ICAS 2016
30th Congress of the International Council of the Aeronautical Sciences
DCC, Daejeon, Korea ; September 25-30, 2016

CFD-BASED AERODYNAMIC SHAPE OPTIMIZATION OF A MANNED RE-ENTRY VEHICLE

M. M. Entezari, M. Mohammadi-Amin*
*** Aerospace Research Institute, Tehran, Iran**

Keywords: *Aerodynamics, CFD, Shape Optimization, Reentry*

Abstract

Most of the methods for aerodynamic design and optimization are based on linear theory and they are not well suited for modelling non-linear phenomenon. In the present study a new method based on both linear and non-linear theories, i.e. the solution of the Navier–Stokes equations (CFD), has been applied to improve the efficiency and accuracy of the optimization. Aerodynamic optimizations of a manned re-entry capsule with respect to the lift-to-drag ratio and the effective volume are presented and discussed. The method proves to be a robust and relative efficient tool for aerodynamic design of modern vehicles. It is shown that the method keeps and sometimes expands the established knowledge base of experienced engineers but reduces the design cycle times significantly.

1 Introduction

At the higher speeds of atmospheric flight vehicles, the flow field primarily imparts a distributed, shear, and normal pressure load to the vehicle. This is a very complex and a computationally intensive problem and to run a direct shape/structural/controls optimization covering stress analysis, thermal protection system design and especially aerodynamics is still a formidable computational challenge due to very large CPU and memory requirements. Due to these difficulties robust tools that can manage all part of the optimization process is not available. But one of the most challenging part of optimization of reentry vehicles is aerodynamics calculations [1, 2].

Most methods for aerodynamic design and optimization, a kind of disciplinary method, are still based on linear theory [3]. They cannot or cannot exactly model nonlinear phenomenon like separations or vortices. So, the results represent only approximations of real optima. Drag coefficient is varied by configuration, angle of attack, Mach and Reynolds number. Reentry mission is involved in hypersonic, supersonic, transonic and subsonic regimes. That is hard to find an aerodynamics code that could be applicable in all regimes [4, 5].

Here, to improve the approximations, an aerodynamic optimization tool has been developed based on non-linear theory, i.e. the solution of the Euler/Navier–Stokes equations. In the present study this method is applied for aerodynamic optimizations of a manned re-entry capsule with respect to the lift-to-drag ratio and the effective volume. Also, optimizations at different Mach numbers have been carried out. All of the optimization process such as meshing, solving, changing geometry parameters and iterating are carried out automatically via an intelligent software developed for aerodynamic database generation and management. Hence, calculation cost errors that enforced by human operator have been reduced significantly.

A commercial CFD solver is employed to solve the RANS equations in conjunction with the SST k-ω turbulence model. Since the body shape is optimized for both the drag and effective volume, error in estimation of either drag or volume can lead to error in the optimized shape. Therefore both the use of appropriate turbulence model and mesh independence of computed solution are vital to the accurate flow field simulation and optimization of the body shape. The shape optimization is accomplished using a genetic algorithm (GA). All the optimization process and managing of different modules has been efficiently done through an integrated program.

2 Aerodynamic Optimization Framework

The aerodynamic optimization system is based on the repeated calculation of flowfields around three-dimensional geometries. A mathematical algorithm gives changes of the respective geometry according to an optimization strategy. Once these changes are carried out, the spatial mesh is created and the flowfield computed. The changes are characterized by the resulting aerodynamic coefficients and judged with an objective function. Finally, the mathematical algorithm determines the changes of the respective geometry, which fulfill the demands formulated through the objective function best.

In the basic structure of the framework, Input parameters are: (1) start values for the geometric and aerodynamic parameters, which are included in the optimization process; (2) constraints limiting their variations; (3) start values for the step sizes, which are used to determine gradients; and (4) the objective function. These parameters have influence on the whole system. Further input parameters are values for the geometric and aerodynamic parameters, which are not included in the optimization process, and instructions for the generation of the surface mesh, the generation of the spatial mesh and the calculation of the flowfield. These parameters have influence only in certain modules. The optimization system is a repeated cycle of four steps: geometry generation, mesh generation, flowfield calculation and optimization (Fig. 1). These steps are carried out within the program by four independent modules. Their communication is completely based on data files. Here advantages regarding easy maintenance and development predominate over disadvantages regarding higher computational effort.

The module for the geometry generation creates a geometry corresponding to the geometric parameters. The number of parameters, which are included in the optimization process, affects directly the number of optimization cycles and so the computational effort. Hence, the module for the geometry generation should be able to define a huge variety of configurations and extensive variations of these configurations with a minimum number of geometric parameters. A schematic re-entry vehicle configuration and parameters is shown in Fig. 2.

