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A Multi-Objective Optimization for the Aerodynamic Configuration of a Re-entry Vehicle based on MOEA/D

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Abstract

In this work, the aerodynamic optimization of a waverider derived re-entry vehicle is presented. The waverider has the advantage of high lift-to-drag ratio. For the re-entry vehicle, the advantage enables not only a wide cross-range but also a lower heating peak compared to the normal ballistic re-entry or the low lifting re-entry. However, there are many constraints when applying waverider configuration on the re-entry vehicles, such as flight range, volume, flight time, lift, aeroheating, etc., which makes the aerodynamic optimization of the vehicles complex. A Multi-objective Evolutionary Algorithm Based on Decomposition is applied for the multi-objective optimization. The surface of the waverider is generated by tracing the streamlines of the flowfield. An engineering method is utilized to calculate the aerodynamic forces rapidly during the optimization. A suboptimal aerodynamic configuration is obtained which meets the requirements of lift-to-drag ratio, volume and stability.

Keywords: Waverider, Re-entry, Multi-objective optimization, MOEA/D

1. Introduction

The manned capsules in service, such as Chinese Shenzhou and Russian Soyuz, usually have blunt surfaces which are used to decelerate the velocity and minimize the thermal loads on the bodies during the descent. However, the manned capsules have to endure a deceleration up to 9g, which discomforts the astronauts. The re-entry corridor of the blunt capsule is usually narrow as well. It is already learnt that with a lifting body the re-entry corridor of the spacecraft can be enlarged[1]. The space shuttle, which has a lift-to-drag ratio (L/D) about 1 during the hypersonic flight, proved its advantages not only of wider re-entry corridor but also the lower peak aeroheating and much lower maximum deceleration of 3 g [2]. A higher L/D may enhance these advantages, but it is a challenge for hypersonic flight.

The waverider configuration is ideal for hypersonic flight vehicles which requires high L/D. The front shock is attached along its leading edge which leads a high-pressure region between its underneath body and the shock surface. Its upper surface is usually tangent to the free stream that will not disturb the inflow. The waverider configuration can significantly increase the L/D. However, the waverider can restrict the freedom to configurate the volume and aerodynamic stability for the flight vehicle as well. The multi-objective optimization technique is required for practical application of the waverider. In this

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work, a Multi-objective Evolutionary Algorithm Based on Decomposition (MOEA/D) is applied to design a re-entry vehicle with waverider derived configuration.

2. Multi-objective Evolutionary Algorithm Based on Decomposition (MOEA/D)

MOEA/D belongs to the generic algorithm family. It is to decompose a multi-objective optimization work

$$\begin{aligned} \min \quad & F(\vec{x}) = \left(f_1(\vec{x}), f_2(\vec{x}), \ldots, f_m(\vec{x}) \right) \\ s.\ t. \quad & g(\vec{x}) \geq 0 \\ & \vec{x}_{i,u} \geq \vec{x}_i \geq \vec{x}_{i,l} \quad i = 1, 2, \ldots, n \end{aligned} \tag{1.1}$$

into different sub-optimizations with single objective and optimize them simultaneously based on a population method. [3] In this work, the Tchebycheff method is employed to decompose the optimization problems:

$$\min \quad \max_{1 \leq i \leq m} \left(w_i \left(f_i(x) - z_i^* \right) \right) \quad s.t. x \in \Omega \tag{1.2}$$

The solution of Eq. (1.2) equals the former multi-objective optimization equations.

When MOEA/D is applied to optimize the configuration of a flight vehicle, a parameterized configuration model should be built as well.

3. The aerodynamic optimization of re-entry vehicle

3.1. Parameterized model

The re-entry vehicle studied in this work is derived from a waverider. The waverider can be describe by an upper surface S_{upper}, an under surface S_{lower} and a back surface S_{back}. The under surface is generated by the classic Osculating Cone method. The aerodynamic forces on the upper surface is calculated by an engineering tool based on panel method, which enables a fast computation of aerodynamic forces during the optimization loop. Figure 1 and 2 show the built mesh of a waverider for the engineering tool. This applied engineering tool is thereafter validated with the CFD technique (Fig 3 and Table 1).

