International Forum on Aeroelasticity and Structural Dynamics
IFASD 2026
16-19 June 2026, Goettingen, Germany

LOW-ORDER MULTIDISCIPLINARY MODELING OF HYPERSONIC VEHICLES WITH COUPLED AEROELASTIC AND AERO–PROPULSIVE EFFECTS

João Cavalcanti[1] **and Roberto Gil Annes da Silva**[2]

[1]Institute for Advanced Studies
São José dos Campos, São Paulo, Brazil
cavalcantijbmc@fab.mil.br
Corresponding author

[2]Aeronautics Institute of Technology
São José dos Campos, São Paulo, Brazil
gil@ita.br

Keywords: Hypersonic vehicle, Low-order Multidisciplinary Modeling, Conceptual Design, Aeroelasticity

1 INTRODUCTION

From a design standpoint, hypersonic vehicles pose demanding multidisciplinary challenges involving aerodynamics, structures, high-temperature gas dynamics, propulsion, and flight dynamics, with strong coupling effects that become increasingly pronounced at high Mach numbers. Comprehensive treatments of hypersonic flow physics and high-temperature gas dynamics can be found in [1, 2]. Waverider concepts, initially introduced in [3] and later extended to viscous and axisymmetric formulations [4–7], provide attractive configurations for air-breathing hypersonic vehicles due to their high lift-to-drag ratios and favorable inlet precompression characteristics. On the propulsion side, [8] offers a comprehensive framework for air-breathing hypersonic engines, while [9] analyzes scramjet performance through thermodynamic Brayton-cycle models at high Mach numbers. For the Brazilian hypersonic scramjet vehicle 14-X, [10] proposes a methodology for two-dimensional engine analysis under various flight conditions, which can be extended to three-dimensional configurations.

Despite this extensive body of work, there remains a lack of low-order, integrated modeling frameworks that explicitly link structural flexibility to flight-dynamic and aero–propulsive behavior of hypersonic vehicles at the conceptual design stage. In particular, most existing approaches treat aeroelasticity, propulsion, and flight dynamics in a largely decoupled manner, limiting their suitability for rapid trade studies and early-stage design exploration. The primary motivation of the present study is to address this gap by developing a computational framework that combines hypersonic aerodynamics, structural dynamics, propulsion, and flight mechanics in a tractable yet physically meaningful way. The central question addressed is how structural flexibility influences trim conditions, stability characteristics, and aero–propulsive coupling in SCRAMJET-integrated hypersonic vehicles during conceptual design.

In the final paper, a low-order modeling framework for hypersonic waverider-type vehicles will be proposed and analyzed, with emphasis on the role of structural flexibility in coupled aero–propulsive–flight-dynamic behavior. To the authors' knowledge, this is among the first low-order frameworks to explicitly investigate structural flexibility effects on aero–propulsive coupling in hypersonic vehicles within a unified conceptual design environment. The use of low-order models is intentional, as it enables rapid parametric studies, sensitivity analyses, and multidisciplinary optimization that are impractical with high-fidelity approaches at the conceptual design level.

This abstract is organized as follows. Section 2 introduces the methodology adopted to develop the low-order hypersonic vehicle model. Section 3 presents representative preliminary numerical results obtained with the proposed framework. Finally, Section 4 outlines the scope and contributions of the final paper.

2 METHODOLOGY

The design methodology presented in Fig. 1 followed what is shown in [11]. Some loops were necessary during the process to achieve the best final aircraft. These iterations or loops are not shown in Fig. 1.

