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

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Summary

Advancing supersonic civil aviation with a focus on technical and environmental sustainability demands a comprehensive approach to the design and performance evaluation of supersonic aircraft. These designs must not only support the requirements of high-speed flight but also adapt to varying external conditions throughout their missions, making the optimization of aerodynamic and propulsion systems essential across diverse operating scenarios (Küchemann, 2012). Consequently, the configuration, optimization, and analysis of high-speed propulsion systems are critical for developing supersonic and hypersonic aircraft. Among the propulsion architectures suited for high-speed missions, ramjet engines offer significant advantages over rocket engines by eliminating the need for onboard oxidizer storage and rotating components. Despite their structural simplicity compared to turbo-based aero-engines, ramjets feature complex internal flow dynamics that require detailed investigation to ensure stability and optimal performance (Curran & Murthy, 2000). To address this, conceptual design methods employing zero- and one-dimensional approaches provide a cost-effective alternative to detailed numerical simulations, enabling the analysis of design parameters, operational variables, and propulsion performance metrics such as thrust, specific impulse, and fuel consumption.

Statement of need

Since the 1960s, researchers have developed and evaluated reduced-order models for high-speed propulsion systems, including ramjet and scramjet engines. Early models concentrated on simulating fuel injection and mixing effects, using a two-shock approach to analyze flow through intake contours (Bauer, 1966). These efforts investigated critical combustion chamber parameters such as pre-ignition conditions, fuel mixing, and ignition techniques, while also assessing propulsion performance across varying altitudes and speeds. Later advancements introduced numerical methods that integrated finite-difference solutions with stirred reactor models and finite-rate chemistry, emphasizing design aspects like overall engine performance and weight optimization (Edelman et al., 1981; Harsha & Edelman, 1978). Subsequently, one-dimensional models incorporating Eulerian-Lagrangian frameworks were developed to study stable and unstable combustion modes and their influence on cycle performance (Bhatia & Sirignano, 1990). These models also evaluated thrust losses caused by incomplete combustion and entropy generated from irreversibility (Riggins & Clinton, 1995). Some approaches combined low-fidelity propulsion analysis with structural integrity considerations for hypersonic engines, enabling performance assessments under aeroelastic conditions (Bolender & Doman, 2007; Chavez & Schmidt, 1994). Despite these advancements, combustion modeling remained a limitation. To address this, Torrez et al. (2011) introduced a reduced-order engine model for ramjet and scramjet mixing and combustion, further enhancing the MASIV (Michigan Air Force Scramjet In Vehicle) tool with the Shapiro method to predict thermal choking positions

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(Torrez et al., 2013).

In parallel with these domain-specific developments, several modern frameworks employing one-dimensional modeling techniques have emerged for propulsion and system-level modeling. NASA's OpenMDAO (Gray et al., 2019) provides a flexible, open-source Python framework for multidisciplinary design, analysis, and optimization, enabling coupling between aerodynamic, structural, and propulsion models. The Numerical Propulsion System Simulation (NPSS) (Lytle, 2000) offers a modular, extensible environment for thermodynamic cycle simulation of gas turbine engines, while tools such as SUAVE (Gawehn et al., 2020) and PyCycle (Gray & Hwang, 2020) extend this approach to open-source aircraft and engine analysis. Within the MATLAB/Simulink ecosystem, NASA's Toolbox for the Modeling and Analysis of Thermodynamic Systems (T-MATS) (NASA Glenn Research Center, 2024) provides a component-based library for general thermodynamic and turbomachinery systems.

Numerous low-fidelity design and analysis studies have been conducted to characterize the performance of ramjet engines. However, most of these tools focus on individual propulsion system components rather than providing a holistic methodology. To date, there has been no significant effort to integrate intake design approaches with combustion analysis modules, and only a limited number of studies consider the combined effects of flight conditions and design parameters across the entire propulsion flow path. While analyzing the performance of individual components is crucial for understanding the physical phenomena that influence various design considerations for ramjet and scramjet engines, a thorough exploration of the design envelope is essential. This approach ensures an accurate definition of mission requirements and enables the effective optimization of design choices for high-speed aircraft.