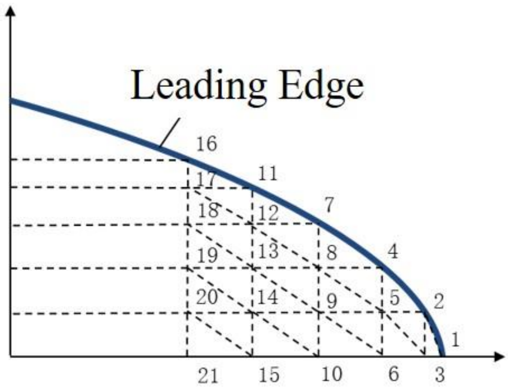

Fig 1. Mesh generating on the surfaces of a waverider

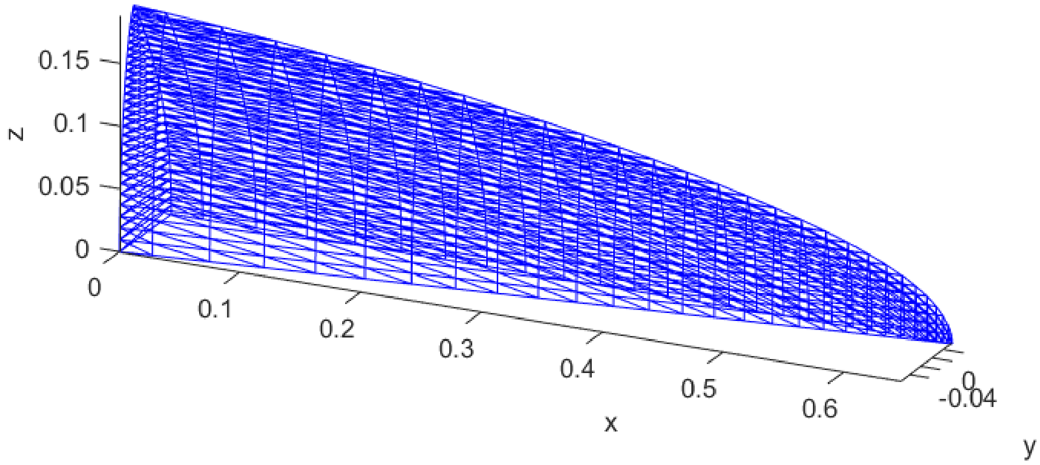

Fig 2. Mesh on the upper surface of a waverider

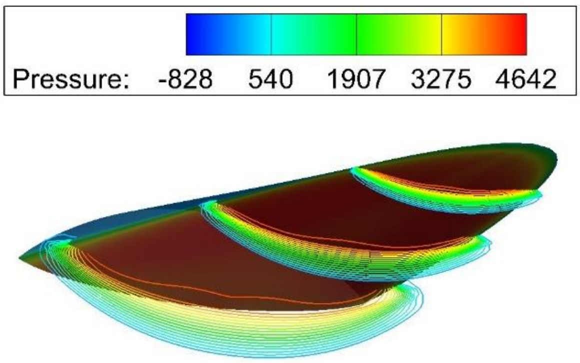

Fig 3. The computed flow field of generated waverider

Table 1. The differences between panel method and CFD

	Cl	Cd	L/D
Engineering method	0.1295	0.0216	5.80
CFD	0.1409	0.0236	5.72
Differences	8.1%	8.5%	5.2%

3.2. Optimization objectives

There are a lot of parameters that can be selected to evaluate a waverider, such as L/D, volumetric efficiency. The waverider has fixed constraints of maximum length and maximum width. The desired optimization objectives for the waverider is the maximum L/D, maximum volumetric efficiency and maximum longitudinal stability.

$$\min F = \left(-L/D, -\eta, \left(C_m Al\right)_\alpha\right)^T \tag{1.3}$$

Where,

$$\eta = V^{2/3} / S \tag{1.4}$$

refers to the volumetric efficiency. V is the volume of the waverider and S is the projected area on one plane.

Fig 4 shows the volume characteristic and L/D of 100 randomly generated waveriders. It appears that there are conflicts between the optimization direction of maximum L/D and maximum volume characteristic, as the high L/D waverider usually has a flat body which has the disadvantage of smaller volume.

