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Extinction–reignition superiority in a single-stage sounding hybrid rocket

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ABSTRACT

Information visualization has been performed for researching a single-stage sounding launch vehicle with hybrid rocket engine by using design informatics. The primary objective of this study is to reveal extinction–reignition superiority, which is one of the beneficial points of hybrid rocket, for extending the downrange and the duration in the lower thermosphere. In our hybrid rocket, swirling-flow oxidizer is furnished with solid fuel; we adopt polypropylene for solid fuel and liquid oxygen for oxidizer. A multidisciplinary design optimization is implemented by using a hybrid evolutionary computation; data mining is carried out by using a scatter plot matrix to efficiently perceive the entire design space. It is consequently revealed that extinction–reignition prolongs duration although it does not provide any effects on spreading downrange. Scatter plot matrix results indicate physical mechanisms of design-variable behaviors for the objective functions and also the roles of the design variables via bird's-eye visualization of the entire design-space constitution. Furthermore, they suggest a hypothesis to extend downrange.

1. Introduction

Single-stage rockets have been researched and developed for scientific observations and experiments of high-altitude zero-gravity condition, whereas multi-stage rockets have been for orbit injections of payloads. Institute of Space and Astronautical Science (ISAS)/Japan Aerospace Exploration Agency (JAXA) has been operating Kappa, Lambda, Mu, and Epsilon series rockets as the representatives of solid rockets to contribute to space science research. In addition, ISAS/JAXA also operates S-series single-stage sounding solid rockets: S-210, S-300, S-310, and S-520. Since they merely flight on ballistic paths due to solid rockets, science missions must have restraints.

Hybrid rocket engines (HREs) using different phases between fuel and oxidizer (solid fuel and liquid/gas oxidizer is generally used) have been researched and developed as an innovative technology in mainly the E.U. [1] and the U.S. [2]. Each country has plans to adopt an HRE to a main engine of space transportation because of several advantages: lower cost, higher safety, and pollution free flight due to no gunpowder use. In fact, Virgin Galactic "SpaceShipOne" [3] and "SpaceShipTwo", which use HREs, are practically operated for manned private spaceflights. Moreover, Taiwan's National Space Organization recently uses HREs for sounding rockets to be applied in suborbital and low-thermospheric experiments [4]. In contrast, disadvantages of HREs proceed from their combustion. Since HREs have low regression rate of solid fuel due to turbulent boundary layer combustion, the thrust of HREs is less than that of pure-solid/liquid engines to implement premixed combustion [5]. In addition, since the mixture ratio between solid fuel and liquid/gas oxidizer (O/F) is temporally fluctuated, thrust accompanies timewise change. Research topics of HREs are improving those performances via experiments.

Now in Japan, ISAS/JAXA recently researches HREs to develop a next-generation space transportation. Research topics are vaporization of liquid oxygen, advancement of exhaust velocity c^* efficiency, progress of regression rate, stable ignition, and numerical simulations of turbulent boundary layer combustion. In contrast, we have developed the multidisciplinary design optimization system to investigate hybrid-rocket advantage via conceptual design as a part of ISAS/JAXA's hybrid-rocket project [6]. The objective of this conceptual design was to quantitatively indicate hybrid-rocket supremacy compared with the current rockets; we drove multidisciplinary design requirements: chemical equilibrium, thrust, structural, aerodynamics, and trajectory analyses as well as we visualize

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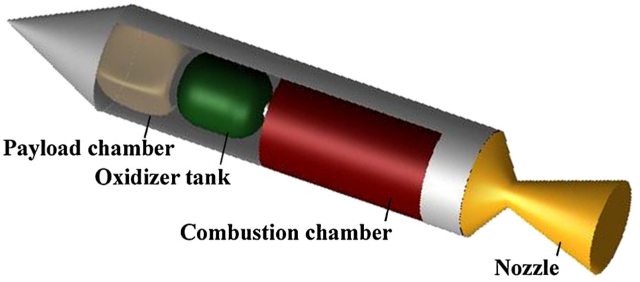

Fig. 1. Conceptual illustration of hybrid rocket.

design-space structure to understand the physics of hybrid-rocket design using design informatics (DI) [7].

DI is essential for not only an operating system itself but also its applications to practical problems so that science contributes toward the real world. Results themselves do not possess versatility in application problems due to their particularity; system versatility is indeed critical in application problems because it is revealed that the application range is expanded. Furthermore, the application results indicate the guidance for system improvements.

We researched step by step in the foregoing studies. As a first step, we defined an optimization problem on single-time ignition, which is the identical condition of the current solid rocket, to understand the performance difference between solid and hybrid rockets [8]. As a second step, the implication of solid fuels in hybrid-rocket performance was revealed because the regression rate is one of the key elements for hybrid-rocket performance [9]. Finally, the recent study indicated that we obtained the advantage to use hybrid rocket in several case studies when we operate extinction–reignition [10]. Since HREs are comparatively easy to perform multi-time ignition [11], we will positively exploit it in mission profiles.

