Conceptual Design of Single-Stage Hybrid Rocket in View of Multidiscipline Using Design Informatics

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***Abstract*—Design Informatics has three points of view. First point is the efficient exploration in design space using evolutionary-based optimizer. Second point is the structuring and visualizing of design space using data mining. Third point is the application to practical problems. In the present study, a single-stage hybrid rocket design has been implemented by using design informatics. A single-stage hybrid rocket needs in order to perform the scientific observation and experiment. The primary objective of the present conceptual design is that the sufficient cross range in the ionosphere is achieved in order to observe Aurora, which is one of the recent topics in the scientific area. The achievement of mission as the observation of aurora using single-stage hybrid rocket will be investigated and efficient design will be also studied by using design informatics.**

***Index Terms*—hybrid rocket, design informatics, evolutionary optimization, data mining.**

I. INTRODUCTION

Single-stage rockets are researched and developed for scientific observations and the experiments of high-altitude zero-gravity condition, whereas multi-stage rockets are also investigated for the orbit injection of payload. The Institute of Space and Astronautical Science (ISAS), Japan Aerospace Exploration Agency (JAXA) has been managing K, L, M rockets as the representatives of solid rocket in order to contribute to the space scientific research. A next-generation single-stage rocket is necessary as well as multi-stage rocket due to the retirement of M-V and in order to promote space scientific research. Since the technologies for between single-stage and multi-stage are not independent, the solution of the fundamental physics regarding single-stage rocket is also the knowledge for multi-stage. On the other hand, the hybrid rocket using solid fuel and liquid oxidizer has been researching and developing in order to become lower cost and manage efficiently in ISAS. In the present study, single-stage hybrid rocket will be focused as a conceptual design. Although three-stage hybrid rocket is parallel studied[1], design requirements are different because of the difference of the operation objectives. A hybrid rocket offers the several advantages as higher safety, lower cost, and environmental friendly. In fact, the SpaceShipOne successfully uses a hybrid rocket for a private manned space flight. On the other hand, the disadvantage of a hybrid rocket is in its combustion. As a hybrid rocket engine has low fuel regression rate, the thrust of hybrid rocket engine is less than that of pure solid and pure liquid engines. Multidisciplinary objectives should be considered in order to improve the fuel regression rate of a hybrid rocket. Moreover, design information will be obtained in order to grasp the design space.

Although solving design optimization problems is important for many disciplines of engineering[2], the most significant part of the process is the extraction of useful knowledge of the design space from results of optimization runs. The results produced by multiobjective optimization (MOO) are not an individual optimal solution but rather an entire set of optimal solutions. That is, the result of a MOO is not sufficient from the practical point of view as designers need a conclusive shape and not the entire selection of possible optimal shapes. On the other hand, this set of optimal solutions produced by an evolutionary MOO algorithm can be considered a hypothetical design database. Then, data mining techniques can be applied to this hypothetical database in order to acquire not only useful design knowledge but also the structuring and visualizing of design space. This approach was suggested as the design informatics[3]. The goal of this approach is the conception support for designers in order to materialize innovation. This methodology is constructed by the three essences as 1) problem definition and implementation, 2) efficient optimization, and 3) structuring and visualizing of design space by data mining. A design problem including objective function, design variable, and constraint, is strictly defined in view of the background physics, then optimization is implemented in order to acquire nondominated solutions as hypothetical database. Data mining is performed for database in order to obtain design information. Mining has the role of a postprocess for optimization. Mining result is the significant observations for next design phase and also becomes the material to redefine a design problem.

In the present study, a single-stage hybrid rocket for aurora observation will be conceptually designed by using design informatics approach in order to obtain the information and also to discover the fundamental physics regarding hybrid rocket.

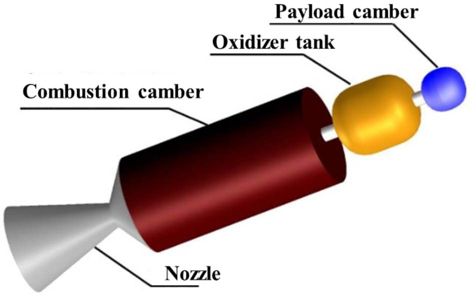

Fig. 1. Conceptual illustration of single-stage hybrid rocket.

