Aerodynamic Design Exploration for Reusable Launch Vehicle
Using Genetic Algorithm with Navier Stokes Solver

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In this study, aerodynamic design exploration for reusable launch vehicle (RLV) is conducted using genetic algorithm with Navier-Stokes solver to understand the aerodynamic characteristics for various body configurations and find design information such as tradeoff information among objectives. The multi-objective aerodynamic design optimization for minimizing zero-lift drag at supersonic condition, maximizing maximum lift-to-drag ratio (L/D) at subsonic condition, maximizing maximum L/D at supersonic condition, and maximizing volume of shape is conducted for bi-conical shape RLV based on computational fluid dynamics (CFD). The total number of evaluation in multi-objective optimization is 400, and it is necessary for evaluating one body configuration to conduct 8 CFD runs. In total, 3200 CFD runs are conducted. The analysis of Pareto-optimal solutions shows that there are various trade-off relations among objectives clearly, and the analysis of flow fields shows that the shape for the minimum drag configuration is almost the same as that of the shape for the maximum L/D configuration at supersonic condition. The shape for the maximum L/D at subsonic condition obtains additional lift at the kink compared with the minimum drag configuration. It leads to enhancement of L/D.

Key Words: Reusable Launch Vehicle, Multi-Objective Genetic Algorithm, CFD, NSGA-II

Nomenclature

- $C_A$: axial force coefficient, axial force/($q_\infty S_{ref}$)
- $C_D$: drag coefficient, drag/($q_\infty S_{ref}$)
- $C_L$: lift coefficient, lift/($q_\infty S_{ref}$)
- L/D: lift-to-drag ratio
- $M_\infty$: free stream Mach number
- $q_\infty$: free stream dynamic pressure
- $Re$: free stream Reynolds number based on the base diameter of the body
- $S_{ref}$: reference area
- $x, y$: kink position represented by Cartesian body axis
- $\theta_{kin}$: kink angle

1. Introduction

The vertical landing reusable launch vehicle (RLV) has been proposed as one of the new space transportation systems in the next generation. Institute of Space and Astronautical Science of Japan Aerospace Exploration Agency (ISAS/JAXA) has been developing a reusable sounding rocket vehicle (RSRV)1) as the technical demonstration and the compact reusable vehicle testing (RVT) has been conducted having many experiments about liftoff and landing as shown in Fig. 1.

It is necessary to have a certain downrange during the return phase for the safety flight, as well as to minimize the aerodynamic drag during the ascent phase for the liftoff capability in the system design of RSRV. Figure 2 shows the planned sequence of the flight. The nose-entry and base-landing are considered as the flight sequence.

The aerodynamic shape design of the vehicle is indispensable to meet the design requirements, mentioned above. The ascent altitude and the downrange of the vehicle were estimated by the conventional preliminary design tools.1) The estimated results and succeeded studies show the difficulties in realization of the design requirements. It is important to learn about the aerodynamic characteristics in various flight conditions because RSRV has a greatly different body configuration from the conventional space transportation vehicles and it flies at a wide range of the flight speed and attack angles. Also, it is important to have relationship information between objectives, and between objective and design parameters. Computational fluid dynamics (CFD) is a suitable tool in the conceptual design stage of the aerodynamic configurations as it can easily evaluate aerodynamic characteristics of a large number of vehicle configurations at various flow conditions. Multi-objective
genetic algorithm is also suitable to find optimal solutions for multi-objective optimization problems, so-called “Pareto-optimal solutions”, more efficiently than other methods, e.g. hill-climb method, or grid search.

The objective of the paper is to reveal aerodynamic knowledge for shape design of RSRV from Pareto-optimal solutions obtained by using multi-objective optimization method with CFD, and to understand the aerodynamic characteristics for various body configurations. For this purpose, multi-objective design explorations for the aerodynamic configuration are conducted by using multi-objective genetic algorithm with CFD. In CFD, not only body configurations but also flow conditions can be easily changed. Thus this approach based on CFD makes it easy to conduct evaluation for various body shapes at some different flow conditions. In this study, the objectives of the optimization are minimization of the aerodynamic drag during the ascent phase, maximization of the maximum $L/D$ during the return phase and maximization of the body volume. Pareto-optimal solutions are efficiently obtained as the result of optimization with CFD. Also detailed flow field information of each body configurations is obtained. Knowledge required for the preliminary aerodynamic configuration design is discussed based on these Pareto-optimal solutions.