Design strategies of our hybrid rocket system may have staging and extinction–reignition; the hybrid rocket research working group in ISAS/JAXA (HRrWG) concurrently researches both of them as candidates of a next-generation space transportation [12]. We will be able to discuss competitive edge between staging and extinction–reignition in the immediate future. However, if staging strategy is employed, we should independently set design parameters on a rocket for each stage, i.e., we should simply deal with parameter number twice that of a single stage rocket under two stages. If simple single stage rockets can take diverse science missions because extinction–reignition properly functions, they will be able to dominantly perform design, manufacture, conservation, and operation. Therefore, the objective of this study is that we will reveal extinction–reignition ascendancies of a single stage sounding hybrid rocket and design-space structure to expand science mission possibilities for aurora observation using DI.

The constitution of this study is as follows. We describe DI methods for optimization and data mining in Chapter 2. Chapter 3 shows the problem definition for designing a hybrid rocket. Optimization and data-mining results are revealed; knowledge is also discussed in Chapter 4. Chapter 5 concludes the study.

2. Problem definition

We consider a conceptual design for a single-stage sounding hybrid rocket, simply composed of a payload chamber, an oxidizer tank, a combustion chamber, and a nozzle [6] shown in Fig. 1. A launch vehicle for aurora scientific observation will be focused because more efficient sounding rockets are desired due to successful obtaining new scientific knowledge on the aurora observation by ISAS/JAXA in 2009. In addition, a single-stage hybrid rocket problem fits for resolving fundamental physics regarding HREs because of its simplicity.

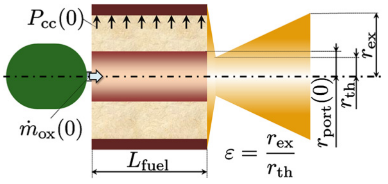

Fig. 2. Design variables for rocket geometry. ϵ is described by using the radius at the nozzle exit r_{ex} and the radius at the nozzle throat r_{th}.

Note that extinction–reignition can be implemented with no frequency limits in our simulation. But we set to be two as highly feasible times in view of HRrWG's recent experimental results [13].

2.1. Objective functions

Three objective functions are defined. First objective is maximizing the downrange in the lower thermosphere (altitude from 90 to 150 [km]) R_d [km] (obj1). Second is maximizing the duration in the lower thermosphere T_d [sec] (obj2). It recently turns out that atmosphere has furious and intricate motion in the lower thermosphere due to energy injection, from which derives aurora, from high altitude. The view of these objective functions is to secure the horizontal distance and time for competently observing atmospheric temperature and the wind so that the thermal energy balance is elucidated on atmospheric dynamics. Third objective is minimizing the initial gross weight of launch vehicle $M_{tot}(0)$ [kg] (obj3), which is generally the primary proposition for space transportation.

2.2. Design variables

We use nine design variables: initial mass flow of oxidizer $\dot{m}_{ox}(0)$ [kg/sec] (dv1), fuel length L_{fuel} [m] (dv2), initial radius of port $r_{port}(0)$ [m] (dv3), total combustion time $t_{burn}^{(total)}$ [sec] (dv4), first combustion time $t_{burn}^{(1st)}$ [sec] (dv5), extinction time from the end of first combustion to the beginning of second combustion t_{ext} [sec] (dv6), initial pressure in combustion chamber $P_{cc}(0)$ [MPa] (dv7), aperture ratio of nozzle ϵ [–] (dv8), and elevation at launch time $\phi(0)$ [deg] (dv9). The design variables for rocket geometry are visualized in Fig. 2.

Note that since this problem assumes

$$\dot{m}_{ox}(t) = \dot{m}_{ox}(0) = \text{const.}, \tag{1}$$

oxidizer mass flow is equal between 1st and 2nd combustions. Constant value is defined by dv1. The relationship among dv4, dv5, and dv6 regarding extinction-reignition operation is conceptually shown in Fig. 3. We set two combustion periods as follows:

$$\begin{aligned} t_{burn}^{(1st)} &= \begin{cases} t_{burn}^{(total)} & (t_{burn}^{(total)} < t_{burn}^{(1st)}) \\ t_{burn}^{(1st)} & (t_{burn}^{(total)} \geq t_{burn}^{(1st)}) \end{cases}, \\ t_{burn}^{(2nd)} &= \begin{cases} 0 & (t_{burn}^{(total)} < t_{burn}^{(1st)}) \\ t_{burn}^{(total)} - t_{burn}^{(1st)} & (t_{burn}^{(total)} \geq t_{burn}^{(1st)}) \end{cases}. \end{aligned} \tag{2}$$

Under $t_{burn}^{(total)} < t_{burn}^{(1st)}$ condition, it is defined that $t_{burn}^{(1st)}$ is set to be $t_{burn}^{(total)}$ and second-time combustion is not performed. Note that there is no constraint except upper/lower limits of each design variable summarized in Table 1. These upper/lower values are exhaustively covering the region of the design space which is physically admitted. When there is a sweet spot[1] in the objective-function space, the exploration space would intentionally become

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[1] The region that all objective functions proceed optimum directions.