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ScienceDirect
Chinese Journal of Aeronautics 23(2010) 170-178
Chinese Journal of Aeronautics
www.elsevier.com/locate/cja

Multidisciplinary Design and Optimization of Multistage Ground-launched Boost Phase Interceptor Using Hybrid Search Algorithm

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Received 20 March 2009; accepted 8 July 2009

Abstract

This article proposes a multidisciplinary design and optimization (MDO) strategy for the conceptual design of a multistage ground-based interceptor (GBI) using hybrid optimization algorithm, which associates genetic algorithm (GA) as a global optimizer with sequential quadratic programming (SQP) as a local optimizer. The interceptor is comprised of a three-stage solid propulsion system for an exoatmospheric boost phase intercept (BPI). The interceptor's duty is to deliver a kinetic kill vehicle (KKV) to the optimal position in space to accomplish the mission of intercept. The modules for propulsion, aerodynamics, mass properties and flight dynamics are integrated to produce a high fidelity model of the entire vehicle. The propulsion module comprises of solid rocket motor (SRM) grain design, nozzle geometry design and performance prediction analysis. Internal ballistics and performance prediction parameters are calculated by using lumped parameter method. The design objective is to minimize the gross lift off mass (GLOM) of the interceptor under the mission constraints and performance objectives. The proposed design and optimization methodology provide designers with an efficient and powerful approach in computation during designing interceptor systems.

Keywords: boost phase; genetic algorithm; grain design; interceptor; optimization; solid rocket motor

1. Introduction

In recent years, evolutionary techniques have found successful applications in solving a lot of optimization problems in design. Moreover, a lot of researches had been performed on optimization of rocket vehicle designs using various evolutionary techniques[1-4]. Most researchers[5-8] adopted global or local optimization techniques to design the ground- and air-launched configurations for short range endo-atmospheric interceptors but did not consider the potentiality of using hybrid algorithms for multidisciplinary design and optimization (MDO) of multistage ground-launched long range exoatmospheric interceptor. This article proposes the MDO strategy for a multistage ground-based interceptor (GBI) comprised of a three-stage solid propulsion system for an exoatmospheric boost phase intercept (BPI) using the hybrid search algorithm, cascading the search properties of genetic algorithm (GA) as a global optimizer with sequential quadratic programming (SQP) as a local optimizer.

2. Design Requirements for Ground-launched BPI

To intercept a target in boost phase[9], the interceptor, apart from necessarily being solid-fueled for responsiveness, must have high thrust and high acceleration. It must be started up in a short time; that is to say, instantly ignited with a brief preparation time. Finally, of course, it is required to work reliably and to implement maintenance scheme with ease. The considerations involved in the GBI design differ from those in design of other surface-based and space-based systems. The GBI must be able to endure the high mechanical and thermal stresses when flying in the atmosphere at supersonic speed. From the view of effectiveness, the first balance that should be stricken in designing an interceptor is between speed and acceleration on one hand and size on the other hand[10]. Table 1 lists the design requirements and tradeoffs.

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doi: 10.1016/S1000-9361(09)60201-6

Table 1 Design requirements and tradeoffs

Minimizing	Maximizing
Size, gross lift off mass (GLOM) and payload mass	Speed and acceleration, velocity
Intercept time	Thrust, specific impulse, combustion speed
Preparation and start-up time and burning time	Propellant burning rate
G-loads	Maneuverability

The interceptor's GLOM varies as a function of structural mass, payload mass, speed and acceleration (booster burn time). The system characteristics that provide desired operational performances should be optimized. The selection of burn time is to seek a compromise between the desired high acceleration (increasing interceptor's reach) and its penalty, which means larger and heavier boosters to provide greater thrust and withstand greater thermal and mechanical stresses. Interceptor with shorter burn time typically requires greater maneuverability on the part of the kinetic kill vehicle (KKV), demanded to make trajectory corrections under the steering commands to the booster end earlier in the interceptor's flight. Trajectory corrections after booster burnout must be made by the KKV. Greater KKV's maneuverability in turn results in increase in KKV weight. For a given KKV size, the interceptor configuration must be optimized to deliver the desired performances.