The module for the mesh generation creates a spatial mesh based on the surface mesh created by the module for the geometry generation. It has to guarantee an automatic generation of high quality within the optimization process. Furthermore, it has to guarantee an automatic generation with minimum computational effort.

The module for the flowfield calculation computes the flowfield around the geometry and determines the aerodynamic coefficients. The flowfield calculation solving the Euler/Navier–Stokes equations has by far the greatest share of the computational effort. Hence, the module should be able to carry out one calculation with minimum computational effort as well as high robustness and accuracy. By means of interpolation and data fusion, if geometry change is not significant, aerodynamic database can update by only a few accurate data of new geometry. The algorithm of aerodynamic database determination at each generation completely drawn in Fig 3.

The module for the optimization analyses, the objective function, makes a decision on the continuation of the optimization process, changes the parameters and checks the constraints. Furthermore, it has to guarantee a

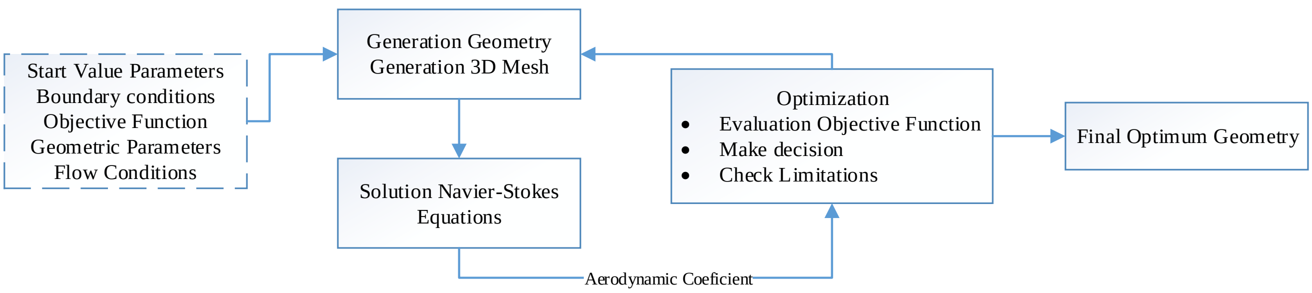

Fig. 1. Basic structure of the Aerodynamic Optimization Framework

determination with a minimum of computational effort. Genetic Algorithms (GA) are search algorithms based on the mechanism of natural selection.

They lay on one of the most important principles of Darwin: survival of the fittest. Globally we make use of the population, submitted to many transformations. After some generations, the population endues no more; the best individual represents the optimal solution. GAs do not require derivative or continuity of a function to be evaluated. They are simple, fast converging and easy to implement and simulate. As genetic algorithm works with a population of strings, they are more suitable than conventional deterministic methods for multi-objective problems.

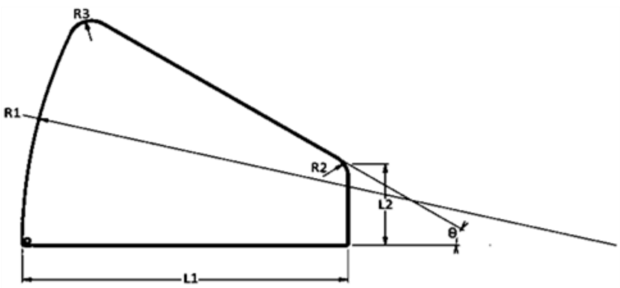

Fig. 2. Reentry Configuration and parameters

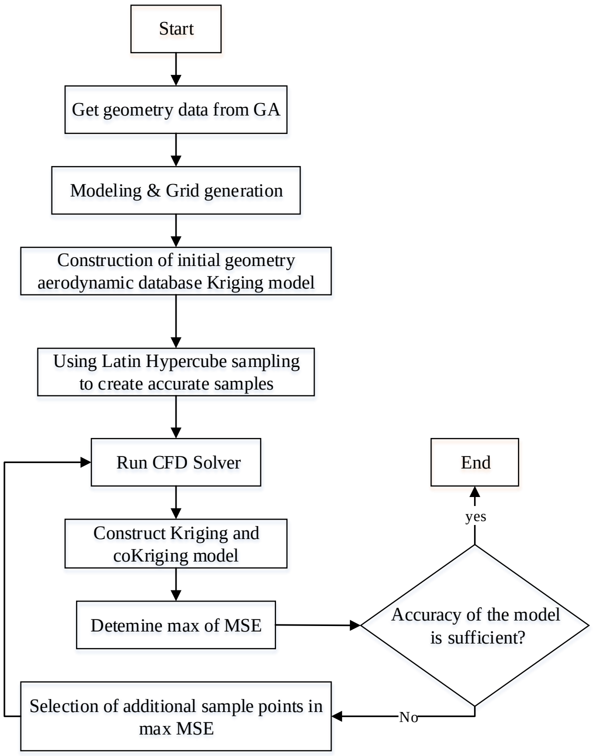

Fig. 3. Aerodynamic data generation in optimization process

Fig. 2 shows the main design parameters of a re-entry capsule. For this type of reentry vehicles, geometry is parameterized as below:

$$\begin{cases}(x-R_1)^2+y^2=R_1^2 \\ y-L_2=\tan\theta\,(x-L_1)\end{cases} \xrightarrow{yields} \begin{cases} y=\sqrt{R_1^2-(x-R_1)^2} \\ \tan\theta\,(x-L_1)+L_2-\sqrt{R_1^2-(x-R_1)^2}=0\end{cases} \qquad (1)$$

