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A review of parametric approaches specific to aerodynamic design process

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ABSTRACT

Parametric modeling of aircrafts plays a crucial role in the aerodynamic design process. Effective parametric approaches have large design space with a few variables. Parametric methods that commonly used nowadays are summarized in this paper, and their principles have been introduced briefly. Two-dimensional parametric methods include B-Spline method, Class/Shape function transformation method, Parametric Section method, Hicks-Henne method and Singular Value Decomposition method, and all of them have wide application in the design of the airfoil. This survey made a comparison among them to find out their abilities in the design of the airfoil, and the results show that the Singular Value Decomposition method has the best parametric accuracy. The development of three-dimensional parametric methods is limited, and the most popular one is the Free-form deformation method. Those methods extended from two-dimensional parametric methods have promising prospect in aircraft modeling. Since different parametric methods differ in their characteristics, real design process needs flexible choice among them to adapt to subsequent optimization procedure.

1. Introduction

Aerodynamic performance is the first consideration for aircraft design [1]. The configuration of the vehicle directly affects other performances such as voyage, ballistic trajectory, economic cost, stability, manipulation and so on [2]. Those vehicles traveling in hypersonic speed have harsher requirements for their configurations because of the special fight environment [3]. Such environment is frequently accompanied with tremendous wave drag and complex interactions within wave system, and this requires careful integration design between the airframe and the propulsion system of hypersonic cruising vehicles [4–7]. The severe heating problem in the hypersonic flow should be remitted by both active and passive heat protection schemes such as the blunt head design [8], the edge blunt design [9–12], the thermal protection shield [13], the counterflowing jet [14–17], the aerodisk design [18–21] and so on. The configuration of the vehicle always varies to adapt to the requirements of different missions and expectations. For example, the hypersonic cruising vehicle, X-51A and the hypersonic gliding vehicle, HTV-2 adopt the wave-ride configuration design to maintain a high lift-to-drag ratio [4,22] while Skylon, X-37B and SpaceLiner are all space shuttle like configurations because of their space round trip missions [3,23,24]. Besides, X-33 and IXV are both lifting bodies [25,26], and common capsules usually employ inverted taper design [13,27]. The rapid development in aeronautic and astronautic fields stimulates the innovation of new configurations. New conceptual vehicles are integrating an increasing amount of factors to make sure that the aerodynamic design coordinates with other disciplines.

There are three factors generally considered in the aerodynamic design process, namely parametric modeling, aerodynamic simulation and optimization. Parametric modeling process is expected to make the configuration be controlled numerically. It is a mapping process from geometric space to parametric space. Effective parametric process can demonstrate a large geometric space by a small amount of variables.

Parametric approach of the aircraft plays a crucial role in the aerodynamic design as well as the structural analysis process. Designers are able to control the geometry of the aircraft by several parameters defined by certain regulations. The following analysis and optimization can also be applied based on this process, thus generating configurations under given constraints and expectations. With the increasing complication of aircraft configurations and the higher accuracy requirements, it is urgent to develop parametric method with high parametric accuracy, wide parametric range, few variable requirement and sensitive response quality to parameters.

2. Traditional parametric approaches

Traditional methods adopt the controlled parameters of primary characteristics as the design variables without changing the general

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feature of the basic configuration. For instance, in the design process of conical-derived waverider, the design shock angle as well as the dihedral angle was frequently used as the design parameter with a polynomial curve being the upper base curve [28]. The booster's diameter was thought to be an influential parameter on its propulsion performance, and it was studied in Zeeshan et al.'s work [29]. Deng et al. [30] optimized the configuration of the winged aircraft, and the width, length as well as radius of the leading edge were adopted as the design variables. Huang et al. [19] investigated the influence of the aerodisk's diameter on its heat protection and drag reduction performances. The similar approach was adopted in the design process of the capsule's configuration [13]. In the integrated design process of hypersonic vehicles, the control and balance between parameters are essential. Javaid and Serghides [31] utilized four sequential slopes to represent the configuration of the two-dimensional inlet integrated in the hypersonic cruising vehicle so that they can figure out the influence of the four slope angles on the inlet's compression efficiency. Prakashand and Venkatasubbaiah [32] adopted the similar approach in the design of the inlet configuration (see Fig. 1). The hypersonic cruising vehicle designed by Zhang et al. [33] integrated the propulsion system and the airframe together based on an existing configuration. Several characteristic angles of the inlet and the nozzle were optimized to increase the lift force as well as to decrease the drag force of the entire vehicle. Chen et al. [34] made a more thorough parametric design of such configuration by taking the lengths of the components, the relative angles between aerodynamic faces et al. into account (see Fig. 2).

In the design of the internal flow path, the size of the fuel injection hole and the position of certain attached device have been frequently studied as design parameters to enhance the mixing efficiency between fuel and air [35–41]. Similarly, the size of cavity in scramjet combustor was also investigated by parametric methods [40,42]. The length of nozzle and its radius were proved to be influential to the thrust of scramjet [43,44].

