DOI: 10.13009/EUCASS2017-391

Performance Evaluation of Altering-intensity Swirling-Oxidizer-Flow-Type Hybrid Rocket Using Multi-Disciplinary Optimization

Masahiro Kanazaki⋆† *Kazuhisa Chiba, Kiki Kitagawa, and Toru Shimada*
⋆*Tokyo Metropolitan University*
6-6, Asahigaoka, Hino, Tokyo, Japan
kana@tmu.ac.jp
†Corresponding author

Abstract

This study investigated the efficiency of an altering-intensity swirling-oxidizer-flow-type (A-SOFT) hybrid rocket (HR) by performing a multi-disciplinary design optimization. In this study, the coefficient of fuel regression rate, which represents the strength of the oxidizer in terms of the fuel, was controlled to simulate the A-SOFT concept. A multi-objective genetic algorithm was applied to explore the optimal design. The design results indicate that non-dominated solutions for a launch vehicle (LV) with an A-SOFT HR are superior to those for an LV using a SOFT HR for both single-stage and multi-stage LVs. This result suggests that the A-SOFT HR can be expected to provide engine performance beyond what is obtainable with a SOFT HR.

1. Introduction

The hybrid rocket (HR) uses a liquid oxidizer (LOX) and a solid fuel. This rocket has the advantages of being highly safe, inexpensive, and environment-friendly in comparison with liquid and solid fuel rocket engines. Therefore, the HR is expected to be a safe and green means of propulsion for future space transportations. However, a disadvantage of HRs is that it is difficult to maintain a constant oxidizer to fuel mass ratio (O/F) during combustion. As a result, HRs provide less stable thrust during combustion than fuel and solid rocket engines.

The thrust of the HR is influenced by the mass flow of the vaporized fuel, which, in turn, is determined by the oxidizer mass flow, the fuel grain length, and the inner radius of the fuel grain port. The thrust can be expected to be sufficient when these parameters are combined optimally. Because these parameters also constitute the engine geometry, they affect the weight and trajectory of the rocket. As a result, knowledge discovery techniques are desirable for the multi-disciplinary design of an HR for a launch vehicle (LV). A previous study (Kosugi et al., 2011)(Kanazaki et al., 2014) developed a multi-disciplinary optimization methodology that included a technique for an empirical-model-based evaluation of the performance of a three-stage LV with an HR. Several solutions have achieved good performance suitable for space transportation. However, performance in terms of parameters such as the maximum payload has been limited heretofore because only one HR is installed for each stage.

This study enables the maintenance of the O/F ratio by controlling the oxidizer in an altering-intensity swirling-oxidizer-flow-Type (A-SOFT)HR using an evaluation method. The developed method is applied to the conceptual design of a single stage LV for a sounding rocket as shown in Fig. 1.

Figure 1: Schematic illustration of an LV with HR.

DOI: 10.13009/EUCASS2017-391

2. Design methods

Fig. 2 shows the overview of the HR design. The evaluation procedure of an A-SOFT HR is nearly the same as that of conventional SOFT HR except for the solid fuel grain sizing required for the maintenance of the O/F. In evaluations of SOFT HR, O/F is decided based on the grain size. In contrary, the grain size is decided based on the given constant O/F in A-SOFT HR evaluations.

2.1 Evaluation of A-SOFT hybrid rocket

The HR in this study comprises of a nozzle, a chamber, an oxidizer tank, and an exterior wall in addition to the payload. A single-port fuel grain is considered here. The regression rate of the fuel is generally expressed as follows:

$$\dot{r}_{\mathrm{port}}(t) = a \times G^{n}_{\mathrm{oxi}}(t). \tag{1}$$

$G_{\mathrm{oxi}}(t)$ is the mass flux of the oxidizer that passes through the fuel grain port. The coefficient a and the exponent n are empirical parameters. The rocket size can be calculated using Eq. 1 and the burn time t_{b}, which is a design variable. The hybrid rocket engine (HRE) considered herein supplies the swirling oxidizer into the Paraffin fuel (FT-0070) (Hikone et al., 2010). a and n in Eq. (1) are determined from an experiment for a non-swirling oxidizer with the FT-0070 fuel; Consequently, Eq. 1 can be written as

$$\dot{r}_{\mathrm{port}}(t) = 0.1561 \times 10^{-3} \times G^{0.3905}_{\mathrm{oxi}}(t). \tag{2}$$

