

Co-Evolutionary Multi-Objective Multidisciplinary Design Optimization for Hypersonic Vehicles

D. Zhang

College of Astronautics
Northwestern Polytechnical University
Xi'an, Shannxi, P.R. China

S. Tang

Notional Key Laboratory of Aerospace Flight Dynamics
Northwestern Polytechnical University,
Xi'an, Shannxi, P.R. China

Abstract--Integrated design of airframe/propulsion of hypersonic vehicles is a problem of multi-objective multidisciplinary design optimization (MDO) for complex coupled systems in nature. In order to implement a MDO on airframe/propulsion integration, firstly the design structure matrix was established based on the analysis of coupling relationships among disciplines for airframe/propulsion integration; secondly, the system optimization model and disciplinary optimization models for airframe/propulsion integration were proposed; finally, simulations for the multi-objective multidisciplinary design optimization of airframe/propulsion integration of hypersonic vehicles were conducted by means of co-evolutionary method and a satisfactory Pareto optimal solution set was obtained.

Keywords--airframe; propulsion; hypersonic vehicle; multidisciplinary; MDO

I INTRODUCTION

For the airframe/propulsion integration of hypersonic vehicles, strong couplings exist among disciplines such as structural mechanics, aerothermodynamics, combustion, trajectory and control, and geometric profile in addition to the coupling between aerodynamics and propulsion. Integrated design of airframe/propulsion for hypersonic vehicles is a typical multi-objective multidisciplinary design optimization problem due to its intrinsic characteristic of multidisciplinary coupling.

The purpose of multi-objective multidisciplinary design optimization of airframe/propulsion integration is to find the set of Pareto optimal solutions that satisfy constraints and requirements on performance of airframe/propulsion integration, and furthermore to provide several design plans that are optional for designers, which is of great importance for the integrated design of airframe/propulsion for hypersonic vehicles.

MDO is a methodology to design complex systems and subsystems by exploring and making full use of synergic mechanisms of interactions in systems [1]. Details about the developments of the main ideology, contents and key techniques of MDO are elaborated in papers [2-4].

II MULTI-OBJECTIVE MULTIDISCIPLINARY DESIGN OPTIMIZATION OF AIRFRAME/PROPULSION INTEGRATION

Based on the analysis of coupling relationships between disciplines, the strongly coupled system of a hypersonic vehicle is decomposed into multidisciplinary systems that are

relatively independent and autonomous by means of appending design variables. In the meantime, the consistency of interdisciplinary coupling constraints is enforced by applying equation constraints in each discipline. In such a way, all disciplines and co-evolutionary multi-objective optimization algorithm can be combined to establish the mappings between populations and disciplines, so that a multi-population self-adaptive co-evolutionary design optimization model is generated. The Pareto solution set is obtained through the storage mechanism of Pareto solutions.

A. Design Optimization Model

System performance indicators, design variables and constraints play fatal roles for multi-objective multidisciplinary design optimization of airframe/propulsion integration of hypersonic vehicles. For a hypersonic vehicle, the airframe is the part that generates lift for the vehicle and the quality of its profile directly affects the aerodynamic performance of the vehicle and thereafter the accomplishment of flight missions. As a result, the L/D ratio of the airframe is an important performance indicator, which is often used to measure the aerodynamic performance of the vehicle. The performance of propulsion system is usually indicated by thrust coefficient C_t . Heat flux q or temperature T_b along the central line on outer surface of airframe is taken as the indicator of aero thermo dynamic characteristic.

Constraints on systems in a hypersonic vehicle includes constraint on inlet starting, constraint on boundary layer separation, combustion condition of combustor and constraint on forebody length, etc. Constraint on inlet starting means Kantrowitz condition [5]:

$$\frac{A_2}{A_1} \geq \left[\frac{\gamma-1}{\gamma+1} + \frac{2}{(\gamma+1)M_1^2} \right]^{\frac{1}{2}} \left[\frac{2\gamma}{\gamma+1} - \frac{\gamma-1}{(\gamma+1)M_1^2} \right]^{\frac{1}{\gamma-1}} \quad (1)$$

Where, A_2 is the area of inlet throat, A_1 is incoming flow capture area, M_1 is Mach number behind the shock induced by the outer compression surface.

With respect to the disadvantage of Kantrowitz condition which is too conservative, it is proposed by paper [6] that inlet starting is determined by the following empirical formula:

$$\frac{H_2}{H_1} \geq -3.25 + 2.17Ma_{cruise} - 0.017Ma_{cruise}^2 \quad (2)$$

Constraint on boundary layer separation [6] means that the ratio of Mach numbers ahead of and behind shock satisfies a certain condition.

For a laminar boundary layer

$$\left(\frac{M_a}{M_f} \right)_{laminar} < 0.898 \quad (3)$$

For a turbulent boundary layer

$$\left(\frac{M_a}{M_f} \right)_{turbulent} < 0.762 \quad (4)$$

Where, M_a is Mach number behind the shock, M_f is the Mach number ahead of the shock.

