Investigation on the performance and feasibility of RBCC-based access-to-space via multi-objective design optimization

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1. Introduction

The advent of fully reusable launch vehicles is yet to be realized, but it is conceived to be a promising approach to disrupting ground-to-space transport solutions by enabling economical and flexible space operations, while presenting a formidable multi-disciplinary design challenge. TSTO (two-stage-to-orbit) systems consisting of winged boosters and orbiter vehicles, powered by RBCC (rocket-based combined cycle) propulsion comprising of airbreathing components, i.e., ramjets and scramjets (supersonic combustion ramjets), removes oxidizer requirements onboard a reusable launch vehicle (RLV), effectively increasing payload mass owing to a higher effective specific impulse, while simultaneously achieving reusability and reducing total mass [1,2]. The engine operates continuously over four flight modes from take-off to engine burnout, that is, the ejector jet, ramjet, scramjet and rocket modes whereby the first stage is a booster, comprising of airbreathing components and a rocket engine, which is jettisoned after delivering sufficient acceleration to an orbiter vehicle, fitted with rocket engines to continue spaceflight. However, RLVs inherently pose a considerable challenge for the design and control of the vehicle due primarily to the need to integrate the propulsion system into the airframe, which must be designed in such a way to fulfill various constraints including the needs to maintain dynamic pressure, acceleration, and aerothermal heating within acceptable levels in consideration of structural, material, and safety aspects, respectively [3]. Such complexities have represented a challenge to assess the true potential of RBCC engine concepts for viable space transport in traditional approaches which cannot account for overall vehicle and engine characteristics simultaneously.

By optimally transitioning through various operating modes, RBCC propulsion systems are expected to produce high trajectory-averaged specific impulse during ascension, resulting in lower propellant mass fractions and lighter gross weight vehicles for a given mission, as compared to traditional rocket engines [5]. One such RBCC-based TSTO prototype has been under development at Japan Aerospace Exploration Agency (JAXA) [6]. The concept operates by successively transitioning through modes, including the ejector (take-off to approximately Mach 3), ramjet (Mach 3–7), scramjet (Mach 7–11), and rocket. Fig. 1 shows a
prototype propulsion system incorporating the four flight modes designed by JAXA.

Additionally, two airframe designs for an orbiter vehicle are applicable both with respective advantages and disadvantages, shown in Fig. 2, namely NAL 0th and WaveRider. Slender bodies such as the NAL 0th are generally advantageous in reducing aerodynamic drag at supersonic and hypersonic speeds, whereas blunt bodies such as WaveRider offer advantages in aero thermal aspects by mitigating the thermal load. To seek the desirable balance to combine the advantages of both configurations, a hybrid version is possible but requires design optimization to determine the desirable size and configuration. Detailed consideration of such combined configurations would essentially require careful treatment of aerodynamic data obtained from numerical simulations and wind tunnel tests.

Owing to the complex characteristics and interactions of aerodynamics and propulsion systems inherent to the problem at hand, conventional single objective design optimization approaches are unlikely to represent an insightful measure of the performance behavior. Multi-objective design optimization (MDO) therefore offers an opportunity to produce crucial insights into the design and feasibility of RBCC-powered space transport systems.

A preceding optimization study investigated the feasibility and major design factors primarily focusing on the configuration and control of the first stage of the TSTO system with RBCC propulsion, by preliminarily applying evolutionary algorithms coupled with pseudo-spectral methods for advanced optimization [7]. This study was then initiated in a further study in order to gain insight into the design of complete reusable RBCC-based TSTO space launch systems, including the orbiter, in a further refined design approach, coupling multi-objective design optimization by surrogate-assisted evolutionary algorithms and trajectory/control optimization by pseudo-spectral methods [3]. However, several limitations of these studies including simplified setup, disregarding crucial elements such as Earth rotation and considerable oscillations observed in the results, rendered it necessary to reevaluate RBCC-based TSTO by taking another comprehensive MDO approach, to allow for further verification and comparison of these results.

The present research has undertaken two MDO approaches to generate insights into the design of complete TSTO space transportation systems including the orbiter by coupling evolutionary algorithms for population-based optimization and numerical integration of 3 degrees-of-freedom (3-DOF) equations of motion for vehicle control and dynamics. These studies are conducted by employing evolutionary algorithms, where individuals in the population pool evolve over generations via various genetic operations including selection, recombination, reproduction and mutation. The optimization algorithms assess and rank the individuals in order to effectively determine favorable population members for the next generation [8,9]. On the other hand, the population-based approach inherently incurs considerable computational cost, which could be intensive if the optimization involves large simulations, necessitating an efficient strategy to realize the design study with reasonable time and resources.

The objective of this study is to herewith investigate the feasibility of the RBCC-based access-to-space via MDO to provide useful insights into the necessary requirements. These analyses intend to reveal the expediency of RBCC-based access to space, thus taking a step towards attaining an outlook on RBCC-powered space transportation systems in future. Analyzed, in particular, is the influence of RBCC engine characteristics, especially in terms of the engine performance (e.g., thrust, specific impulse) and operating characteristics (e.g., RBCC engine mode transition, staging), on the overall performance of the TSTO system. The influence of the scaling of the airframe and engine on the system performance and feasibility is also investigated in comparison with TSTO powered only by rocket engines.

2. Approaches

An MDO framework was developed to search the vast design space for feasible initial guesses, employing 3-DOF equations of motion. Optimization is performed in an iterative manner occurring over generations with a certain number of individuals in the population pool, whereby simulated binary crossover and polynomial mutation are used as recombination operators at a given probability with a specified distribution index. Automated within a process chain, the MDO framework seeks to yield and converge on a Pareto-optimal set of solutions for specified performance parameters.

![RBCC propulsion system][4]

![RBCC TSTO airframe configurations][4]
Two MDO analyses were conducted with variation of the design to gain physical insight into the characteristics and performance of the RBCC-based TSTO system, while another MDO analysis was performed with a rocket-only and rocket-only MDO system for a comparative study. For both RBCC-based and rocket-only MDO studies, the orbiter’s final altitude and velocity were simultaneously maximized while maximum dynamic pressure was minimized with variable apoapsis, periastron, and inclination targets. In the second part of the RBCC-based MDO study, the orbiter’s final apoapsis and periastron were maximized while eccentricity and maximum dynamic pressure were minimized simultaneously. The final state refers to the moment of the second stage burnout, after which no further acceleration is applied to the orbiter.

2.1. Modeling

For propulsion and aerodynamic characteristics, the same data as those used in previous studies [3,7] were employed so as to ensure coherence, while a set of similar but altered parameters was implemented for the decision variables. The modeling primarily relies on the data obtained through various methods and often interpolated, as outlined below.

2.1.1. Aerodynamics

The aerodynamics data is based on the characteristics of the NAL 0th and the WaveRider configurations (see Table 1 for the vehicle specifications). The aerodynamic coefficients $C_l$ and $C_D$ for these configurations are calculated using the database pre-obtained from CFD simulations for the WaveRider configuration [7], while these coefficients are based on wind tunnel data from low speeds to Mach 7 and derived from the Newtonian theory over Mach 7 for the NAL 0th configuration as shown in Fig. 3 [10]. The interactions of the engines on the system’s aerodynamics are not taken into account. Both the NAL 0th and WaveRider configurations are considered for the first booster stage, while the WaveRider is solely assumed for the orbiter. This is achieved by integrating and interpolating both datasets to devise an optimum between both approaches (this is later defined as the blending factor $\lambda$).