The configurations resulting from the optimizations with respect to the lift-to-drag ratio have advantages regarding the cross range, but they have disadvantages regarding the accommodation of crew, systems, etc. A coefficient to characterize the effective volume maybe defined as [4].

$$U = 6.\sqrt{\pi}.{}^{V}/_{S}{}^{3/2} \qquad (2)$$

Where V and S are the volume and the surface of the vehicle. U will be equal to 1 when the configuration is a sphere. For the front cap, S and V can be calculated as below:

$$\begin{cases} S_{cap}=\pi(a^2+h^2) \\ V_{cap}={}^{1}/_{6}\,\pi h(3a^2+h^2) \\ a=y_{intersect} \\ h=x_{intersect}\end{cases}$$

And for the cone part of vehicle, these parameters can be calculated by:

$$\begin{cases} S=\pi\times(R_1+r)\times s \\ V={}^{1}/_{3}\,\pi h({R_1}^2+r^2+R_1.r) \\ s=\sqrt{h^2+(R_1-r)^2} \\ r=L_2 \\ h=L_1-x_{intersect}\end{cases}$$

An objective function for the AOS may be defined as [4].

$$F=\omega_1.\left(\frac{L}{D}\right)\Big/\left(\frac{L}{D}\right)_{ini}+\omega_2.\left({}^{U}/_{U_{ini}}\right) \qquad (3)$$

Where ω_1 and ω_2 are weighting factors for the lift-to drag ratio and the effective volume. These weight functions show that which parameter is much more important than the others.

3 Results and Discussions

Optimizations with respect to the effective volume as well as the lift-to-drag ratio at a Mach number of M_∞ = 2.5 and an angle of attack of 20°have been carried out. The value of weighting factors for the lift-to drag ratio and the effective volume are ω_1=0.7 and ω_2 =0.3. Optimization process is start with $\theta = 18$. Final optimum shape is calculated in $\theta = 26.43$. Fig. 4 shows how optimization process converge to final optimum solution. This solution has some differences with the final geometry of Orion (about 5 degree in theta) and Fig. 5 shows how GA converging to final result. But this discrepancy may be for some design limitation that we don't know anything about them. After finding optimum geometry, we should generate aerodynamic database of the new geometry.

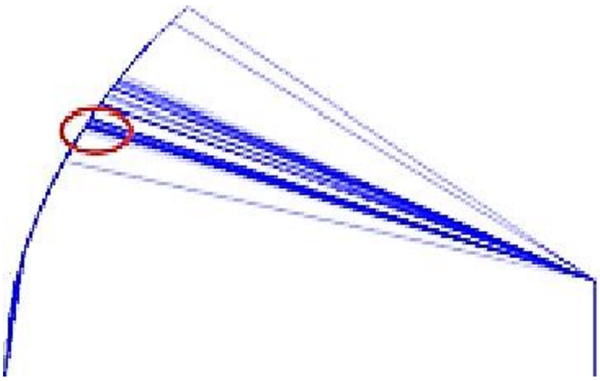

Fig. 4 optimization converging to final optimum solution.

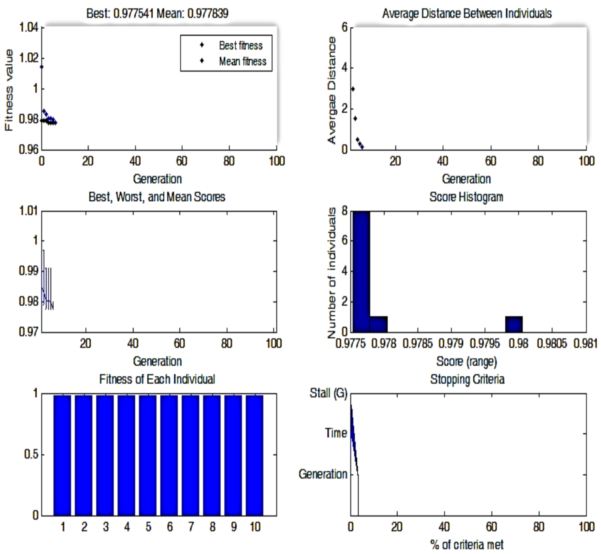

Fig. 5 Genetic Algorithm plots

Table 1. Computational cost comparison with different methods of optimization and database generation