TABLE I
LIMITATION OF LOWER/UPPER VALUES OF EACH DESIGN VARIABLE.

design variable		*design space*	
initial mass flow of oxidizer	$1.0 \leq$	$\dot{m}_{\mathrm{oxi}}(0)$ [kg/s]	≤ 30.0
fuel length	$1.0 \leq$	L_{fuel} [m]	≤ 10.0
initial radius of port	$0.01 \leq$	$r_{\mathrm{port}}(0)$ [m]	≤ 0.30
combustion time	$10.0 \leq$	t_{burn} [sec]	≤ 40.0
initial pressure in combustion	$3.0 \leq$	$P_{cc}(0)$ [MPa]	≤ 6.0
aperture ratio of nozzle	$5.0 \leq$	ϵ [-]	≤ 8.0
launch angle	$60.0 \leq$	ϕ [deg]	≤ 90.0

II. PROBLEM DEFINITION

The conceptual design for a single-stage simple hybrid rocket[4], which is composed of a payload chamber, an oxidizer tank, a thrust chamber, a nozzle, is considered in the present study.

A. Objective Functions

Two objective functions are defined in this study. One is the maximization of the duration time in the lower thermosphere (altitude of 90 to 150km) T_d [sec] (obj1). It recently turns out that atmosphere has furious and intricate motion in the lower thermosphere due to the energy injection, which occurs an aurora, from high altitude The objective of this function is to secure the time for observation of atmospheric temperature and wind in order that the elucidation of atmospheric dynamics and the balance of thermal energy. The other is the minimization of gross vehicle weight $M_{\mathrm{tot}}(0)$ [kg] (obj2).

B. Design Variables

Seven design variables are used as initial mass flow of oxidizer $\dot{m}_{\mathrm{oxi}}(0)$ [kg/sec] (dv1), fuel length L_{fuel} [m] (dv2), initial radius of port $r_{\mathrm{port}}(0)$ [m] (dv3), combustion time t_{burn} [sec] (dv4), initial pressure in combustion chamber $P_{cc}(0)$ [MPa] (dv5), aperture ratio of nozzle ϵ [-] (dv6), and launch angle ϕ [deg] (dv7). Note that there is no constraint except the limitations of lower/upper values of each design variable summarized in Table I.

C. Evaluation Method

An analysis of chemical equilibrium is performed by using NASA-CEA (chemical equilibrium with applications)[1] [5], [6], then trajectory, thrust, aerodynamic, and structural analyses are implemented. It takes roughly 10sec for the evaluation of an individual using a general desktop computer. The contents of each analysis is briefly summarized as follows.

1) Trajectory/Thrust Analysis: The following equation of motion, which ignores the influence of atmosphere, described by using $T(t)$ [N] and drag $D(t)$ [N] is computed for rocket motion.

$$M_{\mathrm{tot}}(t)\left\{a(t)-g\right\}=T(t)-D(t) \tag{1}$$

$T(t)$ is evaluated by using the following equation.

$$T(t)=\eta_T\left\{\lambda\dot{m}_{\mathrm{prop}}(t)\cdot u_e+(P_e-P_a)\cdot A_e\right\} \tag{2}$$

where, η_T is total thrust loss coefficient, λ is momentum loss coefficient at nozzle exit by friction, $\dot{m}_{\mathrm{prop}}(t)$ is mass flow of propellant, u_e is velocity at nozzle exit, P_e is pressure at nozzle exit, P_a is pressure of atmosphere at flight altitude, and A_e describes area of nozzle exit.