The radius of the grain port $r_{\mathrm{p}}(t)$ can be calculated as follows:

$$r_{\mathrm{p}}(t) = r_{\mathrm{p}}(0) + \int_0^t r\dot{(}\tau)d\tau. \tag{3}$$

The mass flow of the fuel $\dot{m}_{\mathrm{f}}(t)$ can be calculated as

$$\dot{m}_{\mathrm{f}}(t) = 2\pi\rho_{\mathrm{f}} r_{\mathrm{p}}(t) l_{\mathrm{f}} \dot{m}_{\mathrm{f}}(t). \tag{4}$$

In the calculations for SOFT HR, $O/F(t)$ is a timely variate, which is expressed as follows:

$$O/F(t) = \frac{\dot{m}_{\mathrm{o}}}{\dot{m}_{\mathrm{f}}}. \tag{5}$$

In the basic concept of A-SOFT HR, $O/F(t)$ is a constant used to control the swirling of the oxidizer through the fuel port. To simulate it, $\dot{r}_{\mathrm{p}}(t)$ is calculated using the following equation, which introduces the swirling factor $\alpha(t) inEq.1$.

$$\dot{r}_{\mathrm{p}}(t) = \alpha(t) \times a \times G^{n}_{\mathrm{o}}(t). \tag{6}$$

$\alpha(t)$ can be calculated as follows:

$$\alpha(t) = \frac{1}{(m_{\mathrm{f}} \times \dot{O}/F)} \tag{7}$$

Note that $\alpha(t)$ is a design variable that is used to simulate the swirling effect of the oxidizer, which can increase the regression rate. $\alpha(t)$ for the SOFT is constant, while $\alpha(t)$ for the A-SOFT is varied with time to maintain a constant O/F.

One advantage of the HR is that it can control the supplement of the oxidizer by throttling. Thus, we considered multi-stage combustion system to acquire a better efficiency. In this study, a two-stage combustion concept is considered to determine the efficiency at low and high altitudes simultaneously. In this concept, the total combustion time as shown in Fig. 3 can be expressed as

$$t_{\mathrm{b}} = t_1 + t_2 + t_{\mathrm{stop}}. \tag{8}$$

Here, t_1 and t_2 are the combustion time and O/F is changed each time. t_{stop} is the interval of the combustion.

The 3-degrees-of-freedom (equations of motion (EoM) are solved by using $T(t)$ in Eq. **??** to calculate the trajectory of the LV.

$$\begin{cases} \dfrac{d^2x}{dt^2} = T(t)\cos\theta_1(t) - D(t)\cos\theta_2(t) \; / M_{\mathrm{tot}}(t) \\ \dfrac{d^2y}{dt^2} = T(t)\sin\theta_1(t) - D(t)\sin\theta_2(t) \; / M_{\mathrm{tot}}(t) - g \\ \dfrac{d^2\theta_1(t)}{dt^2} = \dfrac{N(t)\; X_{\mathrm{c.p.}} - X_{\mathrm{c.g.}}(t)}{I(t)} \end{cases} \tag{9}$$

DOI: 10.13009/EUCASS2017-391

where, $N(t)$ is the normal component of the aerodynamic force and $N(t)$ is estimated by following approximation.

$$N(t) = \frac{1}{2}\rho(t)V^2(t)S_{\mathrm{ref}}\sin(|\theta_1 - \theta_2|). \tag{10}$$

$\rho(t)$ and $V(t)$ respectively denote the air density and velocity of launch vehicle at elapsed time t. θ_1 and θ_2 respectively describes the attitude angle of launch vehicle and the flight path angle. This equation assumes that the thrust vector is equal to the body axis. Therefore, the thrust angle is not generally identical compared with the flight pass due to the revolution of launch vehicle. $I(t)$ is the moment of inertia, which is estimated by using the coordinate of the center of gravity for the whole body $X_{\mathrm{c.g.}}(t)$ and that for the components of the body $X_{\mathrm{c.g.}}^{(n\_\mathrm{comp})}(t)$

