Available online at www.sciencedirect.com
ScienceDirect
Defence Technology 11 (2015) 350–361
www.elsevier.com/locate/dt

Optimal trajectory and heat load analysis of different shape lifting reentry vehicles for medium range application

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Received 18 January 2015; revised 23 May 2015; accepted 12 June 2015
Available online 26 July 2015

Abstract

The objective of the paper is to compute the optimal burn-out conditions and control requirements that would result in maximum down-range/cross-range performance of a waverider type hypersonic boost-glide (HBG) vehicle within the medium and intermediate ranges, and compare its performance with the performances of wing-body and lifting-body vehicles vis-à-vis the g-load and the integrated heat load experienced by vehicles for the medium-sized launch vehicle under study. Trajectory optimization studies were carried out by considering the heat rate and dynamic pressure constraints. The trajectory optimization problem is modeled as a nonlinear, multiphase, constraint optimal control problem and is solved using a hp-adaptive pseudospectral method. Detail modeling aspects of mass, aerodynamics and aerothermodynamics for the launch and glide vehicles have been discussed. It was found that the optimal burn-out angles for waverider and wing-body configurations are approximately 5° and 14.8°, respectively, for maximum down-range performance under the constraint heat rate environment. The down-range and cross-range performance of HBG waverider configuration is nearly 1.3 and 2 times that of wing-body configuration respectively. The integrated heat load experienced by the HBG waverider was found to be approximately an order of magnitude higher than that of a lifting-body configuration and 5 times that of a wing-body configuration. The footprints and corresponding heat loads and control requirements for the three types of glide vehicles are discussed for the medium range launch vehicle under consideration.

Keywords: Trajectory optimization; Hypersonic boost-glide; Waverider vehicle; Heat rate limit; Pseudospectral method; Hypersonic missile; Wing-body; Lifting-body; Medium range; Down-range; Cross-range

1. Introduction

Waverider configuration, originally intended for hypersonic cruise vehicle (HCV) has become extremely popular because of DARPA's X-41 common aero vehicle (CAV) program [1] and the Boeing X-51 scramjet engine demonstrator waverider program [2]. The waverider configuration has an immense aerodynamic advantage because of highest possible trim lift-to-drag ratio of greater than 3.0 in the hypersonic regime [3] as compared to trim lift-to-drag ratio of greater than 2.0 for wing-body configuration [4,5] and that of slightly greater than one for lifting-body design [6–8]. Common examples of lifting body designs include X-33, X-38 and HL-20 vehicles while shuttle orbiter and X-37B orbital test vehicle (OTV) are the examples of wing-body vehicles. The larger nose radius of lifting-body and the wing-body design have a better volumetric efficiency and also allow the use of conventional nose-mounted terminal sensors such as millimeter wave radar. The lifting-body and wing-body vehicles are subject to maximum heat rate on the fin leading edges. With advancement of the material technology (carbon–carbon materials) capable of bearing a temperature up to 2900 K [9], the utility of wing-body and lifting-body designs for medium and intermediate range military applications cannot be ignored.

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Peer review under responsibility of China Ordnance Society.

http://dx.doi.org/10.1016/j.dt.2015.06.003
2214-9147/

Reentry studies performed on lifting-body configuration have focused mainly on crew return vehicles (CRVs) [4], while the research on wing-body configuration is focused on orbital space planes and maneuverable reentry vehicles [10–13]. Li et al. [14,15] carried out trajectory optimization of a boost-glide hypersonic missile waverider configuration using the shooting technique, and calculated the footprint of an HBG missile from 5000 km to 15,000 km down-range and 5000 km cross-range once boosted from a Minuteman III boost vehicle to a speed of approximately 6.5 km/s at a burn-out angle of nearly zero degree. Rizvi et al. [16] computed the optimal trajectories of waverider type hypersonic boost-glide vehicle for medium range applications, and showed that the integrated heat load can be reduced by as much as 50 percent with penalty of only 10 percent in the overall down range. The research carried out by Rizvi et al. [16] shows the dependency of the integrated heat load on the burn-out conditions. The optimal burn-out conditions and subsequent optimal reentry trajectories under constraint heat rate with the objective to maximize the down-range and cross-range performance for medium to intermediate range applications are not available in literature.