The `DARE` (a toolbox for Design and Analysis of Ramjet/scramjet Engines) tool is introduced as a design and analysis framework that integrates individual approaches for high-speed propulsion components into a unified low-fidelity methodology. This tool aims to enable cost-effective characterization of the design space for high-speed propulsion systems. The ramjet/scramjet propulsion flow path comprises four primary components: the intake, isolator, combustor, and nozzle. The proposed analytical tool provides a fully integrated flow path analysis divided into three main modules. The first module focuses on the intake, facilitating the necessary freestream flow modulation before entering the isolator. For ramjet configurations, this module incorporates a normal shock assumption. The resulting flow properties are then used in the second module, which models combustion. This module calculates flow evolution within the combustion chamber using one-dimensional steady, inviscid flow equations coupled with detailed chemical kinetics and JANAF tables, employing the SUNDIALS code (Hindmarsh et al., 2005), developed by Lawrence Livermore National Laboratory. The third module addresses nozzle design and analysis, simulating flow expansion across various expansion ratios and nozzle geometries using one-dimensional steady, inviscid flow equations under cold flow conditions. Key performance metrics, including thrust, fuel consumption, and specific impulse, are then calculated to evaluate 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); 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 fuel-air equivalence ratio (Cakir & Ispir, 2025; Ali Can 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

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cruise vehicles at an affordable computational cost. DARE has also been used in conjunction with machine learning techniques to support data-driven modeling of high-speed propulsion systems. In these studies, artificial neural networks were applied to both operational and design variables of ramjet and dual-mode ramjet/scramjet engines to enable a comprehensive exploration of the design space. The resulting machine learning models were trained to predict and represent the propulsive performance of these engines with improved computational efficiency (Cakir et al., 2023; A. Ispir et al., 2022). Furthermore, efforts were made to enhance the capabilities of DARE, including the addition of a fuel-air mixing model in the combustor. This was achieved by modeling the mixing efficiency as a function of fuel injector configuration parameters along the scramjet propulsion system duct axis, using machine learning applied to a CFD database (Ali C. Ispir et al., 2023).

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References

Bauer, R. (1966). A hypersonic ramjet analysis with premixed fuel combustion. In *2$\hat{}nd$ propulsion joint specialist conference*. https://doi.org/10.2514/6.1966-648

Bhatia, R., & Sirignano, W. (1990). A one-dimensional model of ramjet combustion instability. In *28th aerospace sciences meeting*. https://doi.org/10.2514/6.1990-271

Bolender, M. A., & Doman, D. B. (2007). Nonlinear longitudinal dynamical model of an air-breathing hypersonic vehicle. *Journal of Spacecraft and Rockets*, *44*(2), 374–387. https://doi.org/10.2514/1.23370

Cakir, B. O., & Ispir, A. C. (2025). Reduced order design space analysis and operational mapping for ramjet engines. *Aerospace Science and Technology*, *157*, 109811. https://doi.org/10.1016/j.ast.2024.109811

Cakir, B. O., Ispir, A. C., Civerra, F., & Saracoglu, B. H. (2023). Reduced order design space analysis of for ramjet engines with data mining techniques. In *AIAA SCITECH 2023 forum*. https://doi.org/10.2514/6.2023-2017

Cakir, B. O., Ispir, A. C., & Saracoglu, B. H. (2022). Reduced order design and investigation of intakes for high speed propulsion systems. *Acta Astronautica*, *199*, 259–276. https://doi.org/10.1016/j.actaastro.2022.07.037

Chavez, F. R., & Schmidt, D. K. (1994). Analytical aeropropulsive-aeroelastic hypersonic-vehicle model with dynamic analysis. *Journal of Guidance, Control, and Dynamics*, *17*(6), 1308–1319. https://doi.org/10.2514/3.21349