2. Definition of the Design Problem

The design requirements for RSRV are that the ascent altitude is more than 120 km and the downrange during the return phase is more than 30 km. In this study, multi-objective design exploration for the aerodynamic configuration is conducted with the aerodynamic evaluation base on CFD.

With regard to aerodynamic design of RSRV, several points should be considered. First, the aerodynamic drag during the launch has a great impact on the ascent altitude. The aerodynamic drag is mainly affected around the maximum dynamic pressure region, where Mach number is 2.0 and attack angle is 0 degree. Second, the maximum $L/D$ during the return phase has a great impact on the downrange. There are various flight regions during the return phase as shown in Fig. 3. The aerodynamic characteristics of the subsonic, transonic and supersonic flight regions are greatly different from each other. Although it is important to evaluate aerodynamic characteristics at all flight conditions, $L/D$ at supersonic flight region and subsonic flight region have larger impact to the downrange than transonic flight region. For this point, two flight conditions for the maximization of $L/D$ are considered; one is a subsonic flight region whose Mach number is 0.8 and the other is a supersonic flight region whose Mach number is 2.0. Third, the maximization of the body volume is also necessary in order to enlarge on-board capability for payloads, fuel and equipments.

The objective functions mentioned above are summarized as follows.

1. The drag minimization at Mach number of 2.0 and the zero angle of attack condition.
2. The maximum $L/D$ maximization at Mach number of 0.8 (subsonic condition).
3. The maximum $L/D$ maximization at Mach number of 2.0 (supersonic condition).
4. The maximization body volume

In this study, there is no upper limit of each objective function to get as various Pareto-optimal solutions as possible. On the way of design process, it is possible to select suitable design candidates from Pareto-optimal solutions.
The vehicle body is axisymmetric shape and has one kink, so-called a bi-conical configuration. Figure 4 shows the body geometry. The base diameter and the length of the vehicle body are 3 m and 10 m, respectively. The slenderness ratio is 3.33. They are the same values of geometric parameters for the RSKV currently under development at ISAS/JAXA. The lengths in the figure are non-dimensionalized by the base diameter. The design variable used in this study is the position of the kink, which are represented by the two-dimensional Cartesian body axis, shown in Fig. 4. The body geometry is changed by the position of the kink, namely \( x \) and \( y \). The exploration area of design parameter is shown in Table 1.

Other body configuration parameters such as a nose radius \( r_n \), a base corner radius \( r_c \), and a base radius \( R \) are fixed in this study, also as shown in Fig. 4. It is shown in \(^{2}\) that these fixed parameters have a small impact on the current objectives or they are difficult to be evaluated by the numerical method used in this paper. Especially, it is known that the base radius and the base corner radius have a large impact on the aerodynamic characteristics. So large-eddy simulation, which is computationally expensive method, is required to estimate the effect of these parameters precisely. In this paper, Reynolds averaged Navier-Stokes simulation, which is computationally inexpensive method is used because the aim of the present paper is to obtain the valuable knowledge required at conceptual aerodynamic design stage. Therefore, these parameters are fixed in this study.

The angle of attack and the aerodynamic coefficients (axial force coefficient \( C_n \), lift coefficient \( C_L \), and drag coefficient \( C_D \)) are defined, respectively as shown in Fig. 5. The zero-lift drag is defined as \( C_{D,0} \). With regard to the supersonic case, the maximum \( L/D \) is evaluated by a parabolic polynomial approximation, which requires three calculations with different attack angles (10, 25, and 40 degrees). As for the subsonic case, it is evaluated by a cubic polynomial approximation, which requires four calculations with different attack angles (10, 25, 40 and 55 degrees). This is because the attack angles of the maximum \( L/D \) cannot be known in advance. From previous study\(^{10}\), it was confirmed that the attack angle of maximum \( L/D \) lies within the region of the calculated attack angles, and it was confirmed that this approximation method is sufficient to evaluate the maximum \( L/D \) by validation. Flow conditions are summarized in Table 2.