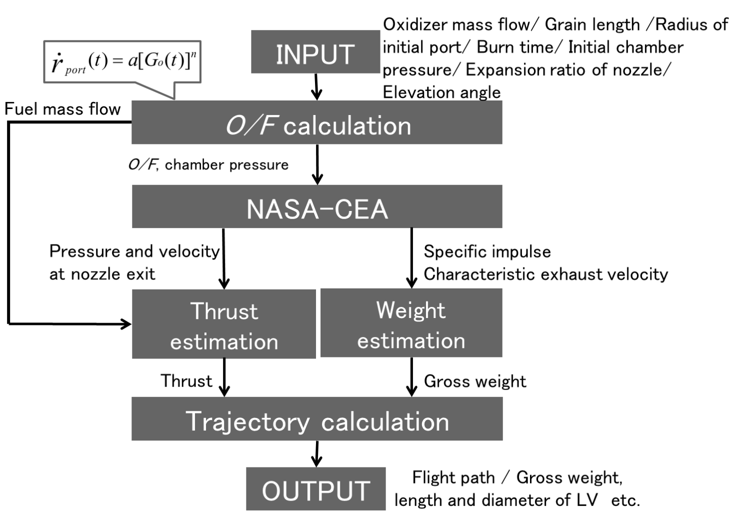


Figure 2: Evaluation procedure for HRE.

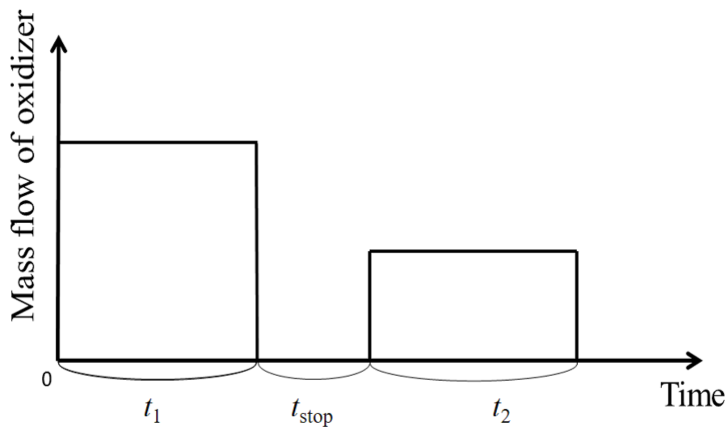


Figure 3: Schematic illustration of the combustion time of A-SOFT.

3. Design optimization

3.1 Non-dominated sorting genetic algorithm-II

Evolutionary algorithm is a popular heuristic optimization technique. Especially, genetic algorithms utilize the operators: selection, crossover, and mutation as shown in Fig. 4. The non-dominated sorting genetic algorithm-II (NSGA-II) is employed in this study, which is characterized by the use of a non-dominated sorting algorithm. In this study, the blended crossover?α (BLX?α)(Eshelman and Schaffer, 1993) is applied and the uniform mutation (Michalewicz92) carried out as genetic operators.

DOI: 10.13009/EUCASS2017-391

3.2 Visualization by parallel coordinate plot

A parallel coordinate plot (PCP) is a statistical visualization technique used to convert high-dimensional data into two-dimensional graphs(Inselberg, 1985)(Wegman, 1990). To generate a PCP, the attribute values in a design problem such as design variables, objective functions, and constraint values have to be normalized for comparison on the same axis as shown in Fig. 5. Subsequently, the axes are arranged in consistent parallel lines. Generally, the distance between one line and the next is equivalent. PCP can be used to easily investigate the design problem at a glance.

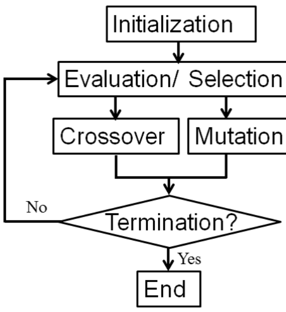


Figure 4: Flowchart of MOGA.

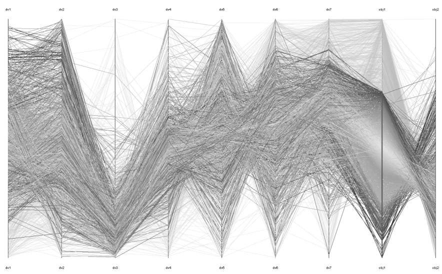


Figure 5: Visualization of image by PCP.