Combustion condition is that in order to guarantee the normal combustion in the combustor, properties of the air flow entering the combustor are constrained [7]:

$$0.5atm < P_{com,in} < 10atm \quad (5)$$

$$2.0 < Ma_{com,in} < 3.0 \quad (6)$$

By applying the constraint on forebody length, the length of the forebody is constrained in order to satisfy the requirements of internal volume and engine structure:

$$L_{OC} \leq 2.7 \quad (7)$$

Based on the above analysis, the multi-objective multidisciplinary design optimization of airframe/propulsion of hypersonic vehicles can be described by a system-level optimization model and three discipline-level optimization models.

The system-level optimization model:

$$\text{Maximize} \quad \left\{ \frac{C_L}{C_D}, C_T, \frac{1}{T_b} \right\} \quad (8)$$

$$s.t. \quad X_{min} \leq X \leq X_{max}$$

Discipline-level optimization models include models of disciplines such as aerodynamics, propulsion and aerothermodynamics.

Discipline of aerodynamics:

$$\text{Maximize} \quad \frac{C_L}{C_D} \quad (9)$$

$$s.t. \quad x_{1min} \leq x_1 \leq x_{1max}, \quad L_{OC} \leq 2.7$$

Discipline of propulsion:

$$\text{Maximize} \quad C_T$$

$$s.t. \quad \delta_1 + \delta_2 + \delta_3 = \delta_4 + \delta_5, \quad M_{a3} \leq 5.0 \quad (10)$$

$$x_{2min} \leq x_2 \leq x_{2max}, \quad \theta_3 \leq \theta_2 \leq \theta_1$$

In the meantime, the discipline-level model of propulsion should satisfy constraint on inlet starting, constraint on boundary layer separation and combustion condition of combustor.

Discipline of aerothermodynamics:

$$\text{Maximize} \quad \frac{1}{T_b} \quad (11)$$

$$s.t. \quad x_{3min} \leq x_3 \leq x_{3max}$$

It is impossible to set all geometric parameters that describe the vehicle profile to be design variables. Under the condition that geometric parameters on the transverse direction of the vehicle, i.e. lateral edge parameters, do not change, the geometric parameters that characterize the shapes of upper and lower surfaces of the vehicle are chosen to be design optimization variables. These 12 variables include angles of deflection δ_i ($i = 1, 2, 3, 4$) that characterize the geometry of the lower surface of the forebody, angles θ_j ($j = 1, 2, 3$) that characterize the geometry of the rear nozzle, the radius of curvature of the vehicle nose R_n and the geometric parameters Y_{OH}, Y_{OG} and L_{OH}, L_{OG} that characterize the geometry of the upper surface of the vehicle.

B. Co-Evolutionary Multi-Objective Multidisciplinary Design Optimization (Cmomdo) Algorithm

Through the analysis of coupling relationships among disciplines involved in airframe/propulsion integration of hypersonic vehicles, the multi-objective multidisciplinary design optimization of airframe/propulsion integration can be formulated as a 2-level MDO structure, based on which a system-level optimization model and models about each discipline were established. After that, co-evolutionary multi-objective multidisciplinary design optimization (CMOMDO) algorithm was employed to implement the multi-objective multidisciplinary design optimization of airframe/propulsion integration.

On the foundation of co-evolution of populations and their neighborhoods, CMOMDO algorithm is a highly efficient random search algorithm which combines local search of partial solutions and global search of complete solutions. Based on this ideology, a CMOMDO code for airframe/propulsion integration of hypersonic vehicles was developed on the platform of Matlab 7.0. The flow chart is shown in Figure. 1.