$$\begin{aligned}\dot{m}_{\mathrm{prop}}(t)&=-(\dot{m}_{\mathrm{oxi}}(t)+\dot{m}_{\mathrm{fuel}}(t))\\ \dot{m}_{\mathrm{fuel}}(t)&=2\pi r_{\mathrm{port}}(t)L_{\mathrm{fuel}}\rho_{\mathrm{fuel}}\;\bar{\dot{r}}_{\mathrm{port}}(t)\\ r_{\mathrm{port}}(t)&=r_{\mathrm{port}}(0)+\int\dot{r}_{\mathrm{port}}(t)dt\end{aligned} \tag{3}$$

A combustion chamber filled with solid fuel with a single port to supply oxidizer. As the regression rate to the radial direction of the fuel $\dot{r}_{\mathrm{port}}(t)$ [m/sec] generally governs the thrust power of hybrid rocket engine, it is significant parameter.

$$\begin{aligned}\dot{r}_{\mathrm{port}}(t)&=8.26\times10^{-5}\times G_{\mathrm{oxi}}^{0.55}(t)\\ &=8.26\times10^{-5}\times\left(\frac{\dot{m}_{\mathrm{oxi}}(t)}{\pi r_{\mathrm{port}}^2(t)}\right)^{0.55}\end{aligned} \tag{4}$$

where, G_{oxi} is oxidizer mass flux [kg/(m^2 sec)], $\dot{m}_{\mathrm{oxi}}(t)$ is oxidizer flow [kg/sec], and $r_{\mathrm{port}}(t)$ is radius of port [m].

2) Structural Analysis: Body is divided into the components as combustion chamber, oxidizer tank, and nozzle in order to decide weight and shape. First, total length L_{tot} is defined by using the length of combustion chamber L_{ch}, the length of oxdizer tank L_{res}, and the length of nozzle L_{noz} as follows;

$$L_{\mathrm{tot}}=1.5\times(L_{\mathrm{ch}}+L_{\mathrm{res}}+L_{\mathrm{noz}}) \tag{5}$$

It is assumed that the outside radius of fuel r_{fuel} is equal to the inside radius of combustion chamber. The outside radius of rocket R_{tot} is also defined as the outside radius of oxidizer tank.

$$R_{\mathrm{tot}}=r_{\mathrm{fuel}}+t_{\mathrm{res}} \tag{6}$$

where, oxidizer tank and combustion chamber are assumed as thin cylindrical/spherical structure. The thickness of oxidizer tank t_{res} is defined as the following equation.

$$t_{\mathrm{res}}=f_s\cdot\frac{P_{\mathrm{res}}r_{\mathrm{fuel}}}{\sigma_{\mathrm{res}}} \tag{7}$$

f_s is safety factor (in the present study, the constant value of 1.5 is set), P_{res} is the internal pressure of oxidizer tank, σ_{res}

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[1] "Chemical Equilibrium with Applications" available online at http://www.grc.nasa.gov/www/ceaweb/ceahome.htm [cited 8 November 2012].

is the allowable stress for oxidizer tank. Initial gross weight is evaluated by the following equation.

$$\begin{aligned} M_{\text{tot}}(0) &= \frac{M_{\text{prop}}(0)}{0.65} + M_{\text{pay}} \\ &= \frac{1}{0.65}(M_{\text{oxi}} + M_{\text{fuel}}) + M_{\text{pay}} \end{aligned} \tag{8}$$

M_{pay} describes mass of payload. Constant value of 0.65 represents that mass of propellant assumes 65% of gross weight. Total weight is defined as the summation of all components. The weight of each component is calculated by the product of volume and density.

3) Aerodynamic Analysis: $D(t)$ is described by using pressure drag $D_p(t)$ and friction drag $D_f(t)$ and is respectively estimated by using the flight data of S-520 as the solid rocket in ISAS.

$$\begin{aligned} D(t) &= D_p(t) + D_f(t) \\ D_p(t) &= \frac{1}{2}\rho V^2 S_{\text{ref}} C_{D_p}^{(\text{S-520})} \\ D_f(t) &= \frac{1}{2}\rho V^2 S_{\text{tot}} C_{D_f} \end{aligned} \tag{9}$$

where, S_{ref} is reference area and S_{tot} is total surface area.

