

¹ DARE: A MATLAB Toolbox for Design and Analysis ² of Ramjet/scramjet Engines

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⁶ 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.

²² 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

42 (Torrez et al., 2013).

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

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

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

81 Research application

82 DARE has been primarily used within the EU funded Stratofly and More&Less projects to
83 focus on the design, analysis, and optimization of ramjet and dual-mode ramjet/scramjet
84 propulsion systems, which are critical for supersonic and hypersonic vehicles operating beyond
85 Mach 3 [Zhang et al. (2016); Cakir et al. (2022)]. DARE provided assessments for flow
86 development, combustion performance, and overall propulsive characteristics such as thrust, fuel
87 consumption, specific impulse, and efficiency are analyzed under varying conditions, including
88 flight Mach number, altitude, intake geometry, and fuel-air equivalence ratio (Cakir & Ispir,
89 2025; Ali Can Ispir et al., 2024). Sensitivity analyses, including Shapley Additive Explanations
90 (SHAP) and feature importance studies, identify key design parameters influencing engine
91 performance. These methodologies are demonstrated to efficiently explore the design space,
92 generate performance maps, and quantify propulsion system feasibility for high-supersonic

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

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