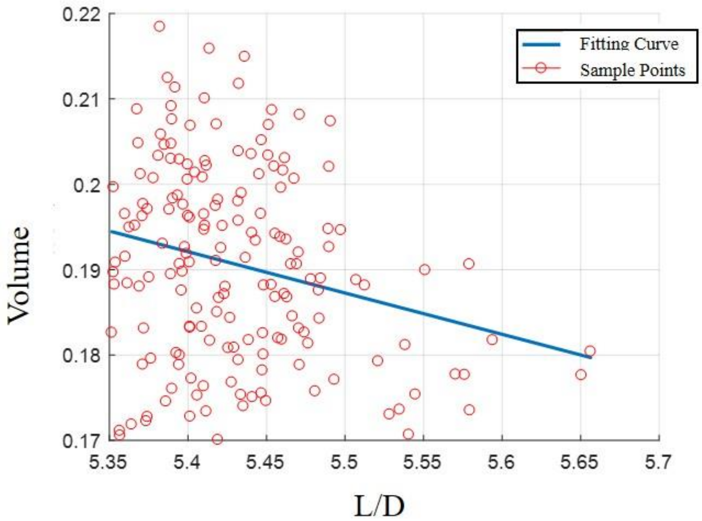

Fig 4. The distribution of sample points

4. Results

Firstly, the Tchebycheff method of MOEA/D is applied to decompose the optimization shown in Eq. (1.3). Figure 5-7 show the decomposed optimization of maximum L/D, maximum volumetric efficiency and maximum static stability respectively. For the optimization of maximum L/D (Fig 5), the optimized configuration is flat and the leading edge is sharp. Compared to the base shape, its L/D has increased 3% but its volumetric efficiency has decreased 23%. The static stability has however reduced 95%. Figure 6 shows the results of the optimization of maximum volumetric efficiency. The volumetric efficiency grows in direct proportion to the volume of the waverider. Compared to the base shape, the optimized configuration has increased its volumetric efficiency of 12.6%. The L/D has only decreased of 0.65% and the static stability has reduced 60%. Figure 7 shows the optimized configuration with maximum static stability. Compared to the base shape, the part near the head is clearly improved. Its static stability has been increased of 109% and its volumetric efficiency is increased of 4%. Its L/D is only reduced 0.35%.

There are evident conflicts among the decomposed optimizations. A sub-optimized result is required, which can compromise among the three results. The sub-optimized configuration is shown in Fig 8. Compared to the base shape, its L/D is increased 0.1%, the volumetric efficiency is increased of 0.8 % and the static stability is increased of 31%.