2.1.2. Propulsion

This section consists of two parts, i.e., RBCC propulsion and the rocket-only propulsion, as the propulsion is the main difference for the comparative study between both systems.

2.1.2.1. RBCC propulsion. The data for the RBCC propulsion is given by a conceptual model explored by JAXA [6]. This includes the RBCC data for the ejector mode, ramjet, scramjet and rocket, with hydrogen used as the fuel. These sets of data are set up in distinct phases to simulate transitions from one phase to the next, as shown schematically in Fig. 4. The ejector mode operates from $M_0$ to $M_1$ in a Mach number range from 0 to 4. The ramjet operates from $M_1$ to $M_2$ in a Mach number range from 2 to 8, and the scramjet from $M_2$ to $M_3$ in a range from Mach 4 to 12, followed by rocket operation until the first stage separation. These variations are implemented within trajectory simulation via phase end conditions such that once the designated Mach number (within the above ranges) is reached in the booster’s trajectory, the phase ends and transitions to the next mode.

The baseline thrust $T_b$ and specific impulse $I_{sp}$ for the booster stage are calculated by interpolating the performance estimated in separate analytical evaluations [1], as shown in Fig. 5 for a dynamic pressure of 10, 30, and 50 kPa and changeover Mach numbers of $M_1 = 3$, $M_2 = 6$, and $M_3 = 10$. For the orbiter, three rockets of constant thrust ($T_r = 240 \text{kN} \times 3$) and specific impulse ($I_{sp} = 320 \text{s}$) are used to power the vehicle.

2.1.2.2. Rocket propulsion (for booster). For the analysis of the rocket propelled winged booster, the basis for the thrust and specific impulse values was taken from the solid rocket boosters of JAXA’s H-IIB rocket, listed in Table 2.

Fig. 6 presents the schematic for the new simulation, this time only requiring two phases overall, one for each stage. The first stage includes the H-IIB booster propulsion, whereas the second stage still continues with the same orbiter propulsion characteristics as used for the RBCC-based TSTO. However, in terms of trajectory simulation, a total of three phases are used for the first booster stage so as to accommodate more angle of attack variables, as described in Section 2.2.3.

2.1.3. Configurations

There are two basic vehicle stages, namely the booster stage and the orbiter. These components have an initial structural and propellant mass, calculated from the initial 755.2-ton baseline. From here, the values for the structural and propellant mass are assigned by the MDO algorithm, dependent on the scaling parameters employed as the decision variables.

All these data sets and values need to be combined to be used in trajectory simulation, with the propulsion and aerodynamic data assigned to each of the aforementioned vehicle stages. Each of the above propulsion modes is then assigned a distinct phase, which ends upon reaching a certain Mach number (as determined by the MDO algorithm, within the transition ranges) or if the propellant mass assigned for each stage runs out. The angle of attack $\alpha$ and throttle values are assigned in a separate linear profile within each phase (these values are also determined by the MDO within a given range). Throttling is only applied to the booster stage, while the angle of attack is variable throughout all phases, defined by aerodynamic angles, which, apart from the last, aims toward a target orbit that is defined by Euler angles. The final apoaopis, periastron and default pitch values are also assigned via the MDO. An initial take-off velocity of 210 m/s at an angle of attack of $\alpha = 3^\circ$ is applied to all trajectories. All constraints and boundary conditions for the variables given by the evolutionary algorithm are presented in Section 2.2.3.

2.2. Multi-objective design optimization

This section describes the approaches used for the MDO process, which was conducted in two phases; (1) 3-objective optimization aiming to maximize the final velocity and final altitude while minimizing dynamic pressure was first conducted in order to achieve the best initial guess; and then (2) 4-objective optimization aiming to maximize the apoapopis and periastron while minimizing eccentricity and dynamic pressure was performed, based on the solutions obtained in the first phase. The dynamic pressure was used as one of the objective functions in both phases because it was unable to be constrained within trajectory simulation using ASTOS.

2.2.1. Algorithm

The MDO was conducted in a closed loop iterative process coupling the evolutionary algorithm [12,13] into trajectory simulation or optimization. It is a population-based approach where the candidate solutions in the population pool evolve over generations. A population size of $N = 96$ is used in this study to be evolved over 40 generations for the initial MDO study employing trajectory simulation. Recombination operators are applied to the previous generation’s decision variable values to create offspring. A simulated binary crossover and polynomial mutation are used as recombination operators at a given probability.
(1.0 and 0.1, respectively, in this study) with a specified distribution index (10 and 20, respectively). Surrogate modeling is commissioned to estimate the possible values of the objectives in an inexpensive manner, imitating the behavior of the solutions from the trajectory simulations by appropriate mathematical functions. Various surrogate models are employed to best predict the output values for given input values with a minimum error threshold satisfied, as discussed below. The surrogate models are constructed by using a fraction (90% in this study) of the actual solutions calculated from the trajectory simulations to prevent overfitting, whereas the remainder (10%) of the evaluated solutions are used to assess the performance of the surrogate models. Multiple surrogate models are considered and evaluated; quadratic response surface model; artificial neural network (ANN) models including the radial basis function network; and Kriging model based on Gaussian process regression. The mean squared error (MSE) in the actual and predicted values of the objectives is calculated for the remaining (10%) solutions and used as the measure to validate the surrogate models. Prediction from the best surrogate model with a minimum error is adopted to replace the simulation analysis, only if; the MSE is within a threshold value of 5% for all objective functions, which has been set to effectively allow for reasonable investigation by striking a balance between prediction accuracy and computational cost; and the distance to the closest point in the archive is smaller than 5%. Upon completion of the MDO process, the non-dominated, optimum individuals are identified, converging to constitute a Pareto optimal front.

2.2.2. Scaling
Scaling parameters are introduced for the length, thrust, and specific impulse in this study, aiming to explore the technological requirements that are necessitated in order to fulfill the intended mission objectives, as compared to the current state of the art (baseline technology). The reference surface area and mass are proportional to the square and cube of the length scaling factor, i.e., $S = S_0 L_{\text{scale}}^2$ and $m = m_0 L_{\text{scale}}^3$. The thrust is scaled by the thrust scaling factor as well as the square of the length scaling factor as $T = T_0 T_{\text{scale}}^2 L_{\text{scale}}^2$ assuming the nozzle area and air intake area (for airbreathing propulsion) are proportional to the square of the length. The specific impulse is scaled as $I_{sp} = I_{sp0} I_{\text{scale}}$, which is applied only to the ramjet mode at the booster stage (no scaling applied to the rocket and scramjet modes, assuming use of the current technologies for these modes) and to the

\begin{center}
\begin{tabular}{l|l|l|l|l|l|l}
 & $M_0$ & Ejector & $M_1$ & Ramjet & $M_2$ & Scramjet & $M_3$ \\
\hline
\hline
Booster – Stage One & & (database) & & (database) & & (database) & \hline
\hline
Orbiter – Stage Two & & Rocket & & & & & Rocket
\end{tabular}
\end{center}

