Wagner, A., Hannemann, K.: Experimental study of second-mode instability growth and breakdown in a hypersonic boundary layer using high-speed schlieren visualization. J. Fluid Mech. 797, 471-503 (2016)
46. Boyd, I. D., Schwartzentruber, T. E.: Nonequilibrium Gas Dynamics and Molecular Simulation. Cambridge University Press (2017). https://doi.org/10.1017/9781139683494
47. Kimmel, R., Adamczak, D.: HIFiRE-1 Background and Lessons Learned. 50th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition, 09 - 12 January, Nashville, Tennessee, Pap. No, AIAA 2012-1088 (2012). https://doi.org/10.2514/6.2012-1088
48. Adam, P. H., Hornung, H. G.: Enthalpy effects on hypervelocity boundary-layer transition: Ground test and flight data. Journal of Spacecraft and Rockets 34(5) (1997). https://doi.org/10.2514/2.3278
49. Nichols, J. W., Candler, G. V.: Input-output analysis of complex hypersonic boundary layers. AIAA Scitech 2019 Forum, 7-11 January, San Diego, California, Pap. No. AIAA 2019-1383 (2019). https://doi.org/10.2514/6.2019-1383
50. Chowdhary, K., Hoang, C., Lee, K., Ray, J., Weirs, V. G., Carnes, B.: Calibrating hypersonic turbulence flow models with the HIFiRE-1 experiment using data-driven machine-learned models. Computer Methods in Applied Mechanics and Engineering 401, Part B, 115396 (2022).
51. Franko, K. J., Lele, S. K.: Breakdown mechanisms and heat transfer overshoot in hypersonic zero pressure gradient boundary layers. J. Fluid Mech. 730, 491-532 (2013). doi:10.1017/jfm.2013.350
52. Bird, G. A.: Molecular Gas Dynamics and the Direct Simulation of Gas Flows. Clarendon Press: Oxford, UK (1994)

53. Gallis, M. A., Torczynski, J. R.: Effect of Collision-Partner Selection Schemes on the Accuracy and Efficiency of the Direct Simulation Monte Carlo Method. Int. J. Numer. Methods Fluids 67, 1057–1072 (2011)

54. Gallis, M. A., Torczynski, J. R., Plimpton, S. J., Rader, D. J., Koehler, T.: Direct Simulation Monte Carlo: The quest for speed. Proceedings of the 29th Rarefied Gas Dynamics (RGD) Symposium, Xi'an, China, 13–18 July (2014)

55. De Tullio, N., Paredes, P., Sandham, N. D., Theoflis, V.: Laminar-turbulent transition induced by a discrete roughness element in a supersonic boundary layer. J. Fluid Mech. 735, 613-646 (2013). doi:10.1017/jfm.2013.520

56. Paredes, P., Gosse, R., Theoflis, V., Kimmel, R.: Linear modal instabilities of hypersonic flow over an elliptic cone. J. Fluid Mech. 804, 442-466 (2016). doi:10.1017/jfm.2016.536

57. Tumuklu, O., Theofilis, V., Levin, D. A.: On the unsteadiness of shock–laminar boundary layer interactions of hypersonic flows over a double cone. Physics of Fluids 30, 106111 (2018).

58. Quintanilha Jr., H., Paredes, P., Hanifi, A., Theofilis, V.: Transient growth analysis of hypersonic flow over an elliptic cone. J. Fluid Mech. 935, A40 (2022). doi:10.1017/jfm.2022.46

59. Klothakis, A., Nikolos, I. K.: Design and evaluation of a hypersonic waverider vehicle using DSMC. Computation 12, 140 (2024). https://doi.org/10.3390/computation12070140

60. Klothakis, A., Nikolos, I. K.: Comprehensive evaluation of the massively parallel Direct Simulation Monte Carlo kernel "Stochastic Parallel Rarefied-gas Time-Accurate Analyzer" in rarefied hypersonic Flows—Part A: Fundamentals. Computation 12, 198 (2024). https://doi.org/10.3390/computation12100198