4. Formulation

The application of the evaluation method described above is first demonstrated by solving the altitude maximization problem while assuming that the LV flies vertically. Two objective functions were considered: one maximized the flight altitude, $Alt_{\max}$, and the other minimized the initial total mass, $M_{\mathrm{tot}}(0)$. Polypropylene, whose density was 910.0kg/m^3, was assumed as the fuel. A liquid oxidizer, whose density was 1140.0kg/m^3, was used as the oxidizer. a and n in Eq. 1 are 0.826×10^{-5} and 0.55, respectively. The design problem can be expressed as

$$\begin{cases} \text{maximize:} \quad Alt_{\max} \\ \text{minimize:} \quad M_{\mathrm{tot}}(0) \\ \quad \text{subject to:} \quad AR \leq 25 \end{cases} \tag{11}$$

Here, AR is the aspect ratio of the LV. In this study, the single-stage combustion A-SOFT HR ($t_{\mathrm{b}} = t_1$ in Eq. 8) and the conventional SOFT HR are evaluated in addition to the two-stage combustion A-SOFT HR powered LV. In the design of the two-stage combustion A-SOFT HR, $\dot{m}_{\mathrm{oxi}}$ and O/F are changed for t_1 s and t_2 s, respectively. The design variables and their ranges are listed in tables 1-3. NSGA-II for each case is performed on 200 generations with a population size of 50 for each generation.

Table 1: Design variables for A-Soft HR powered LV without single-stage combustion.

		Unit	Lower bound	Upper bound
dv1	$\dot{m}_{\mathrm{oxi}}$	kg/s	0.1	30.0
dv2	O/F	-	1.5	3.5
dv3	t_{b}	s	10.0	100.0
dv4	G_{oxi}	kg/m^{2}s.	10.0	300.0
dv5	$P_{\mathrm{ch}}(0)$	MPa	0.5	3.0
dv6	$\alpha(0)$	-	1.0	3.0
dv7	ϵ	-	5.0	20.0

Table 2: Design variables for A-Soft HR powered LV without two-stage combustion.

		Unit	Lower bound	Upper bound
dv1	$\dot{m}_{\mathrm{oxi\_1}}$	kg/s	0.1	30.0
dv2	$\dot{m}_{\mathrm{oxi\_2}}$	kg/s	0.1	30.0
dv3	O/F_1	-	1.5	3.5
dv4	O/F_2	-	1.5	3.5
dv5	t_1	s	10.0	100.0
dv6	t_{b}	s	0.0	100.0
dv7	t_2	s	10.0	100.0
dv8	G_{oxi}	kg/m^{2}s.	10.0	300.0
dv9	$P_{\mathrm{ch}}(0)$	MPa	0.5	3.0
dv10	$\alpha(0)$	-	1.0	3.0
dv11	ϵ	-	5.0	20.0

DOI: 10.13009/EUCASS2017-391

Table 3: Design variables for Soft HR powered LV.

		Unit	Lower bound	Upper bound
dv1	$\dot{m}_{\mathrm{oxi}}$	kg/s	0.1	30.0
dv2	l_{f}	m	2.0	8.0
dv3	r_{p}	s	0.05	0.5
dv4	t_{b}	kg/m^{2}s.	10.0	100.0
dv5	$P_{\mathrm{ch}}(0)$	MPa	0.5	3.0
dv6	ϵ	-	5.0	20.0

5. Results

5.1 Design exploration results

A comparison of the design exploration results is shown in Fig. 6. It is found that Alt_{max} and M_{tot} have a trade-off relationship. In addition, increments of Alt_{max} become smaller for M_{tot} =4000.0 to 5000.0 kg in single-stage and two-stage A-SOFT. In other words, an efficient A-SOFT HR can be acquired for values of M_{tot} =4000.0 to 5000.0 kg. Fig. 6 shows that the A-SOFT HR powered LV is advantageous compared to the conventional SOFT powered LV. This figure also suggests that the two-stage combustion A-SOFT HR can achieve performance similar to the existing solid LV, JAXA's S-310.