Curran, E. T., & Murthy, S. N. B. (2000). *Scramjet propulsion*. American Institute of Aeronautics; Astronautics. ISBN: 9781563473227

Edelman, R. B., Harsha, P. T., & Schmotolocha, S. N. (1981). Modeling techniques for the analysis of ramjet combustion processes. *AIAA Journal*, *19*(5), 601–609. https://doi.org/10.2514/3.50982

Gawehn, T., Selig, M. S., & Ansell, P. J. (2020). SUAVE: An open-source environment for multi-fidelity conceptual vehicle design. *Journal of Aerospace Information Systems*, *17*(12), 641–657.

Gray, J., & Hwang, J. T. (2020). *PyCycle: A thermodynamic cycle analysis tool for NPSS-like engine modeling in OpenMDAO*. NASA Glenn Research Center; https://github.com/OpenMDAO/pycycle.

Gray, J., Hwang, J. T., Martins, J. R. R. A., Moore, K. T., & Naylor, B. A. (2019). OpenMDAO: An open-source framework for multidisciplinary design, analysis, and optimization. *Structural and Multidisciplinary Optimization*, *59*(4), 1075–1104.

Harsha, P., & Edelman, R. (1978). Application of modular modeling to ramjet performance prediction. In *14th joint propulsion conference*. https://doi.org/10.2514/6.1978-944

Hindmarsh, A. C., Brown, P. N., Grant, K. E., Lee, S. L., Serban, R., Shumaker, D. E., & Woodward, C. S. (2005). SUNDIALS: Suite of nonlinear and differential/algebraic equation solvers. *ACM Trans. Math. Softw.*, *31*(3), 363–396. https://doi.org/10.1145/1089014.1089020

Ispir, Ali Can, Cakir, B. O., & Saracoglu, B. H. (2024). Design space investigations of scramjet engines using reduced-order modeling. *Acta Astronautica*, *217*, 349–362. https://doi.org/10.1016/j.actaastro.2024.01.036

Ispir, Ali C., Zdybał, K., Saracoglu, B. H., Magin, T., Parente, A., & Coussement, A. (2023). Reduced-order modeling of supersonic fuel–air mixing in a multi-strut injection scramjet engine using machine learning techniques. *Acta Astronautica*, *202*, 564–584. https://doi.org/10.1016/j.actaastro.2022.11.013

Ispir, A., Cakir, B., & Saracoglu, B. (2022). Design space exploration for a scramjet engine by using data mining and low-fidelity design techniques. In *HiSST: 2nd international conference on high-speed vehicle science & technology*.

Küchemann, D. (2012). *The aerodynamic design of aircraft*. American Institute of Aeronautics; Astronautics, Incorporated. ISBN: 9781600869228

Lytle, J. K. (2000). *The numerical propulsion system simulation: A multidisciplinary design system for aerospace vehicles* (NASA TM-2000-209915). NASA Glenn Research Center.

NASA Glenn Research Center. (2024). *Toolbox for the modeling and analysis of thermodynamic systems (t-MATS)*. https://github.com/nasa/T-MATS.

Riggins, D., & Clinton, C. (1995). Thrust modeling for hypersonic engines. In *International aerospace planes and hypersonics technologies*. https://doi.org/10.2514/6.1995-6081

Torrez, S. M., Dalle, D. J., & Driscoll, J. F. (2013). New method for computing performance of choked reacting flows and ram-to-scram transition. *Journal of Propulsion and Power*, *29*(2), 433–445. https://doi.org/10.2514/1.B34496

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

Zhang, D., Feng, Y., Zhang, S., Qin, J., Cheng, K., Bao, W., & Yu, D. (2016). Quasi-one-dimensional model of scramjet combustor coupled with regenerative cooling. *Journal of Propulsion and Power*, *32*(3), 687–697. https://doi.org/10.2514/1.B35887