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Uncertainty propagation in aerodynamic forces and heating analysis for hypersonic vehicles with uncertain-but-bounded geometric parameters

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A B S T R A C T

In this study, uncertainties in aerodynamic forces and heating properties of hypersonic vehicles are calculated and analyzed with consideration of uncertain-but-bounded geometric parameters. The aerodynamic shape of a hypersonic vehicle is created with a few geometric parameters containing physical meanings after applying the class and shape transformation (CST) method. Considering uncertainties in geometric parameters caused by manufacturing errors, interval variables are introduced to quantify geometric parameters and a novel interval-based CST method (ICST) is proposed to represent the uncertain aerodynamic shape. By means of hypersonic engineering methods, aerodynamic forces and heating properties of hypersonic vehicles can be predicted. The interval analysis method and novel Bernstein-polynomial-based method for calculating the lower and upper bounds of aerodynamic forces and heating properties are developed. The results of analyzing two numerical examples demonstrate the effectiveness and feasibility of the proposed method and further confirm the necessity of accounting for the uncertainties in geometric parameters when investigating aerodynamic forces and heating properties of hypersonic vehicles.

1. Introduction

Aerodynamic shape modeling is crucial to the successful design and analysis of hypersonic vehicles. It is generally desirable to apply a parameterization method with limited number of geometric design variables to improve the efficiency of the modeling process [1]. Indeed, parameterization methods play a significant role in hypersonic aerodynamic shape modeling (HASM) and have attracted considerable research attention in recent years [2,3].

The B-spline, based on CAD, is the most common parameterization method and is currently widely used in HASM [4]. Additionally, Kinney [5] introduced the grid-points method to represent the shape of hypersonic vehicles. Unfortunately, there are an unfavorably high number of parameters necessary when utilizing these methods due to the use of control points as design variables [6]. A more economic and efficient method called class function/shape function transformation (CST) was proposed by Kulfan [7] to represent a complex geometry with relatively fewer geometric parameters containing physical meanings. Owing to its numerous advantages [8], the CST method has been applied successfully to the design of airfoils [9], flying wings [10], and hypersonic vehicles [11].

Hypersonic vehicles experience significant aerodynamic heating during the re-entry process; to some extent, the aerodynamic forces and heating properties at work during re-entry are closely related to aerodynamic shapes [12,13]. However, to accurately model actual aerodynamic shapes is to tackle the geometric uncertainties, as any real aerodynamic shape deviates from its design due to manufacturing errors [14]. Unfortunately, the geometric parameters in the parameterization methods described above are regarded as certain variables and the effects of manufacturing errors are not properly considered.

Recent research efforts have been focused on modeling aerodynamic shapes with consideration of manufacturing errors by quantifying geometric parameters probabilistically. Welch and Sacks [15], for example, investigated manufacturing errors in geometric shapes by considering random variations in input parameters. Garzon [16] measured a large number of blades and concluded that the magnitude of manufacturing error existing in the compressor airfoil is stochastic. Similarly, the Gaussian stochastic process was utilized by Chen [17] to model the manufacturing error on an airfoil along the surface normal direction. Nevertheless, the most notable problem inherent to the probabilistic approach is that the probability distribution function must be constructed with a large amount of statistical information [18–20], while sufficient infor-

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mation regarding uncertainties is often difficult to be obtained [21–24].

As of now, non-probabilistic interval method is well-recognized as a powerful tool because it models uncertainty quantities as interval variables with upper and lower bounds and requires a relatively small amount of information [25–28]. Sederberg [29] proposed the interval representation forms of curves and surfaces to quantify the error of coefficient. Ong [30] investigated the geometric deviations on an airfoil due to manufacturing errors by perturbing the location of the critical control points within lower and upper bounds. However, to the best of our knowledge, the non-probabilistic interval method has never been used to quantify uncertainties in geometric characteristic parameters which contain physical meanings or to represent a complex aerodynamic shape like the wing of a hypersonic vehicle with geometric uncertainties.

Furthermore, variations in aerodynamic forces and heating properties are largely determined by geometric variations, which are difficult to model. For instance, the leading edge of a wing is aerodynamically heated at hypersonic velocity [31] and deviation of the aerodynamic shape may lead to the peak heat-flux fluctuations within a certain range. That is to say, uncertainties in input parameters may propagate through a simulation model to output responses. To this effect, it is necessary to accurately determine uncertainties in aerodynamic forces and heating properties of the wing of a hypersonic vehicle. In the case of uncertainties being quantified as interval variables, the interval perturbation method [32,33] and interval analysis method [34,35] can be employed for uncertainty propagation analysis. Though these methods are advantaged by the simplicity of their mathematical formulations, the assumption of a small interval and the approximate linear relation between the uncertain parameter and response limit their actual effectiveness.