5.2 Comparison of designs using non-dominated solutions

Designs Des1, Des2, and Des3 formulated based on non-dominated solutions around M_{tot} = 700[kg] are compared as shown in Fig. 7. As shown in Fig. 7(a), the *AR* values of Des1 and Des2, which are A-SOFT HR powered LVs, are lower than that of Des3, which is a two-stage combustion HR, while the Alt_{max} of Des1 and Des2 are higher than that of Des3. As shown in Fig. 7(b), the total thrust of Des2, which is the highest thrust the two-stage combustion HR can achieve, and the Alt_{max} of Des2 were the highest as shown in Fig. 7(c). Remarkably, the Alt_{max} of Des2 is over 200% that of Des3 while the total thrust of Des2 is only 150% of Des3. In addition, Des2 could achieve 150% altitude of Des1, which is a single-stage combustion HR. These results suggest that the multi-stage combustion A-SOFT HR can improve the performance of the LV efficiently.

5.3 Visualization of the design space using PCP

Figure 8 shows the visualization of the design problem for single- and two-stage combustion A-SOFT HR and SOFT HR. The red line in the figure indicates the solution that achieves a high Alt_{max}. From Fig. 8(a), it was found that dv2($\dot{m}_{\mathrm{oxi}}$) had a wide spread. It was also found that dv2(O/F), dv4($G_{\mathrm{oxi}}(0)$), and dv6($\alpha(0)$) were constant in the single-stage combustion A-SOFT HR. A comparison of Figs. 8(a) and (c) shows that dv1($\dot{m}_{\mathrm{oxi}}$), dv4(dv3 in SOFT)(t_{b}), and dv5($P_{\mathrm{ch}}(0)$) display similar trends.

In the two-stage combustion A-SOFT HR shown in Fig. 8(b), the combustion data for first and second stages were extracted. In the first stage, it was found that dv2($\dot{m}_{\mathrm{oxi}}$) had a wide spread similar to the single-stage combustion A-SOFT HR. In this stage, dv5(t_1) should be 10 s to 45 s. In contrary, dv6(t_2) displayed unique characteristics and dv2($\dot{m}_{\mathrm{oxi}}$) was smaller. This result suggests that the first stage of the launch propels the LV through low altitudes where the dynamic pressure is high. On the other hand, the second stage of the launch carries the LV across high altitudes using a lower mass of the oxidizer by reducing dv2($\dot{m}_{\mathrm{oxi}}$).

DOI: 10.13009/EUCASS2017-391

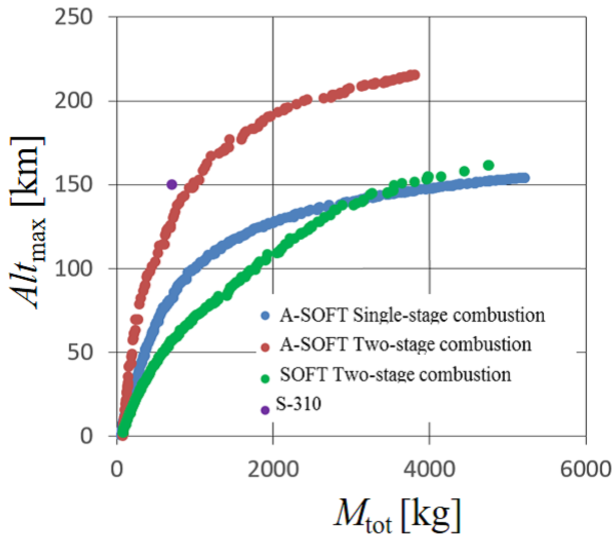


Figure 6: Comparison of non-dominated solutions obtained by MOEA among three cases.