2.1. Design objective

In the aerospace vehicle design, the minimum take-off mass concept has traditionally been viewed as vehicle development cost, which tends to vary as a function of GLOM[4]. The aim of the present effort is to minimize the GLOM of the interceptor under certain mission constraints and solid rocket motor (SRM) envelope constraints. In doing so, we try to configure an optimum propulsion system for interceptor missile to achieve our major goal of effective intercept of target in boost phase. The mission of the interceptor is to deliver a 200 kg payload (KKV) to the proximity of the target to complete the effective intercept. The baseline design under study involves all three stages that are made of sequentially stacked SRMs. The KKV is enclosed in a fairing whose shape is known beforehand. Each SRM has ellipsoidal dome ends. The number of stages is fixed as three.

2.2. Design constraints

The interceptor design is limited by physical and/or performance constraints. They can be categorized as mission constraints and SRM envelope constraints.

Mission constraints are comprised of miss distance (m), intercept time (s), lateral acceleration of gravity (m/s^2), velocity at intercept (km/s), G-loads.

SRM envelope constraints include stage configuration requirements which comprise length to diameter ratio, nozzle expansion ratio, propellant burn rates and grain geometry constraints like web fraction, and volumetric loading efficiency. Intercept velocity is formulated as trajectory constraint. Ratios of thrust to weight ν_0, and propellant mass ratio μ_p are restricted within allowable ranges. Nozzle exit diameters are limited to less than stage diameters.

A dynamic penalty function is used to address the flight and terminal constraints. A symbolic statement can be made as follows

$$\min f(x) = f(x) + h(k)\sum_{i=1}^{m} \max\{0, g_i(x)\} \tag{1}$$

where $f(x)$ is the objective function, $h(k)$ a dynamically modified penalty value and k the current iteration number of the algorithm, the function $g_i(x)$ is violation of the constraints [11].

2.3. Design variables

Table 2 lists the system design variables for each stage. There are 17 variables that govern the interceptor propulsion sizing and furthermore 13 design variables for each stage for detailed grain design and optimization, and one variable to set the effective navigation ratio.

Table 2 Design variables discipline wise

Parameter	Discipline
Relative mass coefficient of grain $\mu_{\mathrm{k}i}$	Structure propulsion
Body diameter D_i/m	Structure propulsion aerodynamics
Chamber pressure $p_{\mathrm{c}i}$/bar	Structure propulsion
Exit pressure $p_{\mathrm{e}i}$/bar	Structure propulsion
Coefficient of grain shape $K_{\mathrm{s}i}$	Structure propulsion
Grain burning rate u_i/(mm·s^{-1})	Propulsion
Navigation coefficient N	Guidance

Note: 1 bar=1×10^5 Pa

3. Optimization Approach

The optimization problem (see Fig.1), as stated above, is solved by using the hybrid search algorithm. In this case, a set of design variables (X) with upper bound (UB) and lower bound (LB) is fed into an optimizer which creates initial random population and performs its further operations. These candidate design variables (X) are then transferred to modules of weight and sizing, propulsion, aerodynamics and intercept trajectory analysis. The constraints are calculated and handled by external penalty function. The algorithm is run on an optimizer in a closed loop until an optimal solution is obtained.

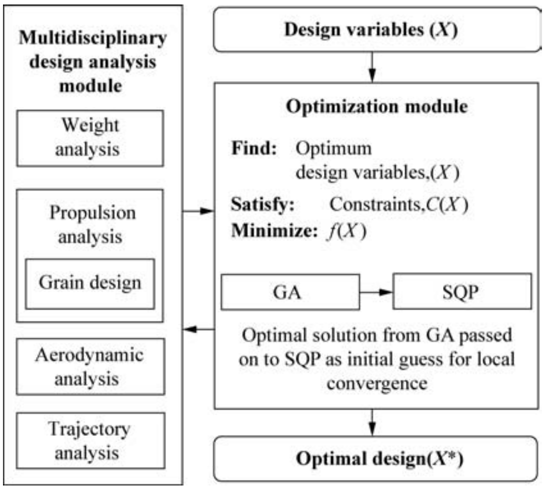


Fig.1 Overall design and optimization strategy.

3.1. Genetic algorithm (GA)

Almost every discipline in aerospace from guidance through navigation, control and propulsion to structures has yielded itself to the power of computational intelligence[12]. The population-based, non-gradient and stochastic direct search optimization methods are the attractive choice for the problem as they are easy to use and effective for highly nonlinear problems. Calculus-based optimization (CBO) schemes use sensitivity derivatives in the immediate vicinity of the current solution and can therefore easily fall into local optima, from which they cannot recover. To avoid these local optima and increase the opportunity of obtaining an acceptable solution, these CBO methods require a reasonable starting-up scheme. GA requires neither sensitivity derivatives nor a reasonable starting-up solution. GA allows the global search of design space for the problem[13].

