

DARE: A MATLAB package for Design and Analysis of Ramjet/scramjet Engines

Ali Can Ispir^{1*} and Bora O. Cakir^{2*}

² Department of Energy Sciences, Lund University, Sweden ¹ Department of Mechanical Engineering, Eindhoven University of Technology, the Netherlands * These authors contributed equally.

DOI: [10.xxxxxx/draft](https://doi.org/10.xxxxxx/draft)

Software

- [Review](#)
- [Repository](#)
- [Archive](#)

Editor: [Open Journals](#)

Reviewers:

- [@openjournals](#)

Submitted: 01 January 1970

Published: unpublished

License

Authors of papers retain copyright and release the work under a Creative Commons Attribution 4.0 International License ([CC BY 4.0](#)).

Summary

The advancement of supersonic civil aviation, with a focus on improving both technical and environmental sustainability, requires a holistic approach to the design and performance assessment of supersonic aircraft. These designs must meet the demands of high-speed flight while also being adaptable to varying external conditions throughout their missions, necessitating optimization of aerodynamic and propulsion systems across different operating conditions (Küchemann, 2012). Therefore, configuring, optimizing, and analyzing a high-speed propulsion system is crucial to the development of supersonic and hypersonic aircraft. When considering propulsion system architectures that align with the mission requirements of high-speed aircraft, ramjet engines present notable advantages over rocket engines, as they eliminate the need for onboard oxidizer storage or rotating components. Although ramjets are structurally simpler than turbo-based aero-engines, their internal flow dynamics are intricate and require careful study to ensure stability and optimal performance (Curran & Murthy, 2000). As such, conceptual design methods using zero- and one-dimensional approaches provide a cost-effective alternative to detailed numerical simulations. These methods enable the analysis of design parameters and operational variables for key components, as well as the evaluation of propulsion performance metrics like thrust, specific impulse, and fuel consumption.

Statement of need

Since the 1960s, reduced-order models for high-speed propulsion systems, including ramjet and scramjet engines, have been developed and tested. Early models focused on fuel injection and mixing effects, simulating flow through intake contours with a two-shock approach (Bauer, 1966). These studies addressed key combustion chamber conditions like pre-ignition states, fuel mixing, and ignition methods, and explored propulsion characteristics at different altitudes and speeds. Further on, numerical approaches combining finite-difference solutions with a stirred reactor model and finite-rate chemistry were proposed, focusing on the design aspects such as complete engine performance and weight optimization (Edelman et al., 1981; Harsha & Edelman, 1978). Later, 1D models with Eulerian-Lagrangian were introduced to examine stable and unstable combustion modes and their impacts on cycle performance (Bhatia & Sirignano, 1990), as well as thrust losses due to incomplete combustion and entropy from irreversibility (Riggins & Clinton, 1995). Other models combined low-fidelity propulsion computations with structural integrity for hypersonic engines, estimating performance under aeroelastic conditions (Bolender & Doman, 2007; Chavez & Schmidt, 1994). However, these models lacked sufficient combustion modeling. To address this, Torrez et al. (2011) developed a reduced-order engine model for mixing and combustion in ramjet and scramjet engines, and improved their MASIV tool with the Shapiro method to predict thermal choking position (Torrez et al., 2013).

These are numerous examples of various low-fidelity design and analysis studies aimed at

accurately characterizing the performance specifications of ramjet engines, most of these tools focus on individual components of the propulsion system rather than a comprehensive methodology. Hence, there exists no prior attempt to couple the intake design approaches with a combustion analysis module with only a few studies considering the combined influence of flight conditions and design parameters throughout the entire propulsive flow path. Although understanding and analysis of the performance criteria for each component is essential on capturing the relevant physical phenomena that influence various aspect of design considerations for ramjet and scramjet engines, proper exploration of the design envelope is necessary for accurate description of mission definition and appropriate optimization of design choices for high-speed aircraft design.