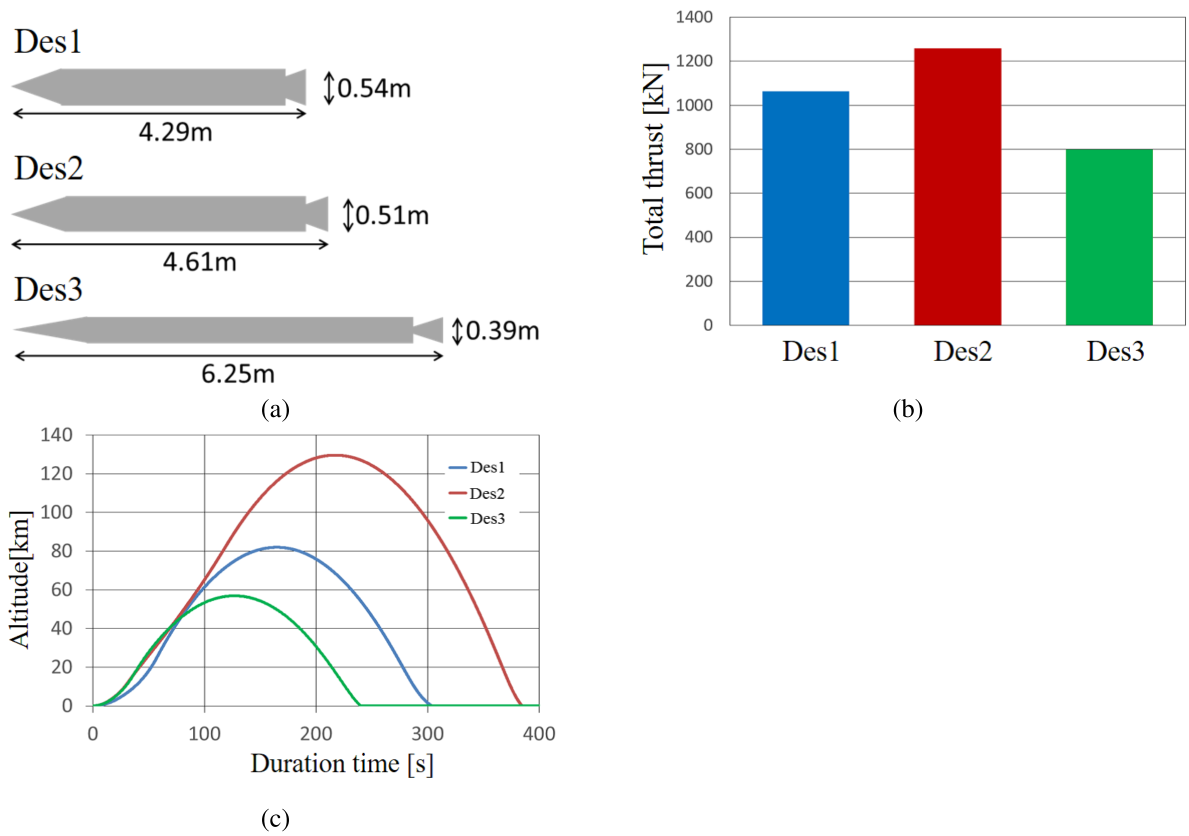
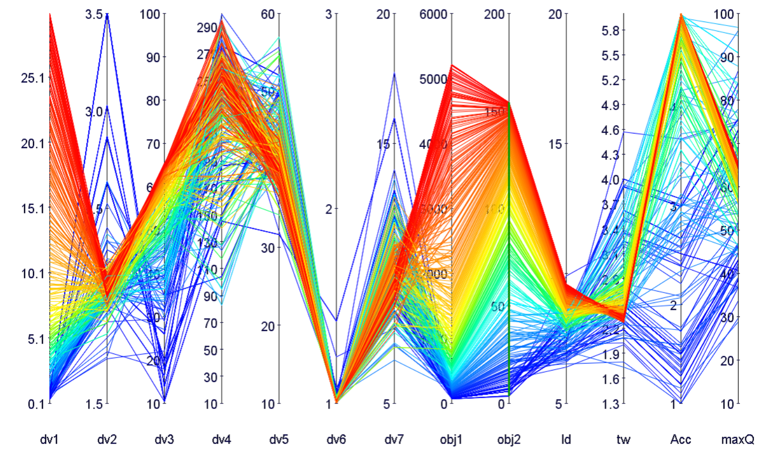
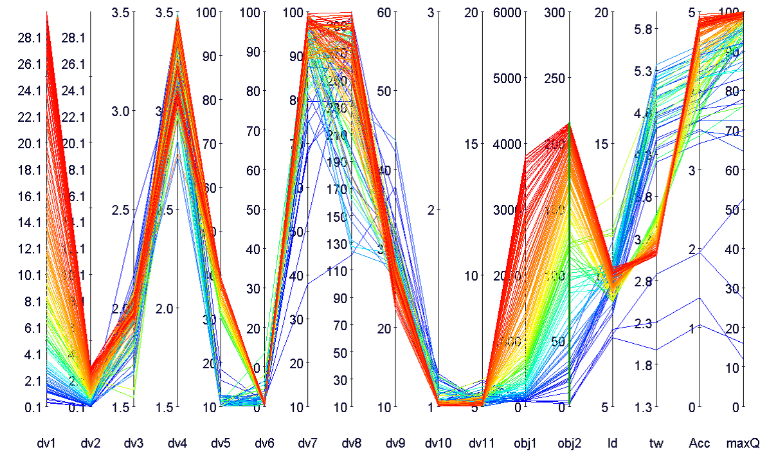