61. Klothakis, A., Nikolos, I. K.: Comprehensive evaluation of the Massively Parallel Direct Simulation Monte Carlo kernel "Stochastic Parallel Rarefied-Gas Time-Accurate Analyzer" in rarefied hypersonic flows—Part B: Hypersonic vehicles. Computation 12, 200 (2024). https://doi.org/10.3390/computation12100200

62. Cutrone, L., Schettino, A., Cardesa, J., Delattre, G., Coder, J., et al.: Transition prediction in hypersonic regime on complex geometries with RANS-based models. AIAA SCITECH 2024 Forum, Orlando, United States (2024)

63. Araya, D. B., Bitter, N. P., Alkandry H.: Geometry-Independent Hypersonic Boundary Layer Transition Prediction. Johns Hopkins APL Technical Digest 36(2), 202-212 (2022). https://secwww.jhuapl.edu/techdigest/content/techdigest/pdf/V36-N02/36-02-Araya.pdf.

64. Fasel, H. F.: Control of hypersonic boundary layer transition. U.S. Patent No. 10,953,979. 23 (2021).

65. Fedorov, A. V., Malmuth, N. D., Rasheed, A., Hornung, H. G.: Stabilization of hypersonic boundary layers by porous coatings. AIAA J. 39(4), 605-610 (2001)

66. Fedorov, A. V., Shiplyuk, A., Maslov, A., Burov, E., Malmuth, N. D.: Stabilization of a hypersonic boundary layer using an ultrasonically absorptive coating. Journal of Fluid Mechanics 479, 99-124 (2003)

67. Zhao, R., Wen, C., Zhou, Y., Tu, G., Lei, J.: Review of acoustic metasurfaces for hypersonic boundary layer stabilization. Progress in Aerospace Sciences 130, 100808 (2022)

68. Wang, X., Zhong, X.: Passive Control of Hypersonic Boundary-Layer Transition using Regular Porous Coating. 7th International Conference on Computational Fluid Dynamics (ICCFD7), Big Island, Hawaii (2012)

69. Wartemann, V., Wagner, A., Kuhn, M., Eggers, T., Hannemann, K.: Passive hypersonic boundary layer transition control using an ultrasonically absorptive coating with random microstructure: Computational analysis based on the ultrasonic absorption properties of carbon-carbon. Procedia IUTAM, 14, 413-422 (2015)

70. Sun, Z.: Micro vortex generators for boundary layer control: principles and applications. International Journal of Flow Control 7(1-2), 67-86 (2015)
71. Wang, X., Zhong, X.: The impact of porous surface on hypersonic boundary layer instability. 40th Fluid Dynamics Conference and Exhibit, 5021 (2010)
72. Oz, F., Goebel, T. E., Jewell, J. S., Kara, K.: Local wall cooling effects on hypersonic boundary-layer stability. Journal of Spacecraft and Rockets 60(2), 412-426 (2023)
73. Grasso, F., Gloerfelt, X.: Second-order analysis of hypersonic boundary-layer stability. Journal of Fluid Mechanics 1000, A56 (2024)
74. Oz, F., Kara, K.: Controlling hypersonic boundary layer transition with localized cooling and metasurface treatments. Scientific Reports 14(1), 15928 (2024)
75. Erfani, R.: Optimization of Dielectric Barrier Discharge plasma actuators and their application to fluid dynamics. PhD Thesis, University of Manchester (2012)
76. Shahrbabaki, A. N., Bazazzadeh, M., Khoshkhoo, R.: Investigation on supersonic flow control using nanosecond dielectric barrier discharge plasma actuators. International Journal of Aerospace Engineering 2021(1), 2047162 (2021)
77. Schneider, S. P.: Hypersonic boundary-layer transition with ablation and blowing. Journal of Spacecraft and Rockets 47(2), 225-237 (2010)
78. Berry, S., Nowak, R., Horvath, T.: Boundary layer control for hypersonic airbreathing vehicles. 34th AIAA Fluid Dynamics Conference and Exhibit, 2246 (2004)
79. Barbarino, S., Bilgen, O., Ajaj, R. M., Friswell, M. I., Inman, D. J.: A review of morphing aircraft. Journal of intelligent material systems and structures 22(9), 823-877 (2011)
80. Bushnell, D. M., Wygnanski I.: Flow Control Applications. NASA Report NASA/TM-2020-220436 (2020).