<table>
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<th>Tab. 1. Exploration area.</th>
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<td>Design Parameter</td>
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### 3. Numerical Methods

#### 3.1. Flow analysis method

Three-dimensional Favre-averaged Navier-Stokes equations are employed as governing equations in this study. Convective terms are evaluated by simple low-dissipation AUSM (SLAU)\(^3\) scheme which is a family of advection-upstream-splitting-method (AUSM)\(^4\) type schemes. Here, SLAU is adopted because it is robust for shock instability. High-order space accuracy is obtained using the third order MUSCL approach\(^5\) with the interpolation of primitive variables. The viscous terms are evaluated by the usual second order central differencing scheme, and the turbulent viscosity is modeled by the Baldwin-Lomax turbulence model\(^6\) with the Degani-Schiff’s modification\(^7\). In this study, a fully turbulent flow is assumed. With regard to the time integration, alternative direction implicit symmetric Gauss-Seidel scheme\(^8\) is adopted. The CFD code applied in this work has been used in a large number of practical applications\(^9\) for many years and the reliability of the current calculation is validated for the similar configurations.\(^9\)

The computational grid is O-O topology as shown in Fig. 6. The computational domain covers half of the body. The grid contains 100 points along the body surface in the flow direction from the nose to the end of the body, 53 points in circumferential direction which are equally-divided for half of the body and 93 points in the radial direction from the body surface to the computational outer boundary. The region of the computational domain is from -20.0 to +20.0 in all directions. The base area is used as the reference area to calculate the aerodynamic coefficients. The reference length is the base diameter and Reynolds number is 10\(^7\).
The grid points in this study is 0.5 million points in total. For this computational grid, grid convergence study with the grid in higher resolution with 4 million points in total was conducted in the previous study. The result of the grid convergence study showed that present grid density is fine enough to predict trend of aerodynamic coefficients, which is required in conceptual design stage.

In this study, it takes 10 hours to conduct 1 CFD run by using 1 node of Fujitsu FX1.

3.2. Optimization method

Non-dominated solution genetic algorithm-II (NSGA-II), which is a fast and elitist multi-objective evolutionary algorithm proposed by Deb, is used to explore the design parameter space to get the optimized body geometry. Flow chart of NSGA-II is shown in Fig. 7. Initially, a random parent population is created in initialization. The parent population is evaluated by using CFD, and sorted based on Goldberg’s Pareto-ranking. Binary tournament selection in reproductive selection is used to select parent’s pairs for creating a child population. Simulated binary crossover (SBX) is applied to selected pairs to create a child population. Polynomial mutation and evaluation by using CFD is conducted for newly created child population. After this procedure, non-dominated sorting in survival selection is applied to a combined population of parent population and child population.

In this study, the size of population is 20, and the number of generation is 20. Crossover rate is 0.7. Mutation rate is 0.1.

4. Results and Discussions

In this section, results of the present study are discussed. Figure 8 is a scatter plot between $C_{D,0}$ and maximum $L/D$ at subsonic condition. Pareto-optimal solutions (non-dominated solutions) are plotted in red, and other solutions (dominated solutions) are plotted in blue. There is a weak trade-off relation between $C_{D,0}$ and maximum $L/D$ at subsonic condition. Figure 9 is a scatter plot matrix (SPM) with the correlation coefficient of the result of optimization. The correlation coefficient which is a measure of the linear dependence between two variables $X$ and $Y$, is as follows,

$$Cor = \frac{\sum_{i=1}^{N}(X_i-\bar{X})(Y_i-\bar{Y})}{\sqrt{\sum_{i=1}^{N}(X_i-\bar{X})^2} \sqrt{\sum_{i=1}^{N}(Y_i-\bar{Y})^2}} \quad (1)$$