3.2. Sequential quadratic programming (SQP)

In SQP method, the function solves a quadratic programming sub-problem in each iteration. An estimate of the Hessian of the Lagrangian is updated in each iteration, so is calculated a positive definite quasi-Newton approximation of the Hessian of the Lagrangian function. After choosing the direction of search, the optimization function uses a line search procedure to determine how far to go in the search direction. SQP algorithm is discussed in detail in Refs. [14]-[18].

3.3. Hybrid search algorithm (HSA)

HSA is a combination of GA and SQP to make the most of their advantages and steer clear of their disadvantages. Belonging to the family of global local search algorithms, HSA presented herein allows global search to be performed by using a cascaded architecture with GA in the primary stage followed by SQP in secondary stage (see Fig.1). Table 3 lists the parameters used for GA and SQP. The cascaded architecture enables the HSA to initially explore the entire search space for promising regions and then exploit these sub-spaces while satisfying the required constraint functions. The elite solution from GA is passed on to SQP as the initial guess for SQP to perform local convergence and identify the minimum GLOM of the interceptor. Fig.2 shows the convergence of HSA. The combination of GA and SQP is a more attractive choice for our problem. Refs.[19]-[23] have proposed hybrid methods by combining GA and gradient-based methods.

Table 3 Parameters for hybrid search algorithm

GA	SQP
Maximum generations G:200	Optimization type: medium scale
Population size: 100	Maximum iteration: 200
Population type: double vector	Function tolerance: 10^{-1}
Selection: stochastic uniform	Constraint tolerance: 10^{-2}
Crossover: single point, $p_c = 0.8$	Variable tolerance: 10^{-2}
Mutation: uniform $p_m = 0.25$	Maximum function evaluations: 5 000
Fitness scaling: rank	
Reproduction: elite count=2	
Function evaluations: 20 000	

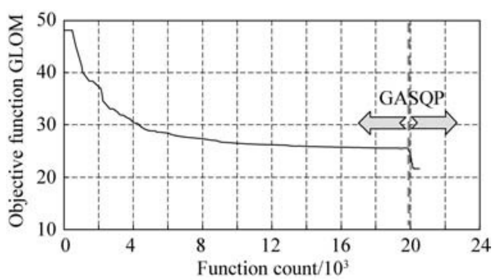


Fig.2 Convergence of design objective.

4. Multidisciplinary Design Analysis

The MDO process requires that analyses of separate disciplines should be integrated into design optimization process, so modules of propulsion characteristics, aerodynamics, mass properties and flight dynamics could be fused into an integral high-fidelity model of the entire vehicle. The data of the baseline vehicle should be imbedded in the code to facilitate startup. More detailed computational methods are used later in design when the number of alternative geometric, subsystem and flight parameters has been reduced to a smaller set of alternatives[24]. An MDO strategy is designed for multi-stage interceptor analysis, which includes weight analysis propulsion analysis and grain design aerodynamic analysis intercept trajectory analysis and optimization techniques. With the help of it, the configurations are “optimized” to maximize the performances and minimize the GLOM.

4.1. Weight analysis

By combining physical methods and empirical relationships, the weight of the SRM components (see Fig.3) and propulsion analysis for solid stages is determined according to Ref.[25]. The mass equation for a multistage interceptor can be written as

$$m_{0i} = m_{pi} + m_{ki} + m_{0(i+1)} \tag{2}$$

where m_{0i} is gross mass of the ith stage rocket, m_{pi} mass of propellant of the ith stage rocket, m_{ki} structural mass of the ith stage rocket, and $m_{0(i+1)}$ payload of the ith stage rocket.

The GLOM m_{01} of the multistage solid interceptor is calculated by[25]

$$m_{01} = m_{PAY} + \sum_{i=1}^{n} (m_{gni} + m_{sti} + m_{svi} + m_{asi} + m_{fei} + m_{fsi}) \tag{3}$$

$$m_{01} = \frac{m_{PAY}}{\prod_{i=1}^{n} [1 - N_i - K_{gni} u_{ki} (1 + \alpha_{sti})]} \tag{4}$$

where m_{gni} is the mass of the ith stage SRM grain; m_{sti} the mass of the ith stage SRM structure; m_{svi} the mass of control system, safety self-destruction system, servo system and cables inside the ith stage after skirt; m_{asi} the mass of the ith after skirt including shell structure, equipment rack, heat-protection structure and the auxiliaries for integration; m_{fei} the mass of equipment and cables inside the ith stage forward skirt; m_{fsi} the mass of the ith stage forward skirt including shell structure, equipment rack, and auxiliaries for integration. Mass of payload m_{PAY} is already known from the design assignment. Slightly dispersed values of skirt mass ratio N_i, and propellant reserve coefficient K_{gni} can be selected from statistical data as presented in Refs.[25]-[26]. Relative mass coefficient μ_{ki} of effective grain to m_{01} as given below in Eq.(5) is a function of range or burnout velocity. It is a design parameter which should be optimized.