\begin{center}
$M_0\quad Ejector$ (database)\quad $M_1\quad Ramjet$ (database)\quad $M_2\quad Scramjet$ (database)\quad $M_3\quad Rocket$
\end{center}

\begin{center}
$T_0 = 3,136\text{ kN} \times 3$
\end{center}

\begin{center}
$T_0 = 240\text{ kN} \times 3$
\end{center}

\begin{center}
$L_{\text{scale}} = 278.3\text{ s}$
\end{center}

\begin{center}
$L_{\text{scale}} = 320\text{ s}$
\end{center}

Fig. 4. Schematic of propulsion phases and stages for RBCC-based TSTO.
rocket engines at the orbiter stage. The length scaling factor of the booster is to be greater than half that of the orbiter so as to ensure larger booster length than orbiter (the original length is 40 m and 20 m, respectively), as imposed as a constraint of the global optimization problem. The other scaling factors are allowed to vary within reasonable ranges to enable the investigation of technological requirements via flexible search, except that the specific impulse of the orbiter is allowed to vary with rather narrow margins, i.e., \(0.9 \leq I_0_{\text{scale}} \leq 1.1\), in consideration of the maturity of the rocket engine technology [3].

2.2.3. Setups

2.2.3.1. RBCC MDO. Tables 3 and 4 summarize the decision variables, objective functions and constraints in effect for the two RBCC MDO studies, differing in objective functions.

2.2.3.2. Rocket-only MDO. Table 5 summarizes the decision variables, objective functions and constraints in effect for the rocket-only MDO study. Angle of attack variables are in place after the booster operation for 20 and 50 s, linearly interpolated between the values at these moments. This study also includes the exit areas of the nozzle for both

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Fig. 5. Baseline thrust and specific impulse variations with respect to Mach number and angle of attack for the dynamic pressure of 10, 30, and 50 kPa [6].

Table 2

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total booster thrust [kN]</td>
<td>9220</td>
</tr>
<tr>
<td>Specific impulse [s]</td>
<td>283.6</td>
</tr>
</tbody>
</table>

the booster and orbiter as decision variables, while the thrust scaling was constrained to 1.5 and no specific impulse scaling was considered for the solid rockets.

### 2.3. Trajectory

#### 2.3.1. Methodology

A commercial solver ASTOS (Aerospace Trajectory Optimization Software) by ASTOS Solutions Inc [14], was utilized for trajectory simulation and optimization. It was incorporated into the MDO framework to simulate the approximate trajectory in Part 1 of the RBCC MDO, which was then used as an initial guess for subsequent trajectory optimization in Part 2. Fig. 7 schematically presents the process chain of the overall framework.

The initial guess was initialized from the control law using the grid automatically generated for collocation. Colloc Hermite integration was applied for the booster stage, a fourth-order collocation method approximating the control time history by linear functions and the state time history by using Hermite-Simpson polynomials. The Runge-Kutta 4/5th-order method was employed as the integration method under connected phases.

ASTOS has various options for trajectory optimization, depending on time and accuracy of desired computation. In particular, CAMTOS is an advanced hybrid optimization tool allowing both collocation and
multiple shooting methods, solving the underlying optimal control problem from a discretized point of view. The default transcription method of CAMTOS (Collocation and Multiple Shooting Trajectory Optimization Software) [15,16] method was used for both stages, along with the default WORHP NLP solver [14].

2.3.2. Optimization

Two individuals (design points) were selected from the Pareto optimal front that resulted from the RBCC MDO Part 2. Trajectory optimization was performed for these design points by using the initial conditions from the MDO in order to identify the optimal flight path and control represented by the three control parameters, namely the pitch (angle of attack) $\alpha$, bank angle $\beta$ and throttling $\tau$ in the 3-DOF model, with further constraints imposed (Table 6).

The flight path angle for the booster stage is restricted to $-5^\circ \leq \alpha \leq 30^\circ$ in consideration of the airbreathing engine operation, whereas it can vary between $-45^\circ$ and $45^\circ$ in the orbiter (rocket) phase. These path constraints, as well as the dynamic pressure and acceleration, are set practically in accordance to operational requirements and safety of passengers and/or payload.

3. Results

3.1. RBCC MDO part 1

The first MDO study was performed by evolving a population of 96 individuals over 40 generations, aiming to maximize the final altitude and magnitude of velocity while minimizing the maximum dynamic pressure simultaneously. Of the 3,840 design possibilities evaluated, 96 were identified as non-dominated hence optimal with respect to at least one objective, constituting a Pareto optimal front, as denoted by the blue circles in Fig. 8. The last objective, i.e., minimization of the dynamic pressure, was imposed so as to find suitable solutions that can satisfy the bounds of 60,000 Pa. As not all solutions were feasible, Fig. 8 (b) provides a summary of the 22 design solutions whose dynamic pressure was less than 70,000 Pa, while achieving optimal performance with respect to altitude and/or velocity.

The design point denoted by an orange circle in Fig. 8 (b) was selected due to its highest potential in reaching orbit by accomplishing the best apoapsis and periapsis among all non-dominated peers. Therefore, this result was used as the basis for the first trajectory optimization, denoted as Design Point 1, where further details of this design can be found in Tables 7 and 8 and Fig. 9. To further understand the potential of the RBCC systems, a second Design Point was selected for additional optimization (albeit not part of the non-dominated solutions), seeking possibilities to dispense with thrust and specific impulse scaling, aiming to achieve the orbit with the current day RBCC technology. This second point is denoted as Design Point 2 and further details are shown in Tables 9 and 10 and Fig. 10. For both Figs. 9 and 10 the trajectories are the initial guess, where a linear relationship was assumed for the angle of attack and throttling, with the bank angle neglected. The final trajectories are shown and discussed in Section 3.5. It is also noteworthy to reiterate that the magnitude of all variables displayed in Tables 7 and 9 were attributed by the MDO algorithm for the trajectory simulation to achieve maximum altitude and velocity, while minimizing maximum dynamic pressure.

3.1.1. Characteristics of optimal designs

The parallel coordinate plot [17] is displayed for all non-dominated hence optimal designs in Fig. 11 for all objective functions and decision variables, with their upper and lower bounds set at the top and bottom, respectively, in a normalized manner. It indicates several interesting characteristics and trends commonly observed among the non-dominated designs.

The blending factor lies in two distinct ranges, i.e., $\lambda = 0.1–0.35$ and $\lambda = 0.7–0.85$, suggesting that shapes close to either a quarter NAL 0th or a quarter WaveRider have been preferred for the aerodynamic characteristics of the optimal designs. Of these types, those with a lower blending factor $\lambda$ of 0.1–0.35 hence with greater NAL 0th proportion experienced a lower dynamic pressure than those resembling a WaveRider with $\lambda$ of 0.7–0.85. Virtually all optimal designs have experienced hence made use of all four RBCC engine modes, according to the distributions of the changeover Mach numbers $M_1$, $M_2$, and $M_3$ within their bounds. The fuel mass ratio ($\mu_0$) was large for most non-dominated designs for both the booster and the orbiter, indicating the need to carry large proportion of fuel, but minimizing the total weight (as per the cube of the length scaling) tended to aid in achieving maximum final velocity and altitude.