Process	Method	Total Time	savings
Optimization	Non-automatic	12.5 Hours	--------
	Automatic	31 min. & 24 sec.	25 order faster
Aerodynamic database generation	Automatic database generation of new geometry	82 Hours & 5 min.	---------
	Updating Database of Baseline Geometry without Cokriging	24 min & 10 sec	70%
Optimization & Database Generation	Automatic Optimization, Using cokriging	24 hours and 41 min	------

By using the process that shown in Fig. 3, aerodynamic database of final geometry is calculated automatically in 24 hours and 46 min. Updating aerodynamic coefficient trend has been done with 8 new accurate aerodynamic data that these data are computed with CFD viscous solver with Intel i7 3.4 GHz processor. Table shown the comparison between different methods of optimization and data generation. Optimization process can be done automatically with coupling the CFD solver and GA code. Also database Generation can be done automatically with updating database of baseline geometry with cokriging method. As shown in Table, the fastest way of optimization and data generation occurred when optimization process has been done automatically and data generation has been done with updating baseline geometry aerodynamic database.

The results of different weighting factor are shown in Fig. 6. The result make clear that higher weighting factors for the lift-to-drag ratio lead to longer and more slender configurations with higher lift-to-drag ratios but with lower effective volume. On the other hand, higher weighting factors for the effective volume lead to shorter and compacter configurations with lower lift-to-drag ratios but with higher effective volume.

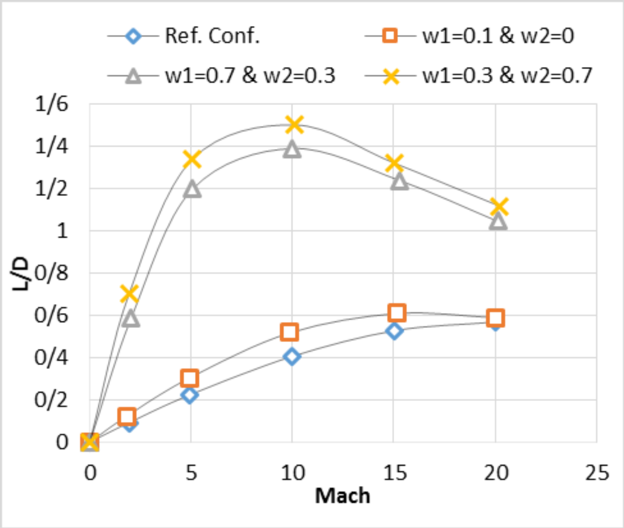

Figure 6. Comparison of lift-to-drag ratios

4 Conclusion

Aerodynamic optimizations of a re-entry capsule with respect to the lift-to-drag ratio and the effective volume have been presented and discussed. The results show that high weighting on the lift-to-drag ratio leads to long and slender capsules. On the other hand high weighting on the effective volume while satisfying stability demands leads to shorter and compacter capsules. In other words, the lift-to-drag ratio is in opposition to the effective volume. The presented aerodynamic optimization framework proves to be a robust and relative efficient tool for aerodynamic design of modem aerospace vehicles. Of course the computational effort for an optimization and aerodynamic database generation is high but an increase in the performance of computer systems will result in an increase in the efficiency as well.

References

[1] Mor M, & Livne E. Multidisciplinary Design Optimization of Reentry Vehicles: Trajectory Optimization and Sensitivities. *In 47th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference 14th AIAA/ASME/AHS Adaptive Structures Conference 7th*, pp. 1718, 2006.

[2] Beyer H G &Sendhoff B. Robust optimization–a comprehensive survey. *Computer methods in applied mechanics and engineering*, Vol. 196, No. 33,pp 3190-3218,2007.

[3] Seager C & Agarwal R K. Shape Optimization of an Axisymmetric Blunt Body in Hypersonic Flow for Reducing Drag and Heat Transfer.*53rd AIAA Aerospace Sciences Meeting, AIAA SciTech*,2015

[4] Tang W, Orlowski M, Longo J M & Giese. Aerodynamic optimization of re-entry capsules. *Aerospace science and technology*, Vol. 5, No.1,pp 15-25, 2001.

[5] Adami A, Mortazavi M, Nosratollahi M and Hosseini M, Multidisciplinary design optimization of a manned reentry mission considering trajectory and aerodynamic configuration. In *Recent Advances in Space Technologies (RAST), 2011 5th International Conference on*, pp. 598-603, IEEE2011.

Contact Author Email Address

mailto: Mmohammadi@ari.ac.ir and
Mohammadi_amin@modares.ac.ir.

Copyright Statement