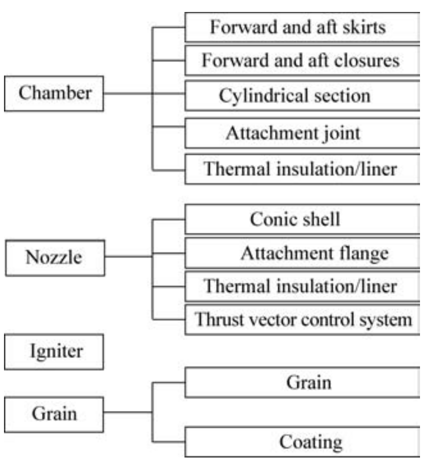


Fig.3 Mass model of SRM.

$$\mu_{ki} = \frac{m_{gni}}{m_{0i}} \tag{5}$$

As a main problem for designing a multistage interceptor, the structural mass fraction α_{sti} depends upon the structural material, grain shape as well as the parameters of internal ballistics of SRM. α_{sti} is the ratio of the sum of chamber case mass m_{cc}, cementing layer mass m_{cl}, nozzle mass m_n and insulation liner mass m_{in} to the grain mass m_{gni}, as shown by

$$\alpha_{sti} = \frac{m_{cc} + m_{cl} + m_n + m_{in}}{m_{gni}} \tag{6}$$

$$m_{cc} = \frac{f p_c \rho_{cc}}{\sigma_i} \left(\frac{\pi}{2} \lambda_{gni} + 1 \right) D_i^3 \tag{7}$$

$$m_{cl} = \frac{\pi}{2} \rho_{cl} \lambda_{gni} (1 - \varepsilon) D_i^3 \tag{8}$$

$$m_n = \frac{k_{sgi} u_i \rho_{gni} \rho_n^{av} \sqrt{R_c T_c} \alpha_n}{\Gamma_o p_c \sin \beta_n} \left(\frac{A_e}{A_t} - 1 \right) \lambda_{gni} D_i^3 \tag{9}$$

$$m_{in} = K_{in} (2 + \pi \lambda_{gni}) \rho_{in} D_i^3 \tag{10}$$

where f is the factor of safety, ρ the density, σ the strength, ε the ratio of cementing layer to SRM diameter, T the combustion temperature, α_n the ratio of nozzle wall thickness to stage diameter, K_{in} the ratio of insulation layer thickness to stage diameter D_i and ψ_i the grain volumetric efficiency.

At the preliminary design stage, the shape of grain is assumed to be a variable k_{si} rather than a fixed value to represent the burning surface area S_{ri} of the grain as a function of the grain length L_i and diameter D_i. As an important design variable, the chamber pressure p_c has effects on motor specific impulse. Raising p_c reduces losses at the nozzle exit and increases the specific impulse. p_c, however, also has effects on the burning rate of propellant, size of nozzle's expansion and thickness of casing to withstand pressure stresses. Burning surface area of the propellant grain plays decisive role in determining the performances of the propulsion system in SRM.

$$m_{gni} = \frac{\pi}{4} \rho_{gni} \psi_i \lambda_{gni} D_i^3 \tag{11}$$

$$D_i = (4 K_{gni} \mu_{ki} m_{0i} / \pi \rho_{gn} \psi_i \lambda_{gni})^{1/3} \tag{12}$$

The mass consuming rate of grain is

$$m_{gni} = \rho_{gni} u_i S_{ri} = \rho_{gni} u_i K_{si} \lambda_{gni} D_i^2 \tag{13}$$

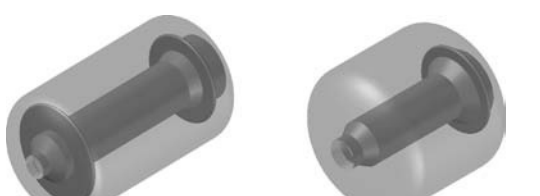
4.2. Propulsion analysis

In the propulsion analysis are involved the important parameters like thrust, burn time, mass flow rate and nozzle parameters[27]. The estimates acquired from the preliminary propulsion design are fed in the grain design module.