As for scaling, all optimal designs are characterized by the length scaling ($L_{scale}$) for the booster being greater than one, mostly in the range between 1.2 and 1.4, whereas $L_{scale}$ for the orbiter mostly ranges between 0.5 and 0.6, indicative of the need to upscale the booster and downscale the orbiter from their baseline dimensions. The values of the thrust scaling ($T_{scale}$) for the booster are typically about 1.4, thus requiring approximately 40% increase in thrust for the booster, while it is interesting to note that $T_{scale}$ is 1.0 for a few booster designs that

Table 6

<table>
<thead>
<tr>
<th>Trajectory optimization constraints</th>
<th>Range or Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max acceleration (booster) $[g]$</td>
<td>3</td>
</tr>
<tr>
<td>Angle of attack (booster) $[^\circ]$</td>
<td>$-5$ \to 30</td>
</tr>
<tr>
<td>Angle of attack (orbiter) $[^\circ]$</td>
<td>$-45$ \to 45</td>
</tr>
<tr>
<td>Bank angle $[^\circ]$</td>
<td>$-45$ \to 45</td>
</tr>
<tr>
<td>Dynamic pressure $[\text{Pa}]$</td>
<td>$5000$ \to 60,000</td>
</tr>
<tr>
<td>Launch altitude $[\text{m}]$</td>
<td>169</td>
</tr>
<tr>
<td>Launch flight path angle $[^\circ]$</td>
<td>3</td>
</tr>
<tr>
<td>Launch heading $[^\circ]$</td>
<td>90</td>
</tr>
<tr>
<td>Launch latitude $[^\circ]$</td>
<td>43.3</td>
</tr>
<tr>
<td>Launch longitude $[^\circ]$</td>
<td>4.59</td>
</tr>
<tr>
<td>Launch velocity $[\text{m/s}]$</td>
<td>210</td>
</tr>
<tr>
<td>Orbit apogee $[\text{km}]$</td>
<td>$100$ \to 1000</td>
</tr>
<tr>
<td>Orbit inclination $[^\circ]$</td>
<td>28.5</td>
</tr>
<tr>
<td>Orbit perigee $[\text{km}]$</td>
<td>$100$ \to 1000</td>
</tr>
<tr>
<td>$M_1$ from booster to scramjet</td>
<td>2 \to 4</td>
</tr>
<tr>
<td>$M_2$ from scramjet to rocket</td>
<td>8 \to 12</td>
</tr>
</tbody>
</table>

Fig. 7. Schematic representation of the overall process chain.
coincide with minimal length scaling. For the orbiter, little scaling was generally maintained at about 15–20° steadily for the booster stage, apart from the initial value, which was required for the vehicle to ascend to a higher altitude, where lower atmospheric density necessitated higher velocity to produce sufficient lift without exceeding the dynamic pressure limit.

### Table 7

**Specifications of design point 1.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value [Parameter Value]</th>
<th>Value [Parameter Value]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final altitude</td>
<td>241.8 km</td>
<td>Throttle of ejector (final) 0.505</td>
</tr>
<tr>
<td>Final velocity</td>
<td>12.9 km/s</td>
<td>Throttle of ramjet (initial) 0.997</td>
</tr>
<tr>
<td>Max dynamic pressure</td>
<td>65.268 Pa</td>
<td>Throttle of ramjet (final) 0.892</td>
</tr>
<tr>
<td>Blending factor $\lambda$</td>
<td>0.248</td>
<td>Throttle of scramjet (final) 0.415</td>
</tr>
<tr>
<td>Length scale of booster</td>
<td>1.35</td>
<td>Throttle of scramjet (final) 0.478</td>
</tr>
<tr>
<td>Thrust scale of booster $T_0$</td>
<td>1.41</td>
<td>AOA for ejector (initial) 21.1°</td>
</tr>
<tr>
<td>$T_0$ scale of booster</td>
<td>1.15</td>
<td>AOA at transition to ramjet 17.2°</td>
</tr>
<tr>
<td>Length scale of orbiter</td>
<td>0.512</td>
<td>AOA at transition to scramjet 15.7°</td>
</tr>
<tr>
<td>Thrust scale of orbiter</td>
<td>1.03</td>
<td>AOA at transition to rocket 19.0°</td>
</tr>
<tr>
<td>$T_0$ scale of orbiter $T_0$</td>
<td>1.09</td>
<td>AOA for rocket booster 27.0°</td>
</tr>
<tr>
<td>$M_t$ from ejector to scramjet</td>
<td>3.85</td>
<td>Orbiter final pitch angle 10.3°</td>
</tr>
<tr>
<td>$M_t$ from scramjet to rocket</td>
<td>4.84</td>
<td>Target apoapsis 1028.8 km</td>
</tr>
<tr>
<td>$M_t$ from scramjet to rocket</td>
<td>9.78</td>
<td>Target orbit inclination 1.06°</td>
</tr>
<tr>
<td>Booster total mass ratio</td>
<td>0.888</td>
<td>Target periaxis 797.6 km</td>
</tr>
<tr>
<td>Booster fuel mass ratio</td>
<td>0.896</td>
<td>Total mass baseline value 797.149 kg</td>
</tr>
<tr>
<td>Orbiter fuel mass ratio</td>
<td>0.899</td>
<td>Reference area booster 236.1 m²</td>
</tr>
<tr>
<td>Throttle of ejector (initial)</td>
<td>0.849</td>
<td>Reference area orbiter baseline 157.4 m²</td>
</tr>
</tbody>
</table>

### Table 8

**Sizing and mass summary of Design Point 1.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Booster [Parameter Value]</th>
<th>Orbiter [Parameter Value]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall length $l_0$ [m]</td>
<td>54</td>
<td>10.2</td>
</tr>
<tr>
<td>Reference surface area $S_0$ [m²]</td>
<td>381</td>
<td>43.4</td>
</tr>
<tr>
<td>Total mass $m_0$ [ton]</td>
<td>1936</td>
<td></td>
</tr>
<tr>
<td>Mass [ton]</td>
<td>1742</td>
<td>194</td>
</tr>
<tr>
<td>Fuel Mass [ton]</td>
<td>1561</td>
<td>174</td>
</tr>
</tbody>
</table>

3.1.2. Sensitivity analysis

Variance-based global sensitivity analysis was performed to investigate the influence of the decision variables on the objective and functions, based on the surrogate models with the best prediction accuracy as of the final generation. The minimum errors from surrogate prediction using the response surface model were 3.0% and 1.8% for the final altitude and final velocity, respectively, and 9.0% for the maximum dynamic pressure. Evaluation was made using 10,000 sample data points represented by Sobol quasi-random numbers within the decision variable ranges \[18,19\].

Figs. 12–14 display the influence that (a) scaling factors, (b) Mach number and (c) attitude control variables had on the final altitude, velocity, and maximum dynamic pressure, respectively. The charts present the first-order sensitivity indices $S_i$ (inner ring) and total-effect indices $S_{ei}$ (outer ring), which represent the main and overall effects, respectively, of the input parameters (decision variables) on the three objective functions (output parameters).

