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Design Optimization of Single-Stage Launch Vehicle Using Hybrid Rocket Engine

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Abstract : The multidisciplinary design optimization (MDO) of a launch vehicle (LV) with a hybrid rocket engine (HRE) was carried out to investigate the ability of an HRE for a single-stage LV. The non-dominated sorting genetic algorithm-II (NSGA-II) was employed to solve two design problems. The design problems were formulated as two-objective cases involving maximization of the downrange distance over the target flight altitude and minimization of the gross weight, for two target altitudes: 50.0 km and 100.0 km. Each objective function was empirically estimated. Several non-dominated solutions were obtained using the NSGA-II for each design problem, and in each case, a trade-off was observed between the two objective functions. The results for the two design problem indicate that economical performance of the LV is limited with the HRE in terms of the maximum downrange distances achievable. The LV geometries determined from the non-dominated solutions were examined.

Key Words : Single-Stage rocket, Hybrid Rocket Engine, Ballistic Performance, Multi-Objective Genetic Algorithm

1. Introduction

A hybrid rocket engine (HRE) [1] is expected to be an efficient propulsion system for future space transport. It has been successfully put to practical use for SpaceShipOne [2], which completed the first private manned spaceflight. In Japan, the hybrid rocket research working group (HRErWG) has been part of the Japan Aerospace Exploration Agency (JAXA), and several studies [3][4][5][6] have been conducted on the HRE.

The HRE has a remarkably different combustion mechanism from a conventional liquid or solid rocket. The oxidizer-to-fuel ratio (O/F) for a conventional rocket can be determined before ignition, but the mixture of fuel and oxidizer in an HRE is determined after ignition. Because the O/F is determined at this point in the combustion process, the solid fuel geometry and supply control of the oxidizer have to be optimally combined to design an efficient HRE.

In an HRE, which supplies solid fuel to gas oxidized via a single port, the O/F is affected by aspects of the solid fuel design, such as the port diameter, fuel length, and mass flow of the oxidizer. In addition, the combustion process depends on the mission requirements. That is, the design results may be different for different missions. As a result, the use of multi-disciplinary optimization (MDO) is desirable in the design of HREs, which requires consideration of the rocket weight, the thrust, and the flight altitude. In authors previous study [5][6], an MDO methodology that includes a technique for evaluation of an HRE has been developed. Using this methodology, a global design for an HRE-powered

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launch vehicle (LV) that launches vertically was investigated using a multi-objective genetic algorithm (MOGA). In this work, 1-degree-of-freedom (1DoF) equation of motion was solved to evaluate the flight altitude.

However, an LV flies not only vertically but also horizontally. Thus, the flight estimation should be enhanced from a one-dimensional analysis to a three-dimensional analysis. In this study, a flight simulation-enhanced evaluation was developed for purposes of design optimization using an arbitral optimizer, such as an evolutionary algorithm or a gradient-based method. In the flight evaluation, the flight-path angle and attitude angle were calculated separately, and the rotation of the LV was estimated. The thrust angle was assumed to be equal to the attitude angle.

After the enhancement of the evaluation method, two design problems for a single-stage LV with an HRE were solved using the non-dominated sorting genetic algorithm-II (NSGA-II), and the behavior of objective functions, such as those for the altitude, downrange distance, and total weight, was investigated. The objective functions were maximization of the downrange distance over the target altitude and minimization of the gross weight. For this problems, optimizations were carried out under the constraint that the LV should reach altitudes of 50.0 km and 100.0 km.

2. Procedure of Performance Evaluation for LV Using HRE

This study addressed the conceptual design of the LV of a single-stage HRE rocket, which has a thrust chamber, an oxidizer tank, a nozzle, and a payload (Fig. 1). The combustion chamber has solid fuel, with a single port to supply the oxidizer. The performance of an HRE can be estimated by the regression rate, which depends on the mass flux. Figure 2 shows the overview of the evaluation procedure [5][6]. In general, the regression rate of the fuel in the radial direction $\dot{r}_{port}(t)$ governs the thrust and determines the performance of the LV. This regression rate $\dot{r}_{\text{port}}(t)$ is expressed as a function of the mass flux of the oxidizer through the fuel port $G_{\text{oxi}}(t)$ as follows.