4.3. Grain design and internal ballistics

Grain design always proves to be a vital and integral part of SRM design. Based on the design objectives set by the system designer, the SRM designer has many options at his disposal to determine the grain configuration. Of them many are able to meet the parametric requirements for volumetric loading fraction, web fraction, fineness ratio, length to diameter ratio (*L/D*) and produce internal ballistic results complying with the design objectives. However, given a set of design objectives, it is imperative to select, design and optimize the possible configuration. It is rather time-consuming for computation to include the grain design module in the overall optimization loop, therefore, once the preliminary sizing of the propulsion is achieved, the design parameters including the propellant mass, thrust time, chamber pressure, area ratios, *L/D* requirements are transferred to the grain design module and the relevant grain configurations are modeled and optimized to meet the specific mission requirements. Fig.4 shows two different grain configurations.

(a) Finocyl grain configuration for first stage



(b) Axisymmetric (Conocyl) grain configuration for second and third stages

Fig.4 Grain configurations.

The 3D finocyl configuration, also called “fin in cylinder”, can provide a variety of thrust time traces depending on the mission requirements. The first stage requires high thrusts in initial flight phase so as to provide the required ratio of thrust to weight. Finocyl grain can be used for a longer period with relatively low *L/D*. A cylindrical cavity followed by a conical one is provided to accommodate nozzle submergence.

A conocyl configuration is selected for second and third stages because of certain excellent features it has like high volumetric efficiency, minor problems about structural integrity, sharp tailoff, easy mandrel design and extraction.

The generalized grain calculation method using basic geometrical shapes to define the initial grain void and surfaces is implemented numerically[28-29]. This method is complex and can produce errors[30]. The methodology adopted in this work is CAD modeling of the propellant grain[31]. A parametric model with dynamic variables is created to define the grain geometry. The CAD software is linked to the optimization module which offers input variables. Lumped parameter method is used to calculate the internal ballistics[27]. The performance prediction is carried out using zero dimensional steady-state gas dynamics. The grain regression is achieved by an equal web increment in all directions. At each step, a new grain geometry is created automatically and then the volume (V) for each web increment (w) is stored in a file. A decreasing trend is observed for the volume of the grain. The burning surface area can be calculated by

$$A_{bk} = \frac{V_{k+1} - V_k}{w_{k+1} - w_k} \tag{14}$$

where k is the web step. Propellant mass is calculated by

$$m_p = \rho_p V_k \tag{15}$$

The motor performances are calculated by using a simplified ballistic model. The steady-state chamber pressure is calculated by equating the mass generated in chamber to that ejected through the nozzle throat.

$$p_c = (\rho_p a c^* K)^{1/(1-n)} \tag{16}$$

$$K = A_b/A_t \tag{17}$$

Thrust is determined by

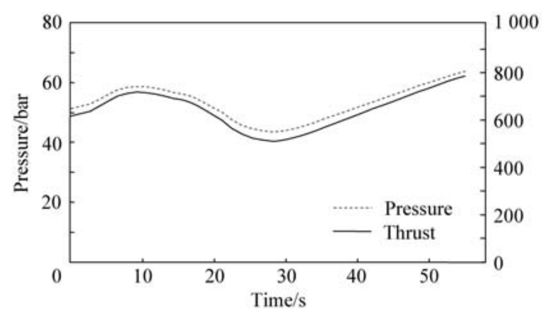
$$F = C_F p_c A_t \tag{18}$$

where thrust coefficient C_F is given by

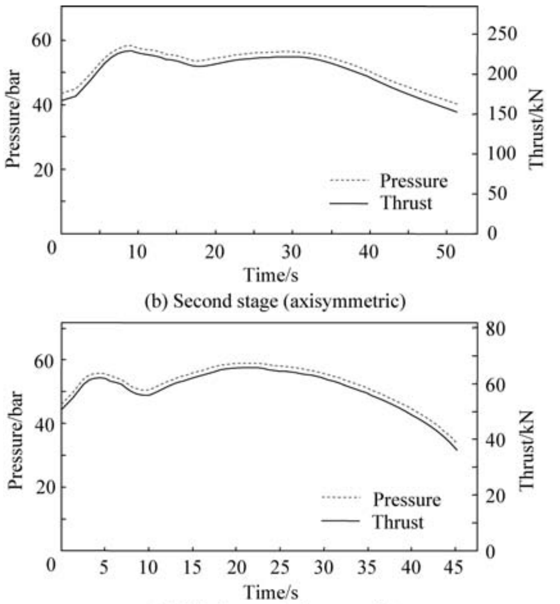
$$C_F = \sqrt{\frac{2\gamma^2}{\gamma-1}\left(\frac{2}{\gamma+1}\right)^{(\gamma+1)/(\gamma-1)}\left[1-\left(\frac{p_e}{p_c}\right)^{(\gamma-1)/\gamma}\right]} + \frac{p_e - p_{amb}}{p_c}\varepsilon \tag{19}$$