Fig. 12 (a) indicates that the final altitude is largely affected by the booster length scaling and least by the specific impulse scaling of the booster, as compared to all other scaling parameters, with the specific impulse and thrust of the orbiter exerting secondary influence. The changeover Mach numbers all had similar total effects on the final altitude, while the changeover Mach number from the scramjet to rocket $M_3$ was found to have the largest first-order impact, as seen in Fig. 12 (b). Fig. 12 (c) shows that the final pitch angle of the orbiter had the greatest influence on the final altitude among all attitude control parameters. These highlight the essential role played by the orbiter parameters in achieving higher maximum altitude.

Fig. 13 (a) indicates that the final velocity is again predominantly influenced by the booster length scaling and least by the specific impulse scaling of the booster, as compared to all other scaling parameters, with the thrust scaling of the booster and orbiter having secondary influence. All three changeover Mach numbers had comparable effects on the final velocity in terms of both first-order and total-effect indices, while the initial changeover from the ejector to the scramjet $M_1$ being a little more influential (Fig. 13b). The final pitch angle of the orbiter again had the greatest impact on the final velocity among all attitude control parameters. These demonstrate the importance of the orbiter parameters in achieving higher maximum velocity as well.

Fig. 14 (a) shows that the thrust scaling of the booster is the most influential on the maximum dynamic pressure, with the booster length scaling having secondary influence. In terms of the changeover Mach
and from ramjet to scramjet mode (AoA3), as seen in Fig. 14(c). These results suggest that optimal combination among the initial thrust, specific impulse, throttling, changeover Mach numbers and angle of attack plays a crucial role in lowering the maximum dynamic pressure, especially in the ejector phase of the booster RBCC, where the vehicle travels through denser atmosphere.

### 3.2. Trajectory optimization

Trajectory optimization was performed for the selected designs from the present MDO study, with guidance by the orbital outcome from the RBCC MDO Part 2 study (discussed later in Section 4.2), by using the solutions identified in these MDO studies as an initial guess for the trajectory. ASTOS Optimization was utilized to optimize the control and trajectory to orbit, with cost functions (objectives) to maximize the apoaiss and periapsis between 100 km and 1000 km, while minimizing the eccentricity, aiming for as circular an orbit as possible.

#### 3.2.1. Design point 1

The time variations of major parameters that characterize the optimum trajectory are displayed for Design Point 1 in Fig. 15. This trajectory utilizes scaling of 1.35 for length, 1.41 for thrust, and 1.15 for specific impulse (speciations of Design Point 1 can be found in Tables 7 and 8). Fig. 16 visualizes the optimized trajectory to the orbit in a three-dimensional manner.

The vehicle reaches the start of the set orbit within 15 min, as seen in Fig. 15 (a). With a starting mass of approximately 1950 tons, the ejector phase lasts for 320 s, before transitioning to the ramjet mode at Mach 4.75 s later, the scramjet phase begins at Mach 5.5 until 690 s into the journey reaching Mach 8.7. The rocket engine then takes over, before the first stage (booster) is separated after 760 s at a speed close to Mach 11. From here, the orbiter fulfills the objective of maximum apoaiss and periapsis and minimum eccentricity, while the booster will re-enter Earth's atmosphere for landing (not considered in the present study). The final altitude of the orbiter is 230 km at Mach 10.5, comparing well to the initial trajectory from MDO for this design point. The apoaiss and periapsis altitudes achieved are 1000 km and 240 km, respectively (Fig. 15 (b)), indicative of successful insertion of the orbiter into the orbit. The inclination of the orbit is 28.5°, as defined in the optimization constraints in Section 2.3.2.

The dynamic pressure is within its maximum bound of 60,000 Pa, peaking during the ejector phase, but also sustained at high levels for the ramjet and scramjet to produce higher thrust and specific impulse for airbreathing propulsion (Fig. 15 (c)). It is also notable that the optimized throttling profile is characterized by either at full throttle or idling at minimum throttle. The angle of attack together with the throttling ensures the vehicle's attitude and enables to sustain within the dynamic pressure constraints, while the bank angle plays a pivotal role in achieving the set orbital inclination of 28.5° (Fig. 15 (d)). Acceleration plotted in Fig. 15 (e) is within a 3 g bound for the complete

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**Table 9**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final altitude</td>
<td>282.3 km</td>
<td>Throttle of ejector (final)</td>
<td>0.498</td>
</tr>
<tr>
<td>Final velocity</td>
<td>12.4 km/s</td>
<td>Throttle of ramjet (initial)</td>
<td>0.924</td>
</tr>
<tr>
<td>Max dynamic pressure</td>
<td>64,527 Pa</td>
<td>Throttle of ramjet (final)</td>
<td>0.655</td>
</tr>
<tr>
<td>Blending factor λ</td>
<td>0.312</td>
<td>Throttle of scramjet</td>
<td>0.382</td>
</tr>
<tr>
<td>Length scale of booster</td>
<td>1.35</td>
<td>Throttle of scramjet (final)</td>
<td>0.418</td>
</tr>
<tr>
<td>Thrust scale of booster</td>
<td>1.39</td>
<td>AoA for ejector (initial)</td>
<td>21.2°</td>
</tr>
<tr>
<td>I&lt;sub&gt;p&lt;/sub&gt; scale of booster</td>
<td>1.44</td>
<td>AoA at transition to ramjet</td>
<td>15.7°</td>
</tr>
<tr>
<td>Length scale of orbiter</td>
<td>0.551</td>
<td>AoA at transition to scramjet</td>
<td>10.5°</td>
</tr>
<tr>
<td>Thrust scale of orbiter</td>
<td>0.98</td>
<td>AoA at transition to rocket</td>
<td>31.8°</td>
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<tr>
<td>I&lt;sub&gt;p&lt;/sub&gt; scale of orbiter</td>
<td>1.09</td>
<td>AoA for rocket booster</td>
<td>24.5°</td>
</tr>
<tr>
<td>M&lt;sub&gt;f&lt;/sub&gt; from ejector to ramjet</td>
<td>2.69</td>
<td>Orbiter final pitch angle</td>
<td>12.4°</td>
</tr>
<tr>
<td>M&lt;sub&gt;f&lt;/sub&gt; from ramjet to scramjet</td>
<td>4.76</td>
<td>Target apoaiss</td>
<td>1062.5 km</td>
</tr>
<tr>
<td>M&lt;sub&gt;f&lt;/sub&gt; from scramjet to rocket</td>
<td>11.0</td>
<td>Target orbit inclination</td>
<td>34.3°</td>
</tr>
<tr>
<td>Booster total mass ratio</td>
<td>0.883</td>
<td>Target periapsis</td>
<td>995.7 km</td>
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<tr>
<td>Booster fuel mass ratio</td>
<td>0.889</td>
<td>Total mass baseline value</td>
<td>802,765 kg</td>
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<td>Orbiter fuel mass ratio</td>
<td>0.895</td>
<td>Reference area booster</td>
<td>235.4 m²</td>
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<tr>
<td>Throttle of ejector (initial)</td>
<td>0.600</td>
<td>Reference area orbiter</td>
<td>153.9 m²</td>
</tr>
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</table>