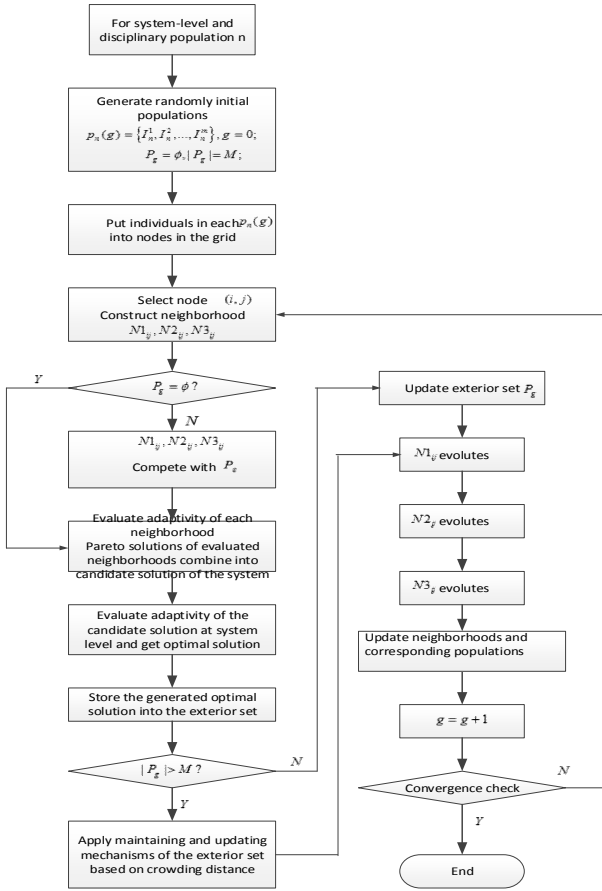


FIGURE I. FLOW CHART OF CMOMDO FOR AIRFRAME/PROPULSION INTEGRATION OF HYPERSONIC VEHICLES.

III SIMULATION RESULTS AND ANALYSIS

Through simulations, the Pareto optimal solution set and Pareto frontier for the multi-objective multidisciplinary design optimization of airframe/propulsion integration of hypersonic vehicles were obtained. Figure. 2 demonstrates the Pareto frontier obtained by CMOMDO algorithm for airframe/propulsion integration. Table 1 shows the comparison between performances of configurations on the boundary of Pareto frontier and the performance of the base configuration.

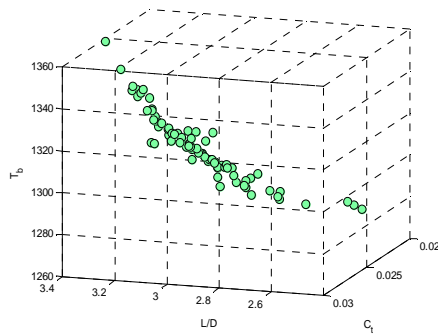


FIGURE II. PARETO FRONTIER OBTAINED BY CMOMDO ALGORITHM FOR AIRFRAME/PROPULSION INTEGRATION.

TABLE I. COMPARISON BETWEEN PERFORMANCES OF PARETO FRONTIER AND BASE CONFIGURATION.

Parameters	Baseline configuration	Pareto Boundary layer solution		
		Max L/D	Max C_f	Min T_b
δ_1	0.636 ⁰	5.38740	4.69450	3.64720
δ_2	1.728 ⁰	1.70220	1.35430	2.96610
δ_3	5.6340	2.54340	3.61170	1.66620
δ_4	2.5280	7.75330	8.64430	5.94980
θ_1	15.000	8.29850	21.97170	10.15240
θ_2	8.000	7.39210	14.76620	7.70490
θ_3	0.000	5.59080	12.7799	6.65280
R_n	0.01	0.012	0.0319	0.04510
L_{OH}	2.00	2.1871	2.1899	1.9036
Y_{OH}	0.0785	0.0591	0.1245	0.0937
L_{OG}	4.300	4.2565	4.1286	4.1936
Y_{OG}	0.140	0.1812	0.1245	0.1389

Conclusions are drawn through analysis of Table 1:

1) Aerodynamic characteristic of hypersonic vehicles with airframe/propulsion depends mainly on the deflection angle of air flow δ of forebody and the radius of curvature at the vehicle nose R_n . Both the increase of deflection angle and the reduction of radius of curvature can increase the lift for the vehicle body. In the meantime, drag on forebody is also increased due to the increase of deflection angle of air flow and larger radius of curvature at the vehicle nose leads to greater drag on the upper surface of the vehicle nose, which reduces the lift-to-drag characteristic of the vehicle. This is the reason why drag increase faster than lift.

2) The aero thermo dynamic performance of the vehicle mainly depends on the radius of curvature at nose. If the radius of curvature increases, heat flux at the vehicle nose is relatively small, which is indicated by relatively low temperature at the vehicle nose. If the radius of curvature decreases, heat flux at the vehicle nose is relatively large, which is indicated by relatively high temperature at the vehicle nose.

3) The propulsion performance of the vehicle is mainly dependent on the angle of rear nozzle θ . The more completely the rear nozzle expands, the greater the Mach number after the air flow accelerates is. In the meantime, the thrust also depends on compression in the forebody. The greater the deflection angle of air flow is, the more heavily air flow is compressed, the less the energy loss due to compression is, the larger the thrust is.

IV CONCLUSIONS

In the work reported by this paper, the co-evolutionary multi-objective multidisciplinary design optimization for airframe/propulsion integration of hypersonic vehicles was investigated. The system-level and discipline-level optimization models for airframe/propulsion integration of hypersonic vehicles were established. Knowledge of each discipline and the CMOMDO algorithm were merged to

generate a model for the multi-population self-adaptive co-evolutionary design optimization process. The Pareto optimal solution set that satisfies requirements of performance and constraints was obtained by means of simulations and analysis of cases for the co-evolutionary multi-objective multidisciplinary design optimization for airframe/propulsion integration of hypersonic vehicles.

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