Thrust and pressure versus time are predicted for the finocyl configuration of the first stage and the axisymmetric one of the second and third stages. HTPB, A_p and A_l are selected to be the propellant.

Fig.5 shows the trend of optimized pressure and thrust versus time.



(a) First stage (finocyl)



(b) Second stage (axisymmetric)

(c) Third stage (axisymmetric)

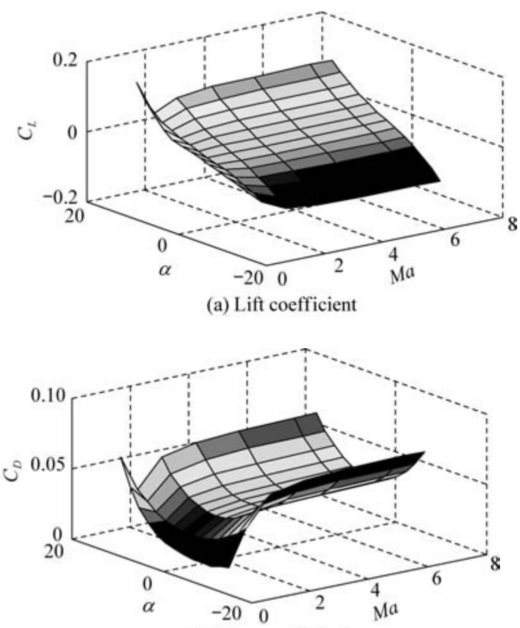
Fig.5 Pressure/Thrust time trace for optimized configurations.

4.4. Aerodynamic analysis

The aerodynamic analysis involves estimation of the vehicle's aerodynamic properties in different flow fields that it encounters during atmospheric flight. To integrate the aerodynamic analysis into the optimization loop, a three degree of freedom (DOF) trajectory simulation is cascaded into the optimization loop. In this study, the interceptor is assumed to be a point-mass flying over the spherical non-rotating Earth[32]. Terminal constraints are imposed on altitude, velocity, and range as well as maximum in flight dynamic pressure, angle of attack α, pitch rate and normal force limits. The aerodynamic analysis incorporates USAF missile DATCOM 1997 (digital)[33], whose predictive accuracy meets our design requirements. The coefficients of lift and drag (C_L and C_D) are estimated with DATCOM. The lift (L) and drag (D) forces are calculated by

$$\left.\begin{aligned} L &= C_L \frac{1}{2}\rho v^2 A_{\text{ref}} \\ D &= C_D \frac{1}{2}\rho v^2 A_{\text{ref}} \end{aligned}\right\} \tag{20}$$

Fig.6 illustrates C_L and C_D versus angle of attack and Mach number for optimized configuration.



(a) Lift coefficient

(b) Drag coefficient

Fig.6 C_L and C_D vs angle of attack and Mach number for optimized configuration.