*Thrust and I<sub>p</sub> scales of the booster have been reduced to 1 for trajectory optimization.*

**Table 10**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Booster</th>
<th>Orbiter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall length l&lt;sub&gt;b&lt;/sub&gt; [m]</td>
<td>54</td>
<td>11.0</td>
</tr>
<tr>
<td>Reference surface area S&lt;sub&gt;b&lt;/sub&gt; [m²]</td>
<td>381</td>
<td>50.1</td>
</tr>
<tr>
<td>Total mass m&lt;sub&gt;b&lt;/sub&gt; [ton]</td>
<td>1975</td>
<td>231</td>
</tr>
<tr>
<td>Mass [ton]</td>
<td>1744</td>
<td>207</td>
</tr>
<tr>
<td>Fuel Mass [ton]</td>
<td>1550</td>
<td></td>
</tr>
</tbody>
</table>

numbers shown in Fig. 14 (b), the initial transition from the ejector to ramjet mode M<sub>f</sub> largely affects the maximum dynamic pressure, so is the transition of the angle of attack from ejector to ramjet mode (AoA<sub>2</sub>) and from ramjet to scramjet mode (AoA<sub>3</sub>), as seen in Fig. 14 (c). These results suggest that optimal combination among the initial thrust, specific impulse, throttling, changeover Mach numbers and angle of attack plays a crucial role in lowering the maximum dynamic pressure, especially in the ejector phase of the booster RBCC, where the vehicle
booster phase, however increases rapidly as the orbiter vehicle approaches the orbit. For passenger and some payload transportation, the acceleration for this part of the trajectory might well need to be attenuated to an acceptable level to make the flight practically viable for manned missions.

3.2.2. Design point 2 (with no thrust and specific impulse scaling)

The trajectory for this outcome was initially optimized with a thrust scaling of 1.0 and a ramjet $I_{sp}$ scaling of 1.09. An optimal trajectory was achieved, where the solution had a final altitude of 195 km at Mach 11.5, reaching an orbit with an apoapsis of 1000 km and periapsis of 180 km, satisfying all constraint bounds. Trajectory optimization was further performed for this configuration, i.e., Design Point 2 with neither thrust scaling nor $I_{sp}$ scaling (this time targeting an apoapsis of 800 km instead of 1000 km used previously). The resultant trajectory and its attributes are presented in Figs. 17 and 18.

The time variations of major characteristic parameters of the optimized trajectory are displayed in Fig. 17 for Design Point 2 without thrust or $I_{sp}$ scaling. The final altitude is 165 km at Mach 12.5, while the apoapsis and periapsis altitudes are 800 km and 155 km, respectively (Fig. 17 (b)), which is again indicative of successful orbital acquisition owing to the RBCC-based TSTO system. The inclination of the orbit was 28.5° to ensure coherence among all trajectory optimizations. The final altitude is lower, compared to the initial trajectory from MDO for this design point (detailed in Tables 9 and 10), but this may well be attributed to the reduced thrust and specific impulse from its original values. However, it is worthwhile to note that reducing thrust and specific impulse led to extension of the ramjet phase, compared to the initial solution of Design Point 2 from trajectory simulation, where the ejector phase was much longer than the ramjet phase (Fig. 10).

The dynamic pressure slightly exceeded its maximum bound of 60,000 Pa momentarily as it peaked at 62,500 Pa during the transition from the ejector to ramjet mode (Fig. 17 (c)). It sustains at its maximum 60,000 Pa bound for the duration of the ramjet and scramjet phases to produce higher thrust and specific impulse by taking advantage of airbreathing propulsion. The optimized throttling profile is also of interest, characterized by full throttle for both the ejector and ramjet phases, initially oscillating between full and minimum throttle for the scramjet phase, followed by minimum throttle maintained for the remainder of the booster’s trajectory.

While this trajectory was not originally deemed fully optimized by ASTOS Optimization, the overall trajectory is of utmost interest, owing to the RBCC-based TSTO system.
to its favorable characteristics including some constraint bounds being minimally exceeded such as dynamic pressure, as well as its capacity of achieving orbit with no upscaling of thrust or specific impulse. It indicates that current-day RBCC propulsion, together with an optimal airframe configuration, can achieve orbital transfer, in terms of the parameters considered in this study.

3.2.3. Comparison of optimized trajectories

It is interesting to note, from the comparison of the results from trajectory optimization, that the optimized trajectory for the Design Point 1 utilized the ejector mode to the maximum, transitioning to ramjet at Mach 4 after 320 s, with a short ramjet phase of 75 s. In comparison, the optimized trajectory for Design Point 2 uses the ejector phase at full throttle over a duration of only 175 s until the vehicle reached Mach 2, i.e., the minimum for ramjet transition, before transitioning through a significant ramjet phase spanning over 570 s. This corroborates that lower thrust values ensure that; the advantage of a higher specific impulse in the form of ramjet operation is utilized in its trajectory to achieve the best possible orbit in terms of altitude in a most efficient manner; or there may possibly be several varieties of trajectories which could be classified as optimal, regardless of thrust scaling. It may also suggest that if higher thrust were available, the optimal route to orbit would be to utilize this additional thrust in escaping earth’s atmosphere, while also minimizing potential gravity losses. However, if this is not the case, that advantages, such as those provided by the ramjet, come into effect more evidently. The scramjet phase is similar in terms of all characteristic parameters for both trajectories. The end of the ramjet and scramjet phases also occurs at a similar Mach number and altitude for both trajectories (slightly higher with Design Point 1, owing to higher thrust), and common trends and characteristics are observed throughout the trajectory.

As for the mass, the optimized results for both Design Points have a starting mass in excess of 1950 tons. According to the investigation, approximately 89% of that is attributed to the fuel, which designate the remaining 11% to that required for structural mass and payload. The time variations of the propellant mass have similar patterns, but there is a considerable difference in the overall duration of the trajectory, indicative of much lower fuel mass flow rate for the Design Point 2 optimized trajectory, where no thrust or specific impulse scaling was applied. On another note, in comparison to the optimized trajectory of Design Point 1, an appreciable advantage of that of Design Point 2 is the acceleration, which is maintained within its 3 g bound for the complete booster phase and increased to 5 g as the orbiter approaches orbit, which is in stark contrast to the trajectory of Design Point 1, which encountered 12 g towards the end of the orbiter stage. The angle of attack, in conjunction with throttling, again ensures the vehicle’s attitude and enables the sustainment of the dynamic pressure within set constraints, while the bank angle plays an important role in achieving the target orbital inclination set at 28.5°.

4. Discussions

4.1. Validation

The MDO studies described in the preceding sections have been conducted, based on the assumptions that the trajectory simulation with ASTOS Modeling using Runge-Kutta integration assuming linear variations for the control variables, i.e., angle of attack and throttling, which are represented by decision variables employed in MDO, should be able to yield trajectories that reasonably perform, as compared to the optimized trajectory from ASTOS Optimization via the pseudo-spectral method, due to the difficulty and computational cost associated with the implementation of trajectory optimization directly into the MDO. This section compares the results from ASTOS Modeling, which calculates the trajectory by numerical integration with linear variations of the control variables, to that from ASTOS Optimization, which optimizes the control parameters, along with the bank angle. A point to reiterate is that the MDO incorporating ASTOS Modeling was performed to primarily maximize the final velocity and final altitude as the objective functions, whereas ASTOS Optimization aimed to achieve
orbit acquisition by optimizing the control variables.

