



Simple method for performance evaluation of multistage rockets

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ABSTRACT

Multistage rockets are commonly employed to place spacecraft and satellites in their operational orbits. Performance evaluation of multistage rockets is aimed at defining the maximum payload mass at orbit injection, for specified structural, propulsive, and aerodynamic data of the launch vehicle. This work proposes a simple method for a fast performance evaluation of multistage rockets. The technique at hand is based on three steps: (i) the flight-path angle at each stage separation is guessed, (ii) the spacecraft velocity is maximized at the first and second stage separation, and (iii) for the last stage the thrust direction is obtained through the particle swarm optimization technique, in conjunction with the use of the Euler–Lagrange equations and the Pontryagin minimum principle. The coast duration at the second stage separation is optimized as well. The method at hand is extremely simple and easy-to-implement, but nevertheless it proves to be capable of yielding near-optimal ascending trajectories for a multistage launch vehicle with realistic structural, propulsive, and aerodynamic characteristics. The solutions found with the technique under consideration can be employed either for a rapid evaluation of the multistage rocket performance or as guesses for more refined optimization algorithms.

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1. Introduction

Multistage rockets are commonly employed to place spacecraft and satellites in their operational orbits. Performance evaluation of multistage rockets is basically aimed at defining the maximum payload mass that can be inserted in the desired orbit. Usually, if the rocket characteristics are specified, this evaluation is obtained from optimizing the rocket trajectory, i.e., by determining the optimal control law that leads to maximizing the final mass at orbit injection.

In general, the numerical solution of aerospace trajectory optimization problems is not trivial and has been

pursued with different approaches in the past. Indirect methods, such as the gradient-restoration algorithm [1,2] and the shooting method [3], or direct techniques, such as direct collocation [4,5], direct transcription [6,7], and differential inclusion [8,9], are to name a few. However, only a relatively small number of publications are concerned with trajectory optimization of multistage launch vehicles [1,2,10–17,19,20]. Calise et al. [10] and Gath and Calise [11] proposed and applied a hybrid analytic/numerical approach, based on homotopy and starting with the generation of the optimal solution in a vacuum. They adopted the approximate linear gravity model, and the same did Lu and Pan [12] and Lu et al. [13], who applied a multiple-shooting method to optimizing exoatmospheric trajectories composed of two powered phases separated by a coast arc. Weigel and Well [14] used a similar indirect, multiple-shooting approach to analyze and optimize the ascent trajectories of two launch

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vehicles with splash-down constraints. Miele [2] developed and applied the indirect multiple-subarc gradient restoration algorithm to optimizing the two-dimensional ascending trajectory of a three-stage rocket in the presence of dynamical and control constraints. The previously cited works [2,10–14] make use of indirect algorithms and require a considerable deal of effort for deriving the analytical conditions for optimality and for the subsequent programming and debugging. Furthermore, these methods can suffer from a slow rate of convergence and an excessive dependence on the starting guess. This difficulty has been occasionally circumvented through homotopy [10,11,15], but this adds further complexity to the solution process. Other papers deal with direct numerical techniques applied to multistage rocket trajectory optimization. Roh and Kim [16] used a collocation method for optimizing the performance of a four-stage rocket, whose two-dimensional trajectory was assumed to be composed of three thrust phases and a coast arc of specified duration. Collocation was also employed by Jamilnia and Naghash [17], with the additional task of determining the optimal staging, and by Martinon et al. [15], for the purpose of validating the numerical results attained through indirect shooting. This latter paper refers to the Ariane V launch vehicle and is specifically devoted to investigating singular arcs. Direct methods convert the optimal control problem into a nonlinear programming problem involving a large number of unknown parameters to optimize. The disadvantage is in the need of using specialized nlp solvers, such as SNOPT [18]. Recently, different methodologies appeared that do not belong to the category of neither the indirect nor the direct techniques. These techniques are usually referred to as heuristics and have been sporadically applied to optimizing ascent trajectories of multistage rockets. Bayley et al. [19] used a genetic algorithm for the purpose of minimizing the overall rocket mass in the context of a high fidelity model of the entire vehicle. Three- and four-stage rockets were considered, with ascending trajectories composed (respectively) of three or four powered arcs. Lastly, Qazi et al. [20] integrated neural networks, particle swarm optimization, and sequential quadratic programming for the simultaneous conceptual design and trajectory optimization of a new multistage launch vehicle.

The work that follows is concerned with a novel approach, which is intended to supply a fast performance evaluation for multistage rockets with given characteristics, under some simplifying assumptions. The technique described in this work is applied to a three-stage rocket, whose three-dimensional trajectory is composed of the following thrust phases and coast arcs:

- (a) first stage propulsion
- (b) second stage propulsion
- (c) coast arc (after the second stage separation)
- (d) third stage thrust phase.

In general, the inclusion of a coast arc (between two powered phases) leads to substantial propellant savings

and this circumstance justifies the trajectory structure assumed in this research. Usually the coast duration increases as the injection altitude increases, as remarked by Lu et al. [13].

Specifically, the methodology presented and applied in this paper is based on three steps:

- (1) the flight-path angle at each stage separation is determined through an iterative process;
- (2) for each stage, the native MATLAB routine *fmincon* is employed for finding the thrust direction that maximizes the velocity at the stage separation, at which the flight-path angle is constrained to the value found at step (1);
- (3) for the third stage, the existence and duration of a coast arc and the optimal thrust direction are determined through a heuristic technique, i.e., the particle swarm algorithm. The Euler–Lagrange equations and the Pontryagin minimum principle are employed to express the control as a function of the adjoint variables conjugate to the dynamics equations.

The method that is being presented requires a reduced deal of effort in programming, debugging, and testing the algorithmic codes, as existing routines are used, in conjunction with analytical developments and a simple implementation of swarming algorithm. Hence, the methodology treated in this paper is intended to: (i) yield a reasonable solution for performance evaluation of multistage rockets and (ii) represent a technique for generating a suitable first-attempt guess trajectory to be employed by more refined algorithms tailored to optimizing the overall trajectory.

2. Problem definition

This research addresses the problem of performance evaluation of multistage rockets through the determination of a near optimal ascending trajectory, which terminates at injection of the payload in the desired operational orbit. This is a circular orbit of radius R_d , inclination i_d , and right ascension of the ascending node (RAAN) Ω_d . The three-stage launch vehicle is modeled as a point mass, in the context of a three-degree-of-freedom problem.

2.1. Rocket characteristics

The three-stage rocket that is being considered is the MultiRole Air Launch Missile (Muralm) [21], which is a rocket specifically designed for airlaunch from fighter aircraft. It has specified structural, propulsive, and aerodynamic characteristics and is portrayed in Fig. 1.

For the sake of simplicity, the mass distribution of the launch vehicle can be described in terms of masses of subrockets: subrocket 1 is the entire rocket, including all the three stages, subrocket 2 is the launch vehicle after the first stage separation, subrocket 3 is the launch vehicle after separation of the first two stages, and therefore is represented by the third stage only. Let $m_0^{(i)}$ denote the initial mass of subrocket i . This mass $m_0^{(i)}$ is composed

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