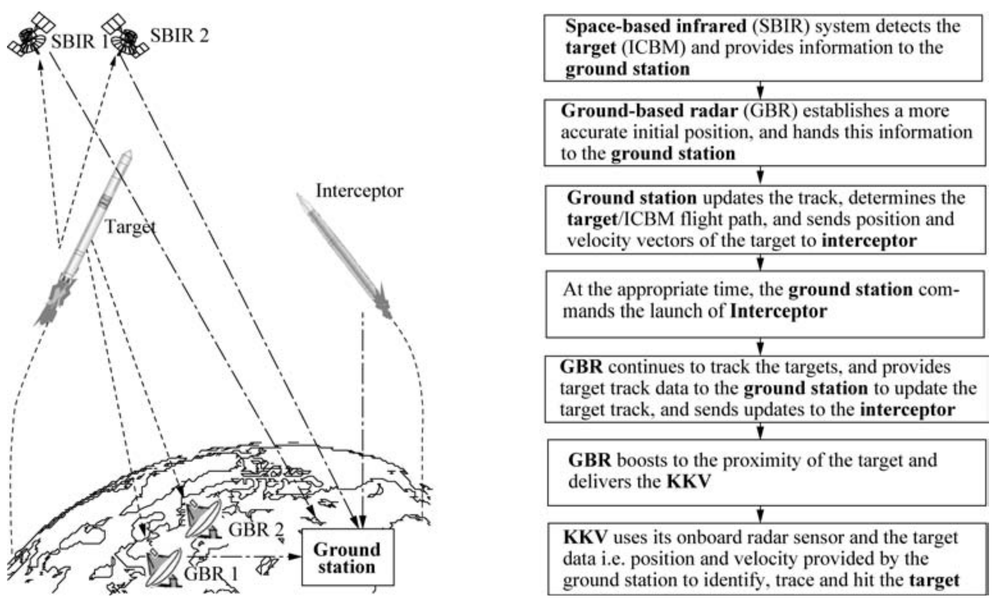


Fig.7 Intercept scheme.

4.5. Intercept trajectory analysis

Trajectory is the yardstick for evaluating the relative merits between alternative designs. Since there is hardly any detailed data at the beginning of conceptual design, it is improper to use 6-DOF trajectory simulation during the conceptual design for the convenient evaluation of guided flight. As the development of the required autopilot for 6-DOF guided flight spends much more time and diverts attention from other more appropriate considerations[24], a 3D model is developed for both interceptor and target with boost phase acceleration profile that depends on total mass, propellant mass and specific impulse in the gravity field. The radar cross section[34-35] and infrared signature[36-37] of the target structure is estimated as a function of the flight profile. Interceptor uses fused target location data provided by two ground-based radio frequency (RF) radar sensors[38-39] and two (LEO) infrared sensors[40]. The intercept scheme is constructed based on the following scenario[41-42] (see Fig.7). An intercontinental ballistic missile (ICBM) is launched from a priori launch site. The target is tracked by two ground-based RF sensors and two space-based infrared sensors. The track data are processed by a simple averaging method and used to guide interceptor to establish the collision geometry with the target.

4.6. Guidance algorithm

The guidance algorithm used herein is standard proportional navigation, which is shown in Fig.8. The system tackles accelerations normal to line of sight (LOS) between the interceptor and the target and proportional to the closing velocity V_c and the LOS rate. Mathematically, the guidance law can be stated as

$$n_c = N'V_c\lambda \tag{21}$$

where N' is the effective navigation ratio or gain. For preliminary design studies, it is proper to assume that there is a perfect seeker and a perfect radar system that can take accurate measurements of the target position and its velocity. According to Ref.[43], the typical ranges for N' are 3 to 5 (non-dimensional) for tactical weapon systems.

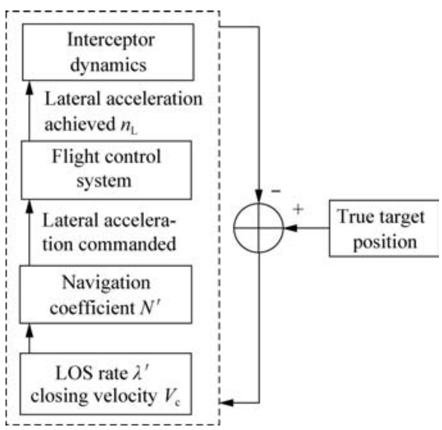


Fig.8 Guidance algorithm.

5. Performances of Optimized Configurations

Table 4 compares the optimized configurations obtained with GA and HSA and Fig.9 shows the improvements gained with HSA rather than the global optimizer GA alone. Fig.10 depicts the flight performances of both interceptor configurations.