Fig. 19 compares the results from trajectory simulation with those from trajectory optimization for Design Point 1. Reasonable agreement can be found in the trajectories in terms of altitude and mass, underpinning the methodology (comparison is made only for Design Point 1 here, because trajectory simulation and optimization were performed for Design Point 2 with and without scaling of thrust and specific impulse, respectively, rendering direct comparison difficult). This agreement is notable, considering that the modeling result is obtained from the first-order approximation of the control variables, while the optimization actively optimized the control variables, both aiming to minimize acceleration and keep dynamic pressure within its bounds. This can also be seen by the comparing differences on the throttling and angle of attack in Fig. 19 (e) and 19 (f), respectively, which were varied only linearly across each phase in the modeling.

Overall, this result supports the approaches employed in present research including the linear representation of control variables with decision variables in the MDO studies, as well as the use of the results from trajectory simulation via ASTOS Modeling as the initial guess for trajectory optimization via ASTOS Optimization, particularly with respect to the parameters considered as the objective functions (e.g., altitude, mass), which are of primary interest in the MDO studies.

4.2. RBCC MDO part 2

This second MDO study was performed by evolving a population of 96 individuals over 40 generations, aiming to maximize the final apoapsis and periapsis, while minimizing the eccentricity and maximum dynamic pressure simultaneously. Of the 3840 possibilities evaluated, 96 were identified as non-dominated design solutions constituting a Pareto optimal front. However, no feasible design solutions have been found in the non-dominated solutions, as all non-dominated solutions that achieved orbit were characterized by prohibitively high dynamic pressure, whereas those that experienced feasible moderate dynamic pressure were not orbital. Therefore, the complete dataset is analyzed to determine all feasible orbital solutions, that is, all data with a workable dynamic pressure (lower than 100,000 Pa), an apoapsis less than 13,000 km and a periapsis of greater than 100 km. Fig. 20(a) shows all data points and apoapsis and periapsis of the 33 feasible designs, respectively. The fuel mass ratio (\(\mu\)) for the booster mostly ranged between 0.5 and 0.65 while for the orbiter mostly ranged between 0.5 and 0.65

The selected design in this MDO study has optimal eccentricity in accomplishing the best combined apoapsis and periapsis among all non-dominated peers. Therefore, this result was used as a guide for the trajectory optimization performed in Section 3.2. For most feasible designs, only three of the four RBCC propulsion modes were required for the booster, with the propellant often used up during the scramjet phase before transitioning to the rocket mode.

4.3. Rocket-only MDO

An additional MDO study was conducted for TSTO solely relying on rocket engines for both booster and orbiter stages. It was performed by evolving a population of 96 individuals over 40 generations, maximizing the final altitude and magnitude of velocity, while minimizing the maximum dynamic pressure, in coherence with the study of the RBCC propulsion in Section 3.1. Of the 3840 design possibilities evaluated, 96 were identified as non-dominated, hence optimal, with respect to at least one objective (denoted by blue dots in Fig. 21), constituting a Pareto optimal front.

As not all solutions were feasible due to excessive dynamic pressure, Fig. 21 also shows all non-dominated design solutions whose dynamic pressure was less than 100,000 Pa, projected onto the altitude and velocity plane, including a design point which produced a balanced, optimal final outcome with respect to all objectives, and was selected to be explored further in trajectory optimization.

4.3.1. Characteristics of optimal designs

All trajectories were generally characterized by a total flight time of approximately 300–400 s, depending on the amount of propellant onboard. Fig. 22 displays the parallel coordinate plot for the non-dominated hence optimal designs, indicating a distinct counteracting trend between the final altitude and velocity as well as several characteristics commonly observed among the non-dominated designs described below.

The blending factor \(\lambda\) congregated in two distinct ranges, i.e., \(\lambda = 0.15–0.45\) and \(\lambda = 0.81–1.0\), suggesting two types of aerodynamic shapes predominantly influenced by either a NAL 0th or WaveRider design, respectively. The fuel mass ratio (\(\mu\)) was high for most non-dominated designs for both the booster and the orbiter, indicative of the need to carry large proportion of propellant. However, minimizing the total weight (via the cube of the length scaling) tended to aid in achieving higher final velocity and altitude. For scaling, the length scaling (\(L_{scale}\)) for the booster was greater than 1.25 for all optimal designs, while \(L_{scale}\) for the orbiter mostly ranged between 0.5 and 0.65 of the baseline value. The specific impulse scaling (\(I_{scale}\)) for the orbiter lies between 1.08 and 1.1.

Initial angle of attack has a wide spread within its range, primarily lying at \(\alpha_{AoA} = 3°–14°\) and \(33°–45°\). Inspection of the results revealed that those with lower starting angle of attack were commonly characterized by immensely large dynamic pressure but greater final velocity. After 50 s nearly all values for the angle of attack were maintained considerably low, which is assumed to suppress acceleration in the denser parts of the atmosphere with higher dynamic pressure, before acceleration again later to gain altitude.
4.4. Comparison between RBCC-based and rocket-only TSTO

4.4.1. Performance and characteristics

Direct comparison is made between the RBCC-based and rocket-only TSTO in Fig. 23, which compares the average values of each variable of all non-dominated designs from both MDO studies (it only shows the variables which are common to both studies, as only these can be directly compared). The launch point was located at 136°E longitude and 31°S latitude for both MDO studies. Major findings from Fig. 23 are summarized below, focusing on the parameters where distinct differences were observed between the two cases.

The final velocity and dynamic pressure are higher for RBCC-based TSTO, whereas the final altitude is much greater for rocket-only study. This can be attributed to the ascending path of the trajectory; the RBCC-powered booster requires a trajectory immersed within Earth's atmosphere as well as a shallower angle of attack for airbreathing propulsion; the TSTO solely powered by rockets, on the other hand, seeks to escape Earth's atmosphere as quickly as possible for minimal aerodynamic drag. This is also underpinned by the significant differences in the angle of attack especially in early phases of flight represented by
AoA₁ and AoA₃, which indicate steeper ascent for the rocket-powered booster. On the other hand, RBCC-powered TSTO is characterized by higher pitch angle in later phases of ascent, as indicated by larger average values of AoA₂ and AoA₃final to compensate for the smaller altitude gain in the preceding phases due to the flat trajectory, while rocket-powered TSTO behaves in an opposite manner by using rather lower angle of attack at the end of the ascent trajectory after coasting.

Another notable difference is the flight time, where the trajectories for RBCC-powered TSTO typically span 2–5 times longer duration, depending on throttling, than rocket-only TSTO. This is where the RBCC-powered system may be advantageous in terms of flexibility, if winged, as throttling can be controlled, enabling adaptable maneuver and trajectory. Also noteworthy is that the trajectories of TSTO solely using rockets commonly underwent substantially large acceleration levels ranging from 10 g to 20 g for the duration of flight.