where $N$ is the number of data set. The correlation coefficient can take value between -1 to +1. The sign of the correlation coefficient defines the direction of the relationship. A positive correlation coefficient means that as one variable increases, the other increases. A negative correlation coefficient means that one variable increases whereas the other decreases. The absolute value of the correlation coefficient measures the strength of the
correlative relationship. SPM contains all the pairwise scatter plots and correlation coefficients of the design parameters and objectives in a matrix format. Upper diagonal plots are all the pairwise scatter plots of the design parameters and objectives and lower diagonal plots are all the pairwise correlation coefficients of the design parameters and objectives. For example, the scatter plot between $C_{D,0}$ and $L/D$ at subsonic condition in Fig. 8 is displayed at the upper-left corner of upper diagonal region. Pareto-optimal solutions in Fig. 9 show that there is strong correlative relationship between $C_{D,0}$ and maximum $L/D$ at supersonic condition. This means that $C_{D,0}$ and maximum $L/D$ at supersonic condition can be improved at the same time. Whereas there is a strong trade-off relation between $C_{D,0}$ and volume of shape. These results of multi-objective optimization correspond to the results of coarse grid search in previous study\cite{10}, and it is strongly confirmed by the Pareto-optimal solutions obtained through multi-objective genetic algorithm.

Figure 10 shows the pressure distributions, streamlines on the surface and Mach number distributions on the symmetric plane of the time-averaged flow fields in subsonic flight during the return phase. Angles of attack (AOA) are 10, 25, 40 and 55. Figure 10 shows four characteristic designs in the Pareto-optimal solutions: Fig. 10a) shows the flow field around the minimum drag configuration; Fig. 10b) shows the flow field around the maximum $L/D$ configuration at subsonic flow condition; Fig. 10c) shows the flow field around the maximum $L/D$ configuration at supersonic flow condition; Fig. 10d) shows the flow field around the maximum volume condition. These designs are depicted in SPM of Fig. 9.

The shapes of the minimum drag configuration and the maximum $L/D$ configuration at supersonic flow condition are almost the same because of no tradeoff relation between two objectives. Whereas, by comparing the shape of the maximum $L/D$ configuration at subsonic flow condition with the maximum $L/D$ configuration at supersonic flow condition, the fore body part of the maximum $L/D$ configuration at subsonic flow condition is larger than the maximum $L/D$ configuration at supersonic flow condition. Interestingly, the shape of the minimum...
Fig. 10. Pressure distributions on body surface, Mach number distributions on the symmetric plane at $M=0.8$. 

(A) AOA=10 degree

(B) AOA=25 degree

(C) AOA=40 degree

(D) AOA=55 degree
drag configuration is not a conical shape, but a bi-conical shape with small kink angle. The reason why a bi-conical shape with small kink angle is better than a conical shape will be discussed in future work. It is similar to that in the previous study with coarse grid search,¹⁰ and it is strongly confirmed by the Pareto-optimal solutions obtained through multi-objective genetic algorithm in the present study.

Meanwhile, $C_D$ of the maximum volume configuration is greater than other configurations as shown in Fig.11(a). This is because there is a large separation at the kink. Close-up image of Fig.10(B-d) is shown in Fig. 12 as an example of separation part. Moreover, $C_D$ of the maximum $L/D$ configuration at supersonic condition is almost the same as the minimum drag configuration and the maximum $L/D$ configuration at supersonic condition, while $C_L$ of the maximum $L/D$ configuration at subsonic condition is larger than those two as shown in Fig. 11. As the result, maximum $L/D$ configuration at subsonic condition has higher $L/D$ than others as shown in Fig. 11(c). This indicates that lift enhancement is more important to increase $L/D$ than drag reduction during subsonic flight. Figure 13 shows the local lift coefficient distributions along the body axis for the maximum $L/D$ configuration at subsonic condition and for the minimum drag configuration. The maximum $L/D$ configuration at subsonic condition has larger lift than the minimum drag configuration at the fore body while drag coefficient distributions of these two configurations are almost the same distributions. Figure 14 shows the close-up image of Fig. 10(C-b). Pressure distribution at the kink become low as shown in Fig. 14. This indicates that flow is accelerated at the kink. As the result, lift is enhanced by kink.