Table 4 Optimum values of design variables

No.	Parameter	LB	UB	GA optimized	GA+SQP optimized
1	μ_{k1}	0.6	0.7	0.679 2	0.661 3
2	μ_{k2}/μ_{k1}	1	1.04	1.000 1	1.013 3
3	μ_{k3}/μ_{k2}	1	1.08	1.040 5	1.043 4
4	D_1/m	1.2	1.8	1.290 2	1.273 2
5	D_3/m	0.7	1.0	0.953 3	0.953 5
6	p_{c1}/bar	50	70	57.433 0	59.061 0
7	p_{c2}/bar	40	60	56.338 0	50.685 0
8	p_{c3}/bar	40	60	51.458 0	57.220 0
9	p_{e1}/bar	0.50	0.90	0.625 2	0.756 8
10	p_{e2}/bar	0.15	0.35	0.280 4	0.211 6
11	p_{e3}/bar	0.10	0.25	0.235 1	0.237 9
12	u_1/(mm·s^{-1})	5	10	7.085 8	6.991 5
13	u_2/(mm·s^{-1})	5	10	7.535 9	7.935 1
14	u_3/(mm·s^{-1})	5	10	5.859 2	6.504 7
15	k_{s1}	1.5	2.3	2.185 7	2.181 1
16	k_{s2}	1.5	2.3	1.966 3	1.969 9
17	k_{s3}	1.5	2.3	2.036 6	1.942 6
18	N	3	5	5	5

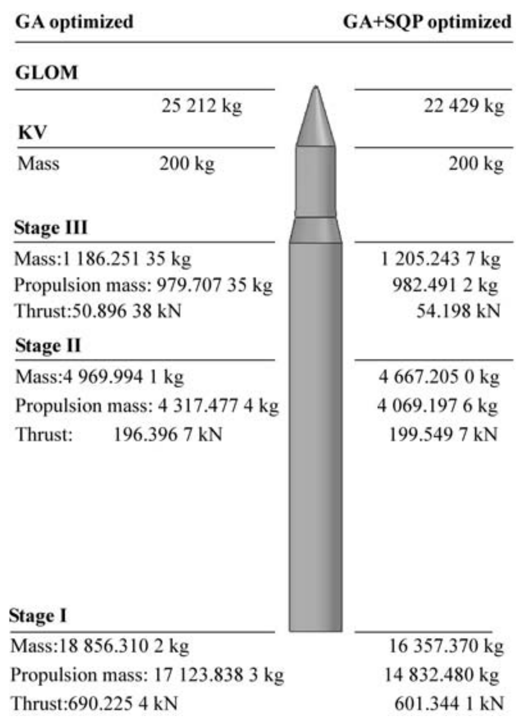


Fig.9 Optimized configurations.

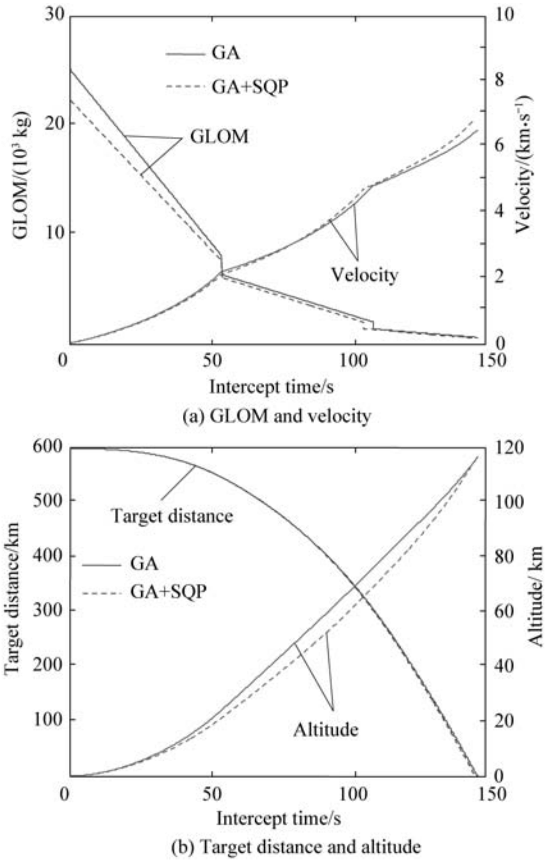


Fig.10 Performances of optimized configuration.

From Fig.10, it can be seen that the GA+SQP-optimized configuration achieves the mission-set goal with a lower GLOM. The reduction in GLOM achieved by using the GA+SQP amounts to around 3 000 kg i.e. about 10%, which is quite significant at conceptual design level.

6. Conclusions

Simulation experiments showed the HSA effectively combines the global search property of GA with local convergence of SQP algorithm. It proved able for the MDO of interceptor to accomplish the mission-set objectives with demanded performances.

In previous design effort, detailed grain design was not integrated and navigation constant were not included in the optimization loop. The inclusion of the grain design module further increases the fidelity of the model. Though, the optimization results and performance are to be considered as preliminary (proof-of-concept) only, but they can be compared to existing systems, and can be used for conceptual design and optimization of interceptors and other aerospace systems.

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