4.4.2. Sensitivity analysis

Fig. 24 presents the influence that the decision variables have on the final altitude, final velocity and maximum dynamic pressure for the rocket-only MDO study. The charts present the first-order sensitivity indices Si (inner ring) and total-effect indices STi (outer ring), which represent the main and overall effect, respectively, of the input parameters on the three objective functions.

Fig. 24 (a) shows that AoA₂ (angle of attack after 50 s) and the length scaling of the booster have the largest effect on all three objectives overall, closely followed by the thrust scaling and the fuel mass ratio of the booster. This is indicative of the crucial effects of thrust variables on all objectives for rocket-only TSTO, as they are influenced by both the length and thrust scaling factors. The fuel mass ratio for the booster had the greatest influence on the final altitude, i.e., the less the overall booster structural mass hence the lighter the structure, the higher the final altitude. The angle of attack AoA₃ has by far the greatest impact on the maximum dynamic pressure.

The sensitivity indices for RBCC-based TSTO is represented in Fig. 25 to allow for direct comparison. Considerable difference can be seen in the influential variables for the final altitude and velocity, as compared to the rocket-only TSTO case, while the sensitivity of maximum dynamic pressure shows some degree of similarity. Mass ratios commonly play important roles in both cases, while the final pitch had large influence on the final altitude and velocity in RBCC-based TSTO, in contrast with its little influence observed for rocket-only TSTO.

4.5. Booster configuration

The blending factor λ indicated trends for the booster design favoring toward either the NAL 0th- or WaveRider configuration, as observed in Sections 3.1 and 3.2. Figs. 26 and 27 show the average values of the variables among all non-dominated designs from the RBCC and rocket-only MDO studies, respectively, for two classes of booster design oriented toward either configuration.

Fig. 26 indicates that the WaveRider-oriented booster design is characterized by higher throttling values in comparison with the NAL 0th-oriented design, especially for the end of the ramjet and start of the scramjet phase, necessitated to overcome the larger drag associated with the blunt body design of the WaveRider. However, this increase in throttling subsequently led to higher overall dynamic pressure experienced by the WaveRider-oriented design. On the other hand, higher dynamic pressure, together with the throttling, conduces to better lift characteristics, therefore the WaveRider-oriented design achieved superior final altitude and final velocity in consequence.

Similar trends are identified in Fig. 27 for rocket-only TSTO albeit no throttling. The WaveRider-oriented design entailed higher dynamic pressure and higher velocity, as the rocket-powered TSTO system opted to escape the thick atmosphere as quickly as possible, incurring minimal aerodynamic drag, as discussed in Section 4.4.1. The higher altitude attained by the NAL 0th-oriented design is attributed to its slender shape hence less wave drag, similar to conventional rocket bodies.

It is also interesting to note that AoA₁ is higher for the NAL 0th-oriented design, substantiating its escape of the denser parts of the atmosphere, as compared to the WaveRider-oriented configuration, which takes advantage of its favorable lift characteristics within denser atmosphere. Even though higher dynamic pressure leads to higher drag, the WaveRider-oriented design can still achieve greater final velocity, possibly owing to acceleration during the later ascent phase with relatively flat trajectory. This velocity advantage of the WaveRider-oriented design is significant, because if the WaveRider design were not dominant in this objective, the NAL 0th would be deemed optimal overall. Therefore, to achieve optimal outcomes for all three objectives simultaneously, both the NAL 0th and the WaveRider oriented designs have their own unique advantages.

5. Conclusions

Multi-objective design optimization (MDO) studies based on surrogate-assisted evolutionary algorithms have been conducted for an RBCC-based TSTO system, complemented by an additional MDO study for TSTO powered only by rockets for comparison. Insights have been gained into the influence of the aerodynamic, propulsive and operating characteristics as well as scaling on the overall performance and feasibility of access-to-space via RBCC-based TSTO.

The first MDO study was conducted for RBCC-based TSTO, aiming to maximize the final altitude and final velocity, while minimizing the maximum dynamic pressure simultaneously. The non-dominated, optimal results from this MDO study commonly exhibited shallower trajectories with higher dynamic pressure to take advantage of
airbreathing propulsion. The second MDO study was then performed, aiming to maximize the apoapsis and periapsis altitudes, while minimizing the eccentricity and maximum dynamic pressure simultaneously. Global sensitivity analysis revealed the dominant influence of the length scaling parameters of the orbiter and final pitch angle on the final velocity and final altitude. Scaling of thrust and specific impulse played a secondary but vital role in minimizing the dynamic pressure.

The comparative study with the rocket-only TSTO provided further insights into the key trajectory differences and design parameters, highlighting the advantage of RBCC propulsion in terms of flexibility offered by adaptable throttling and control during longer flight time. The optimal results from the rocket-only MDO study commonly opted for rather prompt ascent through the denser atmosphere, subsequently characterized by much steeper trajectory and higher final altitude, as compared to RBCC-based TSTO. The sensitivity analysis of the rocket-only MDO results concluded that length and thrust scaling of the booster, in conjunction with mass and aerodynamics, played a key part in achieving maximum final altitude and velocity, while minimizing the
Fig. 18. Optimum trajectory to orbit based on Design Point 2 but without thrust or \( I_{sp} \) scaling (launched from 4.53E˚ longitude and 43.6 N˚).

Fig. 19. Comparison of the trajectories between modeling and optimization for Design Point 1.

(a) Attitude

(b) Booster mass

(c) Acceleration

(d) Dynamic pressure

(e) Angle of attack

(f) Throttling

Fig. 19. Comparison of the trajectories between modeling and optimization for Design Point 1.
Fig. 20. Results of RBCC MDO Part 2 (note that in (a) the axes are reversed for the apoapsis and periapsis, and the color indicates the dynamic pressure). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Fig. 21. Results of rocket-only MDO (note that (a) the axes are reversed for the final velocity and altitude; and (b) the blue dots represent non-dominated data, green feasible and red infeasible designs). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Fig. 22. Parallel coordinate plot of non-dominated designs from rocket-only MDO.
maximum dynamic pressure.

Trajectory optimization was performed for two design points selected from the MDO for RBCC-based TSTO to seek the optimal control strategy represented by three control variables, namely angle of attack, bank angle and throttle, with an objective of reaching maximum orbit with minimum eccentricity. The first design point initially achieved orbit by RBCC propulsion with help of thrust and specific impulse scaling, but scaling for thrust and specific impulse was eliminated for second design point so as to further assess the influence of parameters affecting the feasibility of such systems. The result from the second trajectory optimization indicated that orbital acquisition will indeed be possible with current-day RBCC propulsion and airframe integrated technologies.

The present work has produced knowledge that will be of use to further investigate the feasibility of RBCC systems and the possibilities presented by them in future, as well as a methodology that will be applicable in the research and development of RBCC systems. Further investigation considering additional aspects such as aerothermal heating, gravity and aerodynamic losses, realistic combination of aerodynamic configurations as well as potential return paths for the booster will help to further illuminate potential advantages of reusable space transport with airbreathing propulsion, advancing the technology...
towards the realization of next-generation space transport systems.

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References