Figure 15 shows the pressure distributions, streamlines on the surface and Mach number distributions on the symmetric plane of the time-averaged flow fields in supersonic flight during the return phase. Angles of attack are 10, 25 and 40 degrees. The shape configurations are same as Fig. 10. It has a shock wave in front of the body, and the shock wave in front of the body becomes stronger with increasing the semi-apex angle of the fore body and with increasing the angle of attack. Maximum volume configuration has the stronger shock wave than others.

Figure 16 shows the aerodynamic characteristics in supersonic flight during the return phase. $C_D$ becomes higher with increasing the angle of attack as shown in Fig. 16(a). This is because shock wave becomes stronger with increasing the angle of attack, mentioned above. Also $C_D$ is different among four configurations. On the other hand, trends of $C_L$ are almost the same and difference of $C_L$ is not large at all angles of attack as shown in Fig. 16(b). This indicates that drag reduction is more important to increase $L/D$ than lift enhancement during supersonic flight. As the result, maximum volume configuration has lower $L/D$ than other configurations as shown in Fig. 16(c), whereas the maximum $L/D$ configuration at supersonic flow condition has slightly higher $L/D$ than other
configurations. Note that aerodynamic coefficients computed from base region do not change and difference is observed at the fore body.

From previous study\(^1\), when \(L/D\) is more than 0.8, the downrange during the return phase is more than 30 km. With regard to max ascent altitude, it strongly depends on the rocket engine. Lift-to-drag ratios at supersonic condition and subsonic condition of the most Pareto-optimal solutions are more than 0.8. Thus Pareto-optimal solutions include a lot of solutions which satisfy the design requirement. On the way of design process, it is necessary to consider various design candidates. Therefore multi-objective design exploration based on multi-objective genetic algorithm with CFD which can find various optimal design candidates is useful.

5. Conclusion

In this paper, the multi-objective aerodynamic design optimization for minimizing \(C_{D,0}\) at supersonic condition, maximizing maximum \(L/D\) at subsonic condition, maximizing maximum \(L/D\) at supersonic condition, and maximizing volume of shape is conducted for bi-conical shaped RLV based on CFD. The total number of evaluation in multi-objective optimization is 400, and it is necessary for evaluating one body configuration to conduct 8 CFD runs. In total, 3,200 CFD runs are conducted.

The result from SPM shows that there is strong correlative relationship between \(C_{D,0}\) and maximum \(L/D\) at supersonic condition, while there is a strong trade-off relation between \(C_{D,0}\) and volume of shape. Also, there is a weak trade-off relation between \(C_{D,0}\) and maximum \(L/D\) at subsonic condition. The relationship between objective functions such as correlative and trade-off relationship are clarified by Pareto-optimal solutions obtained through multi-objective exploration with CFD based multi-objective genetic algorithm.

It is possible to obtain not only aerodynamic characteristics of each body shape but also whole information of complex flow field including shock waves by using multi-objective exploration with CFD based multi-objective genetic algorithm. From flow field analysis of four characteristic designs in the Pareto-optimal solutions, lift enhancement is more important to increase \(L/D\) than drag reduction during the subsonic flight of return phase. And lift is enhanced by kink. This indicates that the shape with a certain kink is suitable at subsonic condition. On the other hand, drag reduction is more important to increase \(L/D\) than lift enhancement during supersonic flight of return phase. Drag becomes larger with increasing shock wave strength. This indicates that the shape with small kink is suitable at supersonic condition.

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References

Fig. 15. Pressure distributions on body surface, Mach number distributions on the symmetric plane at M=2.0.

Fig. 16. Aerodynamic characteristics for supersonic cruising.