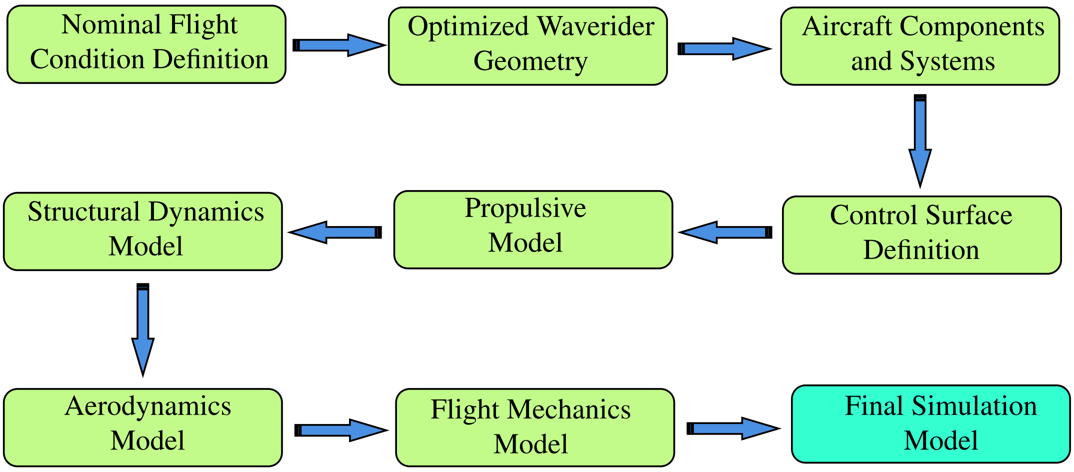

Figure 1: Design flow methodology.

The conceptual design of hypersonic vehicles requires a tightly coupled multidisciplinary framework, as high-Mach flight amplifies interactions among aerodynamics, structural flexibility, propulsion, and controls. Accordingly, this work adopts a conceptual-level methodology, summarized in Fig. 1, which extends classical aeroelastic coupling toward a hypersonic aeroelastic perspective while neglecting selected aerothermoelastic interactions to maintain tractability. The process starts with the definition of a nominal flight condition, followed by the generation and optimization of a wedge-derived waverider under shock-attached constraints. Aerodynamic efficiency is estimated from pressure-based lift and wave, base, and viscous drag components, with skin-friction corrections introduced via a reference-temperature method. The optimized waverider is then integrated with a SCRAMJET propulsion model formulated using a standard station framework, in which external and internal compression, Rayleigh-flow combustion, and internal/external expansion are represented, including simplified off-design limits. Aircraft components, systems, and control surfaces are subsequently defined using lumped-mass representations and conceptual material assumptions, while structural flexibility is captured through a Rayleigh–Ritz beam model with admissible shape functions. Aerodynamic loads are computed by discretizing the vehicle into triangular panels and applying the Modified Newtonian method with explicit treatment of shadow and shielding effects. These loads feed a flight-mechanics model that enables trimming and linearization, with or without quasi-static aeroelastic coupling. The complete formulation and iterative aspects of this methodology will be addressed in detail in the final paper.

3 PRELIMINARY NUMERICAL RESULTS

3.1 Waverider optimization process

Fig. 2 shows the result for the whole process of waverider optimization considering the genetic algorithm provided by MATLAB®. The selected waverider solution, obtained after 50 generations of the genetic-algorithm optimization, lies within a narrow Pareto front characterized by aerodynamic efficiencies consistent with historical hypersonic data. The arithmetic mean of the Pareto-optimal set yields $L/D = 5.3721$, with the chosen design corresponding to the closest available solution on the front. Comparison with Küchemann's empirical relation at $M_\infty = 7.0$ indicates a relative error of approximately 6%, demonstrating good agreement with both theoretical estimates and experimental trends reported in the literature [4]. This consistency is also illustrated in Fig. 2. The resulting optimized wedge-derived waverider geometry is subsequently integrated with the SCRAMJET configuration adopted from [10], forming the baseline vehicle for the multidisciplinary analyses in the final paper.