This kind of parametric approach is suitable for designing configurations composed by simple straight lines and planes because it can simplify the design process and modify the characters that designers concern according to the available information. However, the requirement of the aircraft's configuration is getting more and more precise, and an increasing amount of curves and curved surfaces are adopted in the design of the aircraft. Therefore, unconventional parametric methods, which can directly control the shapes of curves and curved surfaces, are urgent in today's aircraft design.

3. Two-dimensional parametric methods

There are many two-dimensional parametric methods in common literature, and they can control the shapes of the curves directly. These approaches include B-Spline method, Class/Shape function transformation method, Parametric Section method, Hicks-Henne method and Singular Value Decomposition method, and all of them have wide application in the design of the airfoil because the airfoil is a typical curve that should be accurately designed.

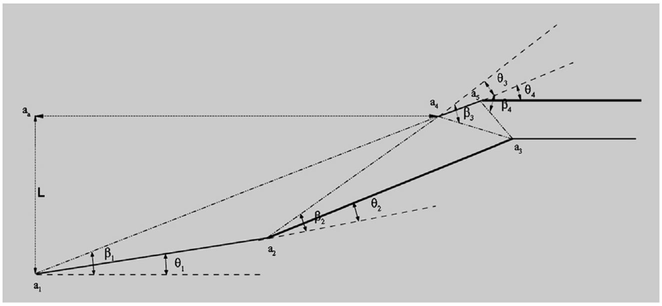

Fig. 1. Two-dimensional inlet parameterized by several sequential slopes' angle [32].

3.1. B-spline method

B-Spline has already been widely applied in the field of commercial CAD software because of its powerful local modification ability and flexible control property [45]. B-Spline function is composed by several base functions, and these base functions are summed up through some control points. Two-dimensional spline functions can be expressed as Eq. (1):

$$C(\xi) = \sum_{i=0}^{n} N_i^p(\xi)\mathbf{B}_i \quad a \le \xi \le b \tag{1}$$

In Eq. (1), a and b define the numerical range of the coordinate, ξ. When the non-dimensional coordinate is considered in this equation, we can define that $a = 0$ and $b = 1$. C is the response value of this function while N_i^p stands for the ith base function with the degree of p. $\mathbf{B_i}$ is the coordinate of the ith control point, and $i = 0,1, \ldots,n$. In the parametric problems on specific curves, like airfoils, $\mathbf{B_0}$ and $\mathbf{B_n}$ should be fixed on both ends of the curve. The chord wise ordinate of control points between the two ends can be distributed linearly or on a cosine scale [46]. That is,

$$\begin{aligned} &B_0 = (0,0), \quad B_i = \left(\frac{i-1}{n-2}, a_i\right), \quad B_{n-1} = (1, z_{te}) \\ &or\ B_0 = (0,0), \quad B_i = \left(\frac{1}{2}\left[1-\cos\left(\frac{\pi(i-1)}{n-2}\right)\right], a_i\right), \quad B_{n-1} = (1, z_{te}) \end{aligned} \tag{2}$$

Herein, a_i represents design variables with the number of n-2. Each of them controls the weight of the corresponding base curve.

Every base spline curve is the segmented polynomial defined in the node vector, T. The B-Spline function, composed by $n+1$ base functions with the order of p, has the node vector of the following form.

$$T = \left\{ \underbrace{a, \ldots, a}_{p}, \xi_{p+1}, \ldots, \xi_n, \underbrace{b, \ldots, b}_{p+1} \right\} \tag{3}$$

The nodes defined in T are distributed with an increasing sequence. Both endpoints are repeated several times to make sure that the curve passes through control points in the both ends, namely $\mathbf{B_1}$ and $\mathbf{B_n}$. It can also ensure that the curve is p order differentiable. Base function represented by $N_i^p(\xi)$ is segmented polynomial defined in T, and its value can be obtained through iteration (i.e. Eq. (4)).

$$\left\{ \begin{aligned} &N_i^0 = \begin{cases} 1 & if \\ 0 & \xi_i \le \xi \le \xi_{i+1} \end{cases} \\ &N_i^p(\xi) = \frac{\xi - \xi_i}{\xi_{i+p} - \xi_i} N_i^{p-i}(\xi) + \frac{\xi_{i+p+1} - \xi}{\xi_{i+p+1} - \xi_{i+1}} N_{i+1}^{p-1}(\xi) \\ &\text{provided: } \frac{0}{0} = 0 \end{aligned} \right. \tag{4}$$

It follows that when the base function's order p and the node vector T are defined, the curve shapes defined by n base functions will be determined. The design process specified for airfoil design actually needs n-2 design variables because of the fixed position of 2 control points in the leading and trailing edges. The design variables are the normal coordinates of the other control points. In addition, the property of base function tells that the position of each control point only influences curves' shape in the range of $k+1$ nodes around it. Therefore, B-Spline approach is typical for its powerful local control ability. For instance, Fig. 3 illustrates the comparison between NACA 2413 and the B-Spline curve composed by 9 base curves with the order of 5. The residual curve is also plotted. The shapes and distribution of the 9 base curves adopted