Therefore, DARE is proposed as a design and analysis tool that combines the individual design and analysis approaches for high-speed propulsive path components to achieve a holistic low-fidelity design method for cost-efficient characterization of a high-speed propulsive design space. Ramjet/scramjet propulsive flow path is composed of an intake, an isolator, a combustor and a nozzle. The analytical tool used aims to provide a fully integrated flow path analysis, which includes three main modules. First module, covers the design and investigation process of the intake which is used to provide the necessary freestream flow modulation prior to the isolator through which a normal shock assumption is applied in case of ramjet configurations. The resultant flow properties are utilized for the combustion module to compute the flow evolution within the combustion chamber based on 1D steady inviscid flow equations coupled with detailed chemistry approach and JANAF tables using the SUNDIALS (Suite of Nonlinear and Differential/Algebraic Equation Solvers) code (Hindmarsh et al., 2005), developed by Lawrence Livermore National Laboratory. Finally, the third model is the nozzle design and analysis module, in which flow expansion through various expansion ratios and nozzle geometries are calculated using the 1D steady inviscid flow equations under cold flow conditions. Consequently, the parameters such as thrust, fuel consumption and specific impulse are calculated to quantify the engine performance for each design.

Research application

DARE has been primarily used within the EU funded Stratofly and More&Less projects to focus on the design, analysis, and optimization of ramjet and dual-mode ramjet/scramjet propulsion systems, which are critical for supersonic and hypersonic vehicles operating beyond Mach 3 (Zhang et al. (2016); Laboratory (2024); Cakir et al. (2022)). DARE provided assessments for flow development, combustion performance, and overall propulsive characteristics such as thrust, fuel consumption, specific impulse, and efficiency are analyzed under varying conditions, including flight Mach number, altitude, intake geometry, and equivalence ratio (Cakir & Ispir, 2025; Ispir et al., 2024). Sensitivity analyses, including Shapley Additive Explanations (SHAP) and feature importance studies, identify key design parameters influencing engine performance. These methodologies are demonstrated to efficiently explore the design space, generate performance maps, and quantify propulsion system feasibility for high-supersonic cruise vehicles at an affordable computational cost. DARE has also been used in conjunction to machine learning techniques to apply artificial neural networks to each operational and design variable within the ramjet and dual-mode ramjet/scramjet design space in order to make a comprehensive exploration of the design space and build machine learning models to represent the propulsive performance of the ramjet (Cakir et al., 2023; Ispir et al., 2022).

Acknowledgements

This project has received funding from the European Union's Horizon 2020 research and innovation programme, MORE & LESS (MDO and REgulations for Low-boom and Environmentally Sustainable Supersonic aviation) and STRATOFly projects under grant agreement numbers 101006856 and @@ respectively.