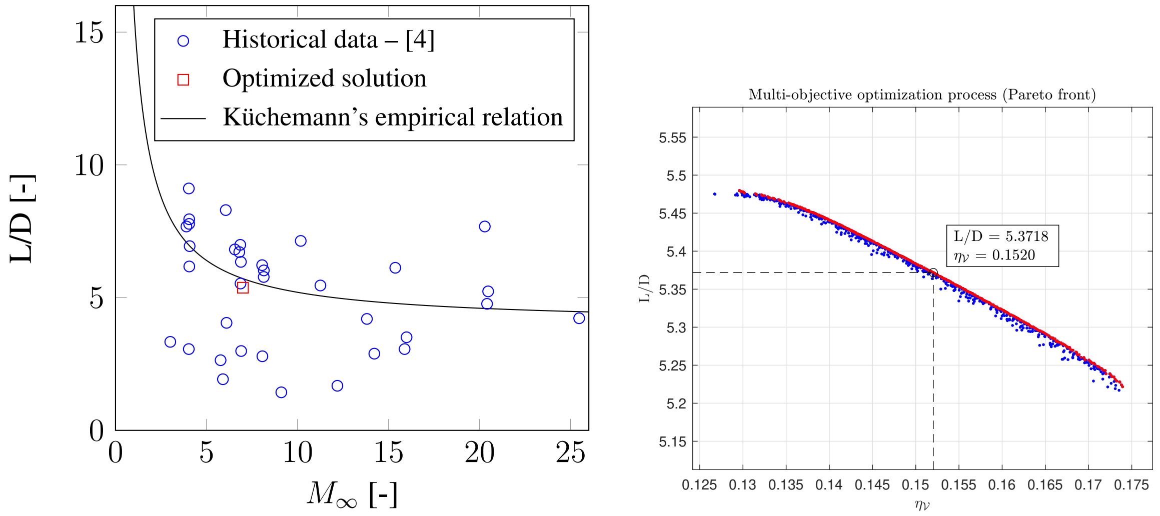

Figure 2: Waverider optimization summary: (a) comparison between the selected solution, historical data, and Küchemann's empirical relation (adapted from [4]); (b) Pareto front for aerodynamic and volumetric efficiency, $\eta_\mathcal{V} \triangleq \mathcal{V}^{2/3}/S_p$.

3.2 Structural-dynamic model

The structural–dynamic model is based on a beam-type discretization of the hypersonic vehicle, enabling an efficient representation of structural flexibility at the conceptual design level. The elastic dynamics are formulated using a Rayleigh–Ritz approach, in which the structure is decomposed into interconnected beam elements representing the primary load-carrying components. The geometric arrangement, beam numbering, and rigid interconnections transmitting translational and rotational motion between ventral and lateral members are illustrated in Fig. 3 and 4.

Bending in two orthogonal directions and torsion are modeled using admissible shape functions derived from classical cantilever beam solutions, and a truncated modal basis retaining five modes per deformation type is adopted for each beam to balance model fidelity and computational efficiency. Major subsystems, including aerodynamic surfaces, SCRAMJET engine, payload, fuel tank, and onboard equipment, are represented as lumped rigid bodies with constant mass and inertia properties over the short flight duration considered.

The influence of structural deformations on the external geometry is captured through a kinematic mapping procedure that transfers beam bending and torsional deformations to surface panels, as shown in Fig. 3, enabling direct modification of the aerodynamic loading. Parametric variations of structural stiffness are introduced via a scaling factor applied to the stiffness matrix, allowing systematic investigation of how structural flexibility affects modal characteristics, trim conditions, and coupled aero–propulsive–flight-dynamic behavior. Preliminary results indicate that the proposed formulation captures meaningful sensitivity of vehicle response to structural stiffness variations while preserving the computational efficiency required for early-stage multidisciplinary trade studies.

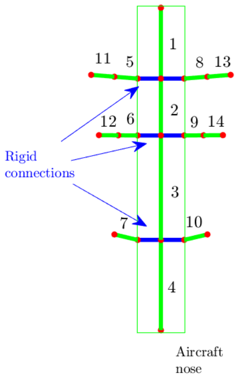

Figure 3: Numerical identification of beams in structural model. Green contour shows the real size of the central beam.