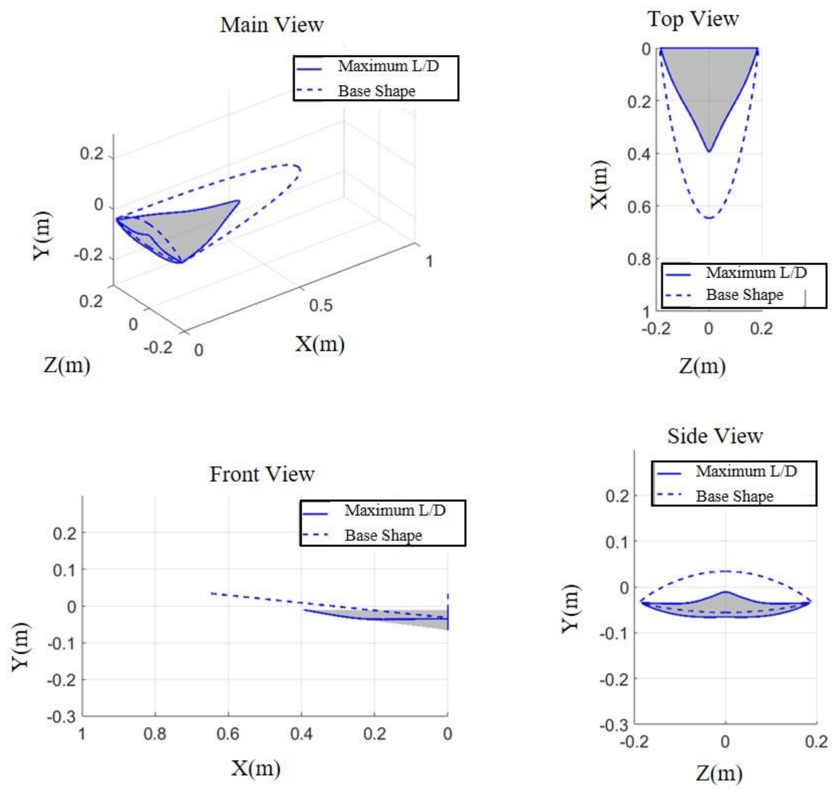

Fig 5. Maximum L/D (decomposed optimization)

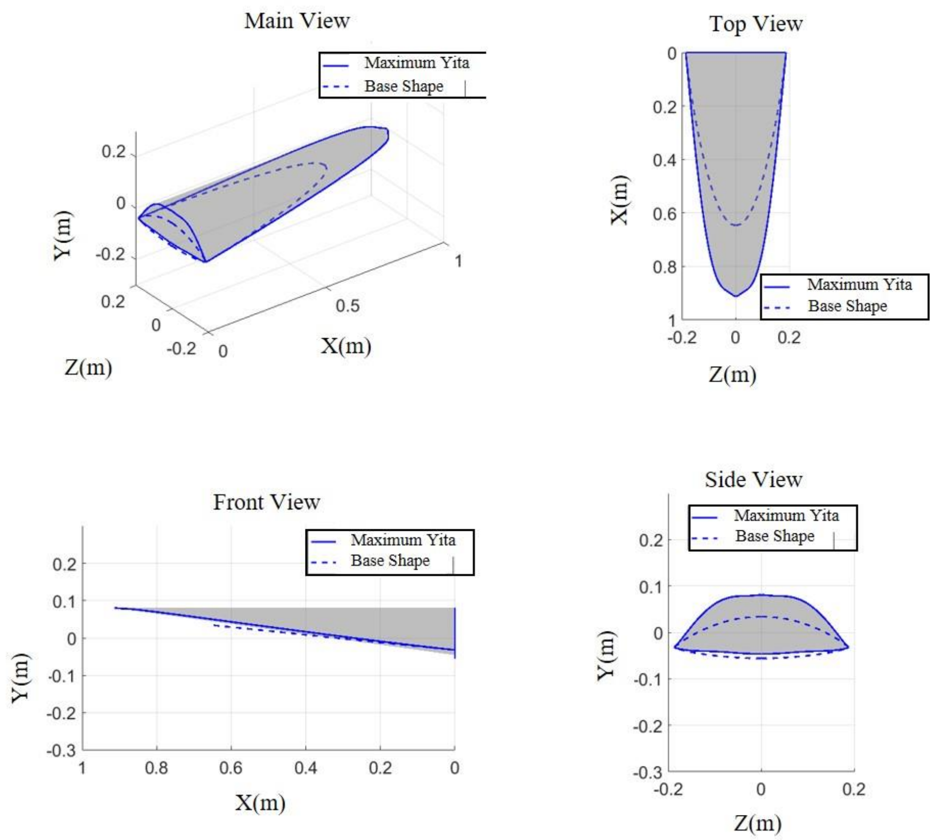

Fig 6. Maximum volumetric efficiency (decomposed optimization)