For a ballistic vehicle with a particular burn-out speed and a fixed reentry vehicle shape and wing loading, the critical parameter is the burn-out angle. Low burn-out angles imply a small free-flight range but a higher reentry range and vice versa. Longer flight time at a shallow reentry angle also results in the increase in the total heat load [17]. The heat rate problem is more severe for small size vehicle because of small nose/leading-edge-radius (for wing-body and lifting-body designs). Limiting the heat rate restricts the reentry angle and lowers the down-range/cross-range performance of a reentry vehicle. Sharper re-entry angle results in high decent rates and the vehicle quickly approaches the heat rate boundary, resulting in infeasible trajectories.

The importance of the burn-out angle therefore necessitates it to be optimized. The approach used to optimize the burn-out conditions is to model the boost phase. The multiphase optimization problem is solved using a hp-adaptive pseudospectral method. For the free-flight and the glide phase, the path limits include the heat rate limit of 4 MW/m^2 which can either be at the nose or at a fin-tip, as well as dynamic pressure constraint of 320,000 Pa corresponding to the terminal constraint. The heat rate limit corresponds to the temperature limit of 2900 K which the reinforced carbon–carbon material can sustain [9]. Ablative materials are not suitable for lifting vehicle because of significant reduction in aerodynamic properties with modification in the body shape [18].

The aim of the numerical study is therefore to compute the optimum burn-out altitudes and the flight path angles for the ballistic vehicle, and the best angle-of-attack and bank angle profile for the waverider, wing-body and lifting-body vehicles which would result in maximum down-range/cross-range of the vehicles under heat rate and dynamic pressure constraints.

The planform loading of lifting-body, wing-body as well as waverider configurations is assumed to be 400 kg/m^2 which is consistent with that of fighter aircrafts as well as MaRRV data considered in Ref. [19]. The non-linear optimal control problem is solved using hp-adaptive pseudospectral method implemented in Gauss pseudospectral optimization software (GPOPS) [20].

2. Definition of phases

The various phases include:

1) The first 5s of first stage boost phase, during which pitch maneuver does not take place.
2) The first stage boost phase, after the first 5s, during which the launch vehicle pitches down using angle-of-attack control.
3) The second stage boost phase during which the flight path angle is changed to meet the burn-out conditions.
4) The free flight and the reentry stage during which the glide vehicle is steered to an optimal down-range or cross-range distance with the help of angle-of-attack and bank angle control.

The states at the end of the third phase, which includes the burn-out angle, burn-out altitude and the burn-out speed, are treated as free parameters and can be optimized. The fourth phase includes the free flight phase as well as the reentry phase.

3. Physical model

3.1. Earth and atmosphere

The earth is assumed to be a perfect, non-rotating sphere. The acceleration due to gravity is given by Newton's inverse square law

$$g = \frac{\mu}{r^2} \tag{1}$$

The density variation with altitude is assumed to be exponential and given by the relation

$$\rho = \rho_0 e^{(-h/\beta)} \tag{2}$$

where ρ_0 is the sea level density; and β is a constant that represents the inverse of density scale height and is given in Table 2.

3.2. Ballistic vehicle and reentry vehicle data

The data of the launch vehicle and the two types of reentry vehicles under consideration as well as the physical constants are summarized in Tables 1 and 2, respectively. The lifting-body and wing-body vehicles have same spherical nose radius denoted by R_{ND}, of which the fin radius and fin sweep angle are denoted by R_{F} and Λ, respectively. The bi-conic reentry vehicle is assumed to have the same mass as that of the lifting vehicles with a ballistic coefficient of approximately 2900 kg/m^2.