$$\dot{r}_{\text{port}}(t) = aG_{\text{oxi}}^{n}(t) \tag{1}$$

The coefficient a and index n are evaluated by testing with several propellants, and Eq. 1 is empirically defined. Using Eq. 1, $\dot{r}_{\text{port}}(t)$ can be used to estimate the oxidizer-to-fuel ratio at time *t*. After the thrust is estimated, the following 3-degree-of-freedom (3DoF) equation of motion is calculated to simulate the flight of the LV.

$$\begin{cases} \frac{d^2x}{dt^2} = (T-D)\cos\theta \\ \frac{d^2y}{dt^2} = (T-D)\sin\theta - g \\ \frac{d^2\theta}{dt^2} = \sum_{i=1}^{5}(L_i/I_i) \end{cases} \tag{2}$$

where $N(t)$ is the normal component of the aerodynamic force.

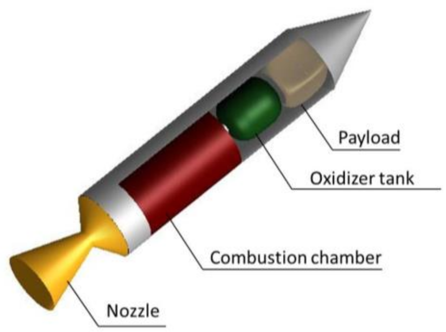


Fig. 1 Conceptual illustration of the HRE

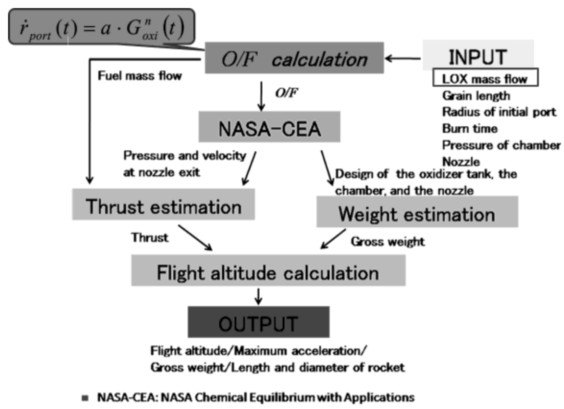


Fig. 2 Conceptual illustration of the HRE

3. Optimization Method

3.1. Non-dominated Sorting Genetic Algorithm-II (NSGA-II)

Genetic algorithms are popular heuristic optimization techniques that use operators such as selection, crossover, and mutation. The non-dominated sorting genetic algorithm-II (NSGA-II) [8][9] is employed in this study. NSGA-II is characterized by non-dominated sorting and crowding distance sorting. Based on these sorting combining elitism, the new generation is filled until the population size exceeds the current population size.

3.2. Parallel Coordinate Plot (PCP)

A parallel coordinate plot (PCP) is a statistical visualization technique used to convert high-dimensional data into two-dimensional graphs. [6] To generate a PCP, the attribute values in the design problem, such as the design variables, objective functions, and constraint values, have to be normalized for comparison along the same axis. After normalization, the axes are arranged in consistent parallel lines. In general, the distances between each line and the next are equivalent. Using a PCP, it is easy to inspect the design problem at a glance.

4. Formulations

3.1. Non-dominated Sorting Genetic Algorithm-II (NSGA-II)

Two objective functions are considered: maximization of the downrange distance of the LV, $DR_{\max}$, and minimization of M_{tot}. In addition, $Alt_{\max}$ must be greater than Alt_{target}. The geometric aspect ratio of the vehicle L/D is limited to 25.0, and the LV is to deliver a 40-kg payload, as in Problem1. The design problem can be expressed as follows:

$$\begin{cases} \text{Minimize} \;\; DR_{\max} \\ \text{Minimize} \;\; M_{\text{tot}} \\ \quad \text{Subjectto} \;\; L/D \leq 25.0 \\ \quad \text{Subjectto} \;\; Alt_{\max} \geq Alt_{\text{target}} \end{cases} \tag{3}$$

In this study, Alt_{target} was set to 50.0 km for the desi gn problem referred to as Problem1 and 100.0 km fo r the design problem referred to as Problem2.