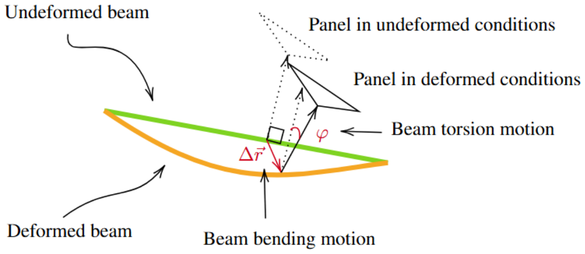

Figure 4: Panel displacements according to beam bending and torsion deformations.

4 FINAL PAPER

The final paper will present a complete and rigorous exposition of the multidisciplinary framework introduced in this extended abstract, with particular emphasis on quantifying the role of structural flexibility in the coupled aero–propulsive–flight-dynamic behavior of hypersonic vehicles. Building upon the preliminary results presented herein, the full paper will explicitly assess how elastic degrees of freedom influence trim conditions, stability characteristics, and control authority in SCRAMJET-integrated configurations.

A detailed description of the vehicle modeling strategy will be provided, including the generation and optimization of the wedge-derived waverider geometry, the evaluation of aerodynamic loads using low-order hypersonic methods, and the integration of a station-based SCRAMJET propulsion model. The structural–dynamic formulation based on the Rayleigh–Ritz method will be presented in detail, including the selection of admissible shape functions, lumped-mass representations, and the adoption of a mean-axes framework for coupling elastic and rigid-body dynamics.

The flight-mechanics analysis will be expanded to include trimming and linearization of both rigid and aeroelastic models, enabling direct comparison of equilibrium conditions, stability margins, and control requirements. Finally, the implications of the proposed framework for conceptual hypersonic vehicle design will be discussed, emphasizing its suitability for rapid trade studies and multidisciplinary optimization, while critically addressing the limitations inherent to low-order modeling approaches.

REFERENCES

[1] Anderson, J. D. (2006). *Hypersonic and high-temperature gas dynamics*. Reston, VA: American Institute of Aeronautics and Astronautics. ISBN 978-1-56-347780-5.

[2] Hirschel, E. and Weiland, C. (2009). *Selected aerothermodynamic design problems of hypersonic flight vehicles*. Berlin: Springer-Verlag. ISBN 9783540899730.

[3] Nonweiler, T. (1963). Delta wings of shapes amenable to exact shock-wave theory. *The Journal of the Royal Aeronautical Society*, 67(625), 39–40. doi:10.1017/S0368393100090027.

[4] Bowcutt, K., Anderson, J., and Capriotti, D. (1987). Viscous optimized hypersonic waveriders. AIAA Aerospace Sciences Meeting, Reston, VA: AIAA.

[5] Corda, S. and Anderson, J. (1988). Viscous optimized hypersonic waveriders designed from axisymmetric flow fields. AIAA Aerospace Sciences Meeting, Reston, VA: AIAA.

[6] Ding, F. et al. (2017). An overview of research on waverider design methodology. *Acta Astronautica*, 140, 190–205. ISSN 0094-5765. doi:https://doi.org/10.1016/j.actaastro.2017.08.027.

[7] Rasmussen, M. (1994). *Hypersonic flow*. New York: Wiley. ISBN 978-0-47-151102-1.

[8] Heiser, W. et al. (1994). *Hypersonic airbreathing propulsion*. AIAA education series. Reston, VA: American Institute of Aeronautics and Astronautics. ISBN 9781563470356.

[9] Zhang, D. et al. (2015). Thermodynamic analysis on optimum performance of scramjet engine at high mach numbers. *Energy*, 90, 1046–1054. ISSN 0360-5442. doi:https://doi.org/10.1016/j.energy.2015.08.017.

[10] Capistrano-Teixeira, P. (2015). *Análise de desempenho do veículo hipersônico aeroespacial 14-X B*. Master in science and space technology, Aeronautics Institute of Technology, São José dos Campos. In Portuguese.

[11] Raymer, D. P. (2018). *Aircraft design*. American Institute of Aeronautics and Astronautics, 6th ed. ISBN 978-1-62-410490-9.