$$\begin{aligned} C_{D_p}^{(\text{S-520})} &= C_D^{(\text{S-520})} - C_{D_f}^{(\text{S-520})} \cdot \frac{S_{\text{tot}}^{(\text{S-520})}}{S_{\text{ref}}^{(\text{S-520})}} \\ C_{D_f}^{(\text{S-520})} &= \frac{0.455}{(\log_{10} Re)^{2.58}} \cdot \frac{1}{(1+0.144M^2)^{0.655}} \\ Re &= \frac{VL_{\text{tot}}^{\text{S-520}}}{\nu}, \qquad M = \frac{V}{\sqrt{\gamma RT}} \end{aligned} \tag{10}$$

where, $L_{\text{tot}}^{\text{S-520}} = 8.715$ [m], specific heat ratio $\gamma = 1.4$, and gas constant $R = 287$ [J/(kg·K)].

$$\begin{aligned} C_{D_f} &= \frac{0.455}{(\log_{10} Re)^{2.58}} \cdot \frac{1}{(1+0.144M^2)^{0.655}} \\ Re &= \frac{VL_{\text{tot}}}{\nu} \end{aligned} \tag{11}$$

Kinematic viscosity coefficient ν and atmospheric temperature T are variables for altitude, referred by International Standard Atmosphere.

III. DESIGN INFORMATICS

The design informatics is constructed by two phase as optimization and data mining. Evolutionary method is used for optimization. Although a surrogate model like as the Kriging model can be employed, it will be not selected because it is difficult to deal with a large number of design variables. In addition, since the designers require to present many exact optimum solutions for the decision of a compromise one, an evolutionary-based Pareto approach as an efficient multi-thread algorithm is employed instead of gradient-based methods. The present optimizer is the hybrid evolutionary method between the differential evolution (DE) and the genetic algorithm (GA)[7]. Moreover, global design information is primarily essential. Therefore, a functional analysis of variance (ANOVA) and a self-organizing map (SOM) are used as data mining techniques because these extract the global information in design space[8].

REFERENCES

[1] Y. Kitagawa, K. Kitagawa, M. Nakamiya, M. Kanazaki, and T. Shimada, “Multi-stage hybrid rocket conceptual design for micro-satellites launch using genetic algorithm,” *Transactions of the Japan Society for Aeronautical and Space Sciences*, vol. 55, no. 4, pp. 229–236, 2012.

[2] A. Arias-Montaño, C. A. C. Coello, and E. Mezura-Montes, “Multiobjective evolutionary algorithms in aeronautical and aerospace engineering,” *IEEE Transactions on Evolutionary Computation*, vol. 16, no. 5, pp. 662–694, 2012.

[3] K. Chiba, Y. Makino, and T. Takatoya, “Design-informatics approach for intimate configuration of silent supersonic technology demonstrator,” *Journal of Aircraft*, vol. 49, no. 5, pp. 1200–1211, 2012.

[4] Y. Kosugi, A. Oyama, K. Fujii, and M. Kanazaki, “Multidisciplinary and multi-objective desgin exploration methodology for conceptual design of a hybrid rocket,” 2011, AIAA Paper 2011-1634, 2011.

[5] S. Gordon and B. J. McBride, “Computer program for calculation of complex chemical equilibrium compositions and applications i. analysis,” 1994, NASA Reference Publication RP-1311.

[6] B. J. McBride and S. Gordon, “Computer program for calculation of complex chemical equilibrium compositions and applications ii. user’s manual and program description,” 1996, NASA Reference Publication RP-1311-P2.

[7] K. Chiba, “Pure and hybrid optimizers applicable to large-scale design problem,” in *Proceedings on the 6th International Conference on Genetic and Evolutionary Computing*, 2012, pp. 409–412.

[8] K. Chiba and S. Obayashi, “Knowledge discovery in aerodynamic design space for flyback-booster wing using data mining,” *Journal of Spacecraft and Rockets*, vol. 45, no. 5, pp. 975–987, 2008.