As is discussed above, the aim of this study is to establish the aerodynamic shape of the wing of a hypersonic vehicle in an innovative manner by accounting for manufacturing errors and predict the corresponding aerodynamic forces and heating properties. We focus mainly on the effect of manufacturing errors on the geometric shape of the wing and aerodynamic forces and heating properties while other factors, like the shock wave produced by the airframe have not been considered because the geometric shape of the airframe does not change. That is to say, uncertainties are limited to geometric parameters of the wing in our work. The reminder of this paper is structured as follows. The modeling process of the wing with geometric uncertainties and hypersonic engineering methods (HEM) are introduced in Section 2. Two different numerical procedures for the uncertain propagation analysis of aerodynamic forces and heating properties are presented in Section 3, and Section 4 provides numerical examples. Finally in Section 5 conclusions are drawn.

2. Modeling the wing with geometric uncertainties

The aerodynamic shape of the wing of a representative hypersonic vehicle is shown in Fig. 1. Two types of shapes, namely, planform shape and cross-sectional or airfoil shape, are used to define the wing as shown in Figs. 2 and 3. The planform shape design parameters include the wing root chord length C_r, wing tip chord length C_t, control-surface width C_a, half span length L, and the curve of the leading edge.

The wing in our work is originated from a reusable aerospace plane, like X-37B and a re-entry trajectory is considered. During the re-entry process, the flight velocity of aerospace plane decreases dramatically and thus the drag makes contribution to reducing the flight velocity. On the other hand, the aerospace plane experiences significant aerodynamic heating during the re-entry process and the blunt leading edge of the wing can help to reduce the heat-flux at the stagnation point. Therefore, the "Clark-Ys" airfoil (shown in Fig. 3) is used in this work.

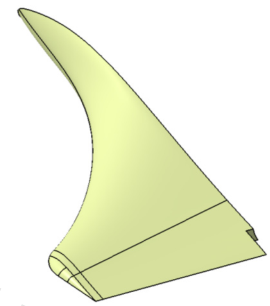

Fig. 1. Aerodynamic shape of the wing.

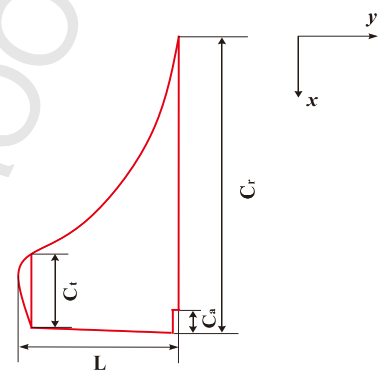

Fig. 2. Planform shape of the wing.

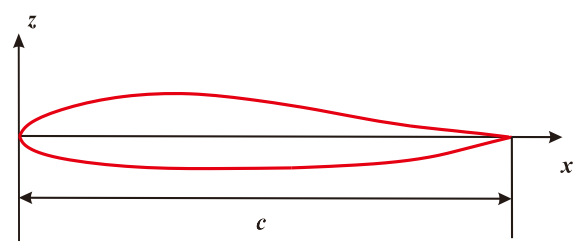

Fig. 3. Airfoil of the wing.

2.1. Fundamental CST method

A parametric geometry representation method called CST [7] is utilized to define the airfoil curves with respect to airfoil design parameters. The upper and lower airfoil curves can be expressed by combining the class function $C_{N_1}^{N_2}(\psi)$ and shape function $S(\psi)$ as follows:

$$\zeta_k(\psi) = C_{N_1}^{N_2}(\psi) \cdot S_k(\psi) + \psi \cdot \xi_k, \quad k = u, l \tag{1}$$

where c is the chord length, $\zeta = z/c$ is the non-dimensional z coordinate, $\psi = x/c$ is the non-dimensional x coordinate, $\xi = z_{te}/c$ is the non-dimensional trailing edge thickness, and the subscripts u and l denote the upper and lower curves, respectively.

The class function $C_{N_1}^{N_2}(\psi)$ which defines the classification of airfoil is:

$$C_{N_1}^{N_2}(\psi) = \psi^{N_1} \cdot (1-\psi)^{N_2} \tag{2}$$

where $N_1 = 0.5$ and $N_2 = 1$ are the class function index parameters.

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