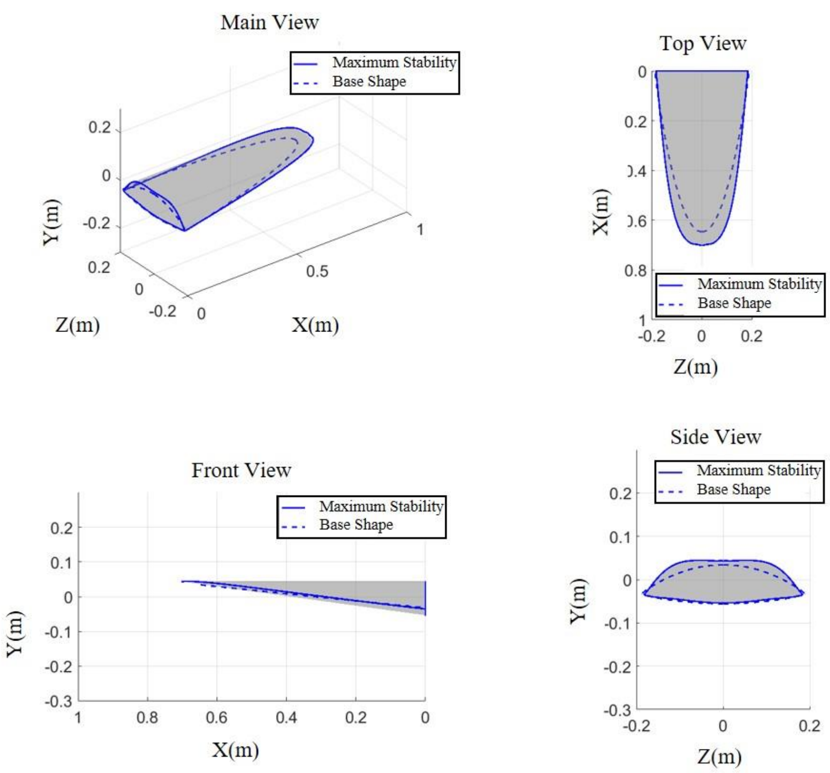

Fig 7. Maximum stability (decomposed optimization)

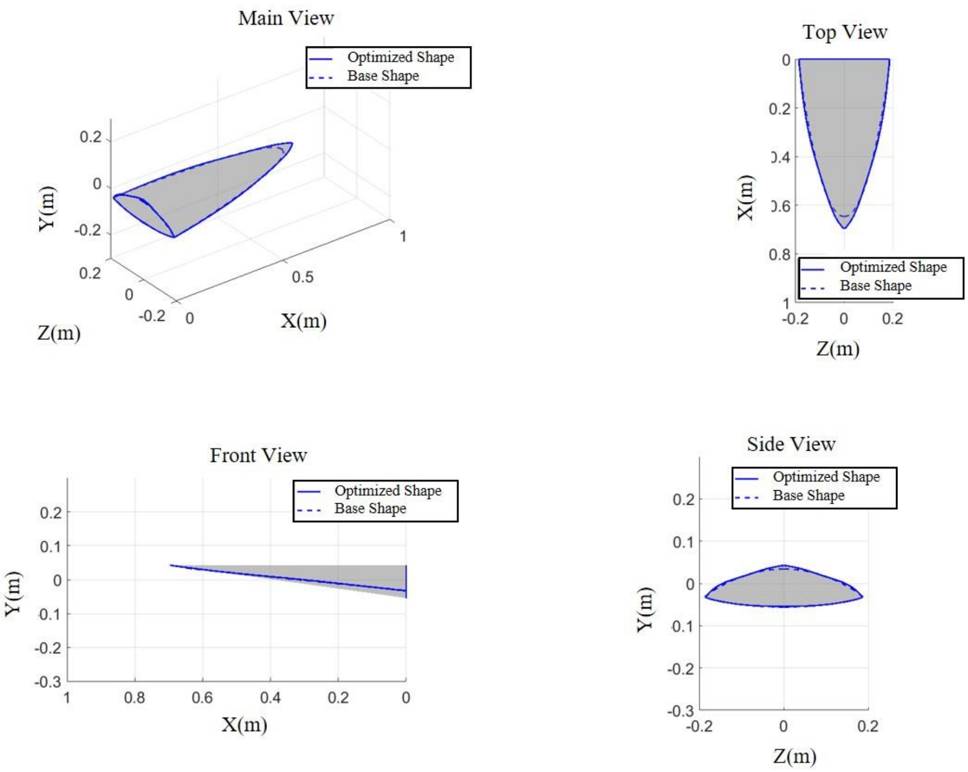

Fig 8. Optimized shape

5. Conclusions

The MOEA/D is a practical tool to design a spacecraft which derives from a waverider. High L/D can enable a comfortable re-entry for the astronauts. But a L/D near 3.0 should be enough. The optimized configuration is usually an input for further design work of the practical spacecraft. For the spacecraft, the volumetric efficiency and the static stability are more important. A high volumetric efficiency enables more space for astronauts and the equipment. The high static stability is crucial for a safe re-entry.

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