References

- 91
- 92 Bauer, R. (1966). A hypersonic ramjet analysis with premixed fuel combustion. In *2nd*
93 *propulsion joint specialist conference*. <https://doi.org/10.2514/6.1966-648>
- 94 Bhatia, R., & Sirignano, W. (1990). A one-dimensional model of ramjet combustion instability.
95 In *28th aerospace sciences meeting*. <https://doi.org/10.2514/6.1990-271>
- 96 Bolender, M. A., & Doman, D. B. (2007). Nonlinear longitudinal dynamical model of an
97 air-breathing hypersonic vehicle. *Journal of Spacecraft and Rockets*, 44(2), 374–387.
98 <https://doi.org/10.2514/1.23370>
- 99 Cakir, B. O., & Ispir, A. C. (2025). Reduced order design space analysis and operational mapping
100 for ramjet engines. *Aerospace Science and Technology*, 157, 109811. <https://doi.org/https://doi.org/10.1016/j.ast.2024.109811>
- 101
- 102 Cakir, B. O., Ispir, A. C., Civerra, F., & Saracoglu, B. H. (2023). Reduced order design space
103 analysis of for ramjet engines with data mining techniques. In *AIAA SCITECH 2023 forum*.
104 <https://doi.org/10.2514/6.2023-2017>
- 105 Cakir, B. O., Ispir, A. C., & Saracoglu, B. H. (2022). Reduced order design and investi-
106 gation of intakes for high speed propulsion systems. *Acta Astronautica*, 199, 259–276.
107 <https://doi.org/https://doi.org/10.1016/j.actaastro.2022.07.037>
- 108 Chavez, F. R., & Schmidt, D. K. (1994). Analytical aeropropulsive-aeroelastic hypersonic-
109 vehicle model with dynamic analysis. *Journal of Guidance, Control, and Dynamics*, 17(6),
110 1308–1319. <https://doi.org/10.2514/3.21349>
- 111 Curran, E. T., & Murthy, S. N. B. (2000). *Scramjet propulsion*. American Institute of
112 Aeronautics; Astronautics. ISBN: 9781563473227
- 113 Edelman, R. B., Harsha, P. T., & Schmotolocha, S. N. (1981). Modeling techniques for
114 the analysis of ramjet combustion processes. *AIAA Journal*, 19(5), 601–609. <https://doi.org/10.2514/3.50982>
- 115
- 116 Harsha, P., & Edelman, R. (1978). Application of modular modeling to ramjet performance
117 prediction. In *14th joint propulsion conference*. <https://doi.org/10.2514/6.1978-944>
- 118 Hindmarsh, A. C., Brown, P. N., Grant, K. E., Lee, S. L., Serban, R., Shumaker, D. E., &
119 Woodward, C. S. (2005). SUNDIALS: Suite of nonlinear and differential/algebraic equation
120 solvers. *ACM Trans. Math. Softw.*, 31(3), 363–396. <https://doi.org/10.1145/1089014.1089020>
- 121
- 122 Ispir, A. C., Cakir, B. O., & Saracoglu, B. H. (2024). Design space investigations of
123 scramjet engines using reduced-order modeling. *Acta Astronautica*, 217, 349–362.
124 <https://doi.org/https://doi.org/10.1016/j.actaastro.2024.01.036>
- 125 Ispir, A., Cakir, B., & Saracoglu, B. (2022). Design space exploration for a scramjet engine
126 by using data mining and low-fidelity design techniques. In *HiSST: 2nd international*
127 *conference on high-speed vehicle science & technology*.
- 128 Küchemann, D. (2012). *The aerodynamic design of aircraft*. American Institute of Aeronautics;
129 Astronautics, Incorporated. ISBN: 9781600869228
- 130 Laboratory, L. L. N. (2024). *CVODE - solver for ordinary differential equations*. <https://computing.llnl.gov/projects/sundials/cvode>
- 131
- 132 Riggins, D., & Clinton, C. (1995). Thrust modeling for hypersonic engines. In *International*
133 *aerospace planes and hypersonics technologies*. <https://doi.org/10.2514/6.1995-6081>
- 134 Torrez, S. M., Dalle, D. J., & Driscoll, J. F. (2013). New method for computing performance
135 of choked reacting flows and ram-to-scram transition. *Journal of Propulsion and Power*,

136 29(2), 433–445.

137 Torrez, S. M., Driscoll, J. F., Ihme, M., & Fotia, M. L. (2011). Reduced-order modeling of
138 turbulent reacting flows with application to ramjets and scramjets. *Journal of Propulsion*
139 *and Power*, 27(2), 371–382. <https://doi.org/10.2514/1.50272>

140 Zhang, D., Feng, Y., Zhang, S., Qin, J., Cheng, K., Bao, W., & Yu, D. (2016). Quasi-one-
141 dimensional model of scramjet combustor coupled with regenerative cooling. *Journal of*
142 *Propulsion and Power*, 32(3), 687–697.

DRAFT