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Uncertainty analysis and design optimization of hybrid rocket motor powered vehicle for suborbital flight

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Abstract In this paper, we propose an uncertainty analysis and design optimization method and its applications on a hybrid rocket motor (HRM) powered vehicle. The multidisciplinary design model of the rocket system is established and the design uncertainties are quantified. The sensitivity analysis of the uncertainties shows that the uncertainty generated from the error of fuel regression rate model has the most significant effect on the system performances. Then the differences between deterministic design optimization (DDO) and uncertainty-based design optimization (UDO) are discussed. Two newly formed uncertainty analysis methods, including the Kriging-based Monte Carlo simulation (KMCS) and Kriging-based Taylor series approximation (KTSA), are carried out using a global approximation Kriging modeling method. Based on the system design model and the results of design uncertainty analysis, the design optimization of an HRM powered vehicle for suborbital flight is implemented using three design optimization methods: DDO, KMCS and KTSA. The comparisons indicate that the two UDO methods can enhance the design reliability and robustness. The researches and methods proposed in this paper can provide a better way for the general design of HRM powered vehicles.

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1. Introduction

With the increasing demands for green, nontoxic and cheap propulsion technologies, hybrid rocket motors (HRMs) show great potential as they are less complex and cheaper than liquid rocket motors (LRMs), and more easily throttled and restarted than solid rocket motors (SRMs).[1–3] It makes sense to develop sub-orbit vehicles with HRMs which have such advantages as safety, cheapness and non-toxicity, since the near space of 30–100 km altitude is becoming increasingly important in scientific research and military applications in recent years. Therefore, there are many academic studies and projects about sub-orbit vehicles with HRMs recently.[4–7]

It is necessary and important to apply design optimization methods in the aerospace vehicle design process in order to improve the design level and efficiency. In the traditional design optimization methods, the input parameters are considered as deterministic values to simplify the modeling process. However, it may be inconsistent with the objective reality. Therefore, the studies on the uncertainties in the aerospace vehicle design process have important theoretical and practical values to improve the overall design level.

Compared with the traditional SRMs or LRMs, HRMs have both a liquid oxidizer feeding system and a solid fuel combustion chamber, so the system design model of HRMs has more input variables and model parameters. Moreover, since the combustion mechanism of HRMs is not fully researched at present, there are more uncertainties in the design process of HRMs. The uncertainties probably result in the fact that the optimal design results under deterministic design optimization (DDO) are infeasible or unreliable in the following manufacturing process. Nevertheless, the current studies on design optimization of HRMs or its applications typically focus on the DDO method,[4,5] so it is necessary to study the uncertainties and develop uncertainty-based design optimization (UDO) methods to enhance the design reliability and robustness. Therefore, an approach to the uncertainty analysis and design optimization of HRM powered vehicles is proposed in this paper, based on our former work about the conceptual design of HRM powered rockets.[8,9]

The main problem in UDO is the low efficiency of the uncertainty analysis when the system design model is complicated. The approximate model technology is one of the most popular methods to solve this problem. Kriging model is a widely used approximate model for its advantages such as unbiased estimator at the training sample point, desirably strong nonlinear approximating ability, flexible parameter selection of the model and accurate global approximation ability.[10,11] An approach that applying the Kriging model to two uncertainty analysis methods, i.e., Monte Carlo simulation (MCS) and Taylor series approximation (TSA), is proposed in this paper. Both newly formed methods are applied to the design optimization of the HRM powered vehicle for suborbital flight and the design results with high reliability and robustness are obtained.

2. System design model

The HRM powered sub-orbit vehicle is a ballistic rocket with an aerodynamic stable shape. The system design process involves many disciplines including structure, propulsion, aerodynamic, launching dynamics and trajectory. Each discipline is analyzed to find out possible mathematical relationships between design variables and performance parameters, such as the rocket lift-off mass M_R or the rocket body length L_R, and develop a feasible multidisciplinary design model of the rocket system.

2.1. Rocket structure design

The structure of the HRM powered rocket consists of head (containing payloads), fins, HRM and the linking structures,[8] as shown in Fig. 1. The rocket lift-off mass M_R can be obtained by

$$M_R = M_m + M_s + M_{pay} \quad (1)$$

where M_{pay} is the payload mass. The HRM mass M_m is deduced by HRM design. The rocket structure mass M_s consists of head mass, fin mass and linking structures mass. It is related to rocket diameter D_R and defined as

$$M_s = 75D_R - 7.5 \quad (2)$$

The rocket body length L_R can be obtained by

$$L_R = L_m + L_h \quad (3)$$

where L_h is the rocket head length and it is 1 m in this paper. The HRM length L_m is also deduced by HRM design.

2.2. HRM design

HRM is the main part of the rocket. Its mass and dimension almost determine the mass, dimension and trajectory of the rocket. A wheel port grain is selected in the HRM with a propellant combination of 98% hydrogen peroxide (HP) and hydroxyl-terminated polybutadiene (HTPB). A nitrogen gas pressure feed subsystem is used. The oxidizer mass flow rate is controlled to keep constant by an ideal venturi section. The HRM is designed as shown in Ref.[8] The propellant, including the solid fuel and liquid oxidizer, constitutes the

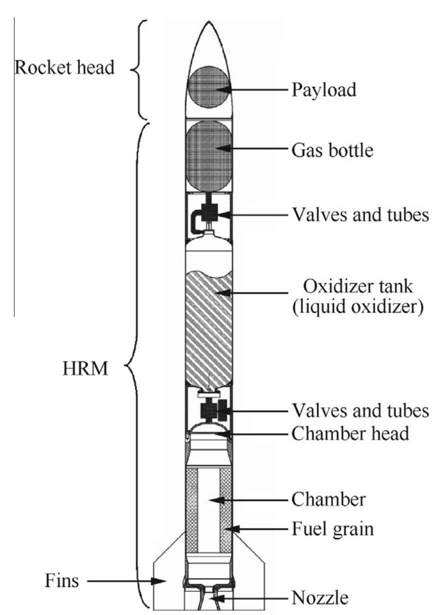

Fig. 1 HRM powered rocket structure.