5. Results

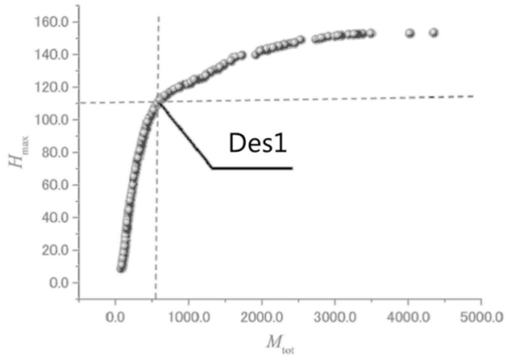
5.1. Exploration Results by Means of NSGA-II

Figure 3 shows a comparison of the non-dominated solutions for Problem1 and Problem2. According to Figure 3(a), the maximum $DR_{\max}$ is approximately 180.0km for an altitude of 50 km. The results for Problem1 suggest that an LV that flies less than 160.0km downrange is an economical design for a 50.0km altitude. According to Figure 3(b), the maximum $DR_{\max}$ is approximately 180 km for an altitude of 100 km, as in Problem2. The non-dominated solution has an inflection point at approximately $DR_{\max} = 170.0$ km and $M_{\text{tot}} = 900.0$ kg. As a result, M_{tot} increases rapidly if the designer wants to obtain a design that yields a value of more than 170.0 km for $DR_{\max}$. Thus, these results suggest that an LV that flies less than 170.0 km downrange is an economical design for a 100.0km altitude.

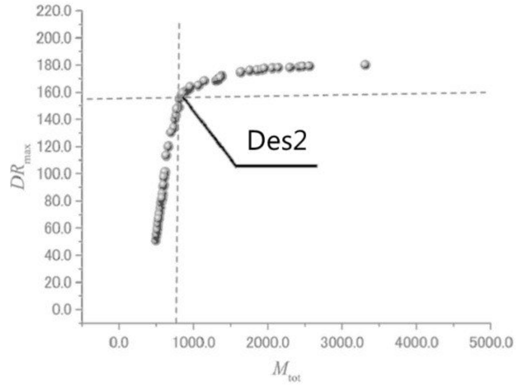
5.2. Exploration Results by Means of NSGA-II

Figures 4 (a)-(b) show the design examples obtained by solving Problem1 and Problem2. Each example is a compromise solution selected in the vicinity of the inflection point of the non-dominated solution, as shown in Fig. 3.

Figure 4 (a) shows Des1, which can achieve $H_{\max} = 110.0$km. The rocket diameter of Des1 is 0.34 m, which is similar to the size of the JAXA's solid fuel LV, S-210, which can fly at an altitude of approximately 100.0 km with a 40-kg payload. A comparison of Figs. 2, which were obtained by solving Problem2, shows that the L/D becomes larger when the constraint H_{target} is set higher. A narrower LV can reach higher altitudes because the aerodynamic drag is reduced.

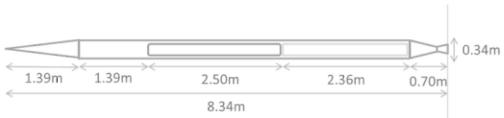


(a)

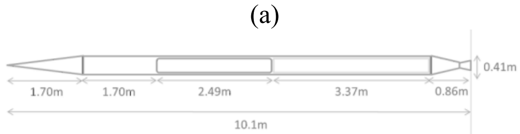


(b)

Fig. 3 Non-dominated solutions obtained by MOGA.(a)Problem1 and (b)Problem2



(a)



(b)

Fig. 4
Design examples from four cases.(a)Des1 and (d)Des2

4. Conclusions

In this study, a multi-disciplinary evaluation method for an LV with an HRE was developed, and multi-objective design was carried out by means of NSGA-II. 3-degree-of-freedom equations of motion were solved to determine the downrange distance of the LV, taking into consideration the displacement of the center of gravity due to fuel burn. The evaluation process developed in this study was used to consider two design problems.

According to the MOGA results, each problem demonstrates the trade-off between the objective functions with respect to the inflection point. The inflection points also indicate the upper limit of economical LV design. Drawing the compromised solution from the non-dominated solution, the LV's aspect ratio becomes larger when the target altitude is set higher in the case of maximization of the down range distance.

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