Figure 7: Comparison of designs based on the non-dominated solutions. (a)Designs of LV, (b) Thrusts of the HR under each design, and (c) Time history of the altitude for each design.

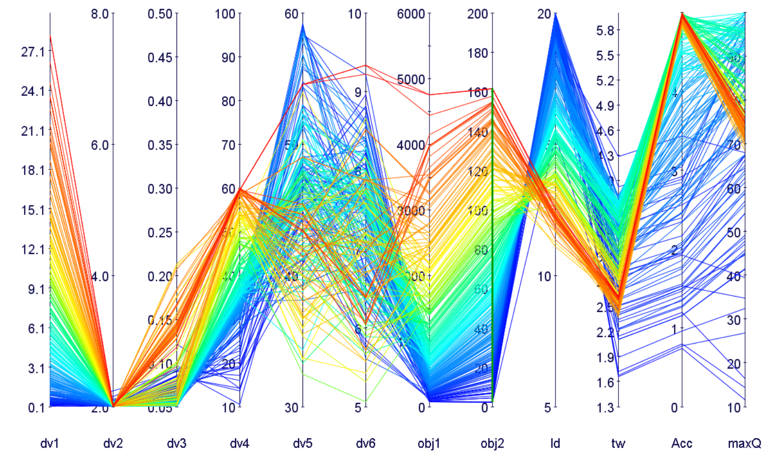
DOI: 10.13009/EUCASS2017-391



(a)



(b)



(c)

Figure 8: Comparison of design spaces of single- and two-stage combustion A-SOFT HR powered LV and SOFT HR powered LV. (a)Single-stage combustion A-SOFT HR, (b)two-stage combustion A-SOFT HR, and (c)SOFT HR.

DOI: 10.13009/EUCASS2017-391

6. Conclusions

In this study, we considered the preliminary design of a single stage LV with A-SOFT HRs. To simulate an A-SOFT HR, the coefficient that represents the swelling strength of the oxidizer was controlled to maintain a constant oxidizer to fuel mass ratio. A multi-objective genetic algorithm was applied to explore the optimal design. According to the design results, the non-dominated solutions for an LV with an A-SOFT HR are superior to those for an LV with a SOFT HR in both single stage and multi-stage LVs. This result suggests that the A-SOFT HR can be expected to provide improved engine performance and that further development of technology to control oxidizer swelling is important for future HR development.

References

[1] Eshelman, L. J., and Schaffer, J. D., Real-Coded Genetic Algorithms and Interval-Schemata, Foundations of Genetic Algorithms 2,(1993), pp. 187–202.

[2] Hikone, S, Regression rate characteristics and combustion mechanism of some hybrid rocket fuels, 46th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Nashville, Tennessee, (2010), AIAA 2010-7030.

[3] Kanazaki, M., Kanamori, F., Kitagawa, Y., Nakamiya, M., Kitagawa, K. and Shimada, T., Conceptual design: Dependence of parameterization on design performance of three-stage hybrid rocket, Journal of Fluid Science and Technology Vol. 9, No. 5, (2014), JFST0071.

[4] Michalewicz, Z., Genetic Algorithms + Data Structures = Evolution Programs.,Springer-Verlag, New York, (1992), pp. 101-103.

[5] Inselberg, A., The Plane with Parallel Coordinates, The Visual Computer, Vol. 1, No. 2, (1985), pp. 69-91.

[6] Wegman, E. J., Hyperdimensional Data Analysis Using Parallel Coordinates, Journal of the American Statistical Association, Vol. 85, No. 411, (1990), pp. 664-675.