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Short communication

An improved geometric parameter airfoil parameterization method

Lu Xiaoqiang [a], Huang Jun [a], Song Lei [a,*], Li Jing [b]

[a] School of Aeronautic Science and Engineering, Beihang University, XueYuan Road No. 37, HaiDian District, Beijing, 100191, PR China
[b] Research and Development Center, China Academy of Launch Vehicle Technology, NanDaHong Men Road No. 1, DongGaoDi, FengTai District, Beijing, 100076, PR China

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ABSTRACT

In the process of airfoil optimization, it is required to represent an airfoil with parameters, and the goal is to represent arbitrary airfoils with less parameters. In this paper, a new airfoil parameterization method is proposed, called the IGP method, which realized camber-thickness decoupling so that camber and thickness could be constructed respectively with fewer parameters compared to the previous methods. Also the IGP method is featured with clear physical meaning and consecution of parameter domain. The mathematical model is introduced. With this camber-thickness decoupling method, the definition and the domain of the control parameters was determined. To validate the feasibility, the most used airfoils were fitted and reconstructed by this method. Then according to the results of geometric and aerodynamic comparative analysis between original airfoils and fitted airfoils, the precision of the IGP method could meet the requirement of airfoil optimization.

1. Introduction

In the design process of an aircraft, aerodynamic optimization is throughout the conceptual design and the detailed design. Airfoil parameterization methods, namely expressing an airfoil by several parameters, is fundamental for aerodynamic optimization. The reasons are twofold: on one hand, airfoil parameterization methods determine whether the design space (the search range of optimal design) could cover the alternative airfoil library; on the other hand, airfoil parameterization methods also have an important influence on the nonlinearity and continuity of the optimization problem in mathematics aspect.

Airfoil parameterization methods can be categorized as either constructive or deformative: deformative methods take an existing airfoil then deform it to create the new shape; constructive methods represent an airfoil shape based purely on a series of parameters specified [1]. For a particular shape of the airfoil, the deformative method could obtain more precise fitting effect compared with the constructive method [2,3]. However, when the alternative airfoil library is large, the constructive method can use fewer control parameters to describe more airfoils. As an airfoil parameterization method applied in an initial aircraft shape optimization of the conceptual design phase, constructive method clearly has a greater advantage.

In the past, there are many classic constructive methods during the airfoil construction. Among them, The PARSEC method uses 11 physical parameters to describe the airfoil [4]; The orthogonal basis function method (OBF method)uses orthogonal polynomial to describe the upper and lower surfaces of the airfoil, and the airfoil shape is determined by the five coefficients of the upper and lower surfaces of the airfoil [5]; Class-Shape function Transformation method (CST method) is defined by Bernstein polynomials and generally uses 11 component shape parameters to determine the shape of the airfoil [6–9].

There are three issues to be aware of in the optimization process of the airfoil by using the constructive method.

1) In the optimization process, the amount of computation increases exponentially, due to the growth of the number of variables. Under the premise that the design space could cover the alternative airfoil library, the less the number of variables, the higher the computational efficiency of the optimization process.
2) In the optimization process, the continuity of the design space should be ensured. For a curve defined by the polynomial function, the degenerate state may appear at specific parameter combinations. In this case, the degenerate state means that the curve generated by the function cannot be used as an airfoil.

* Corresponding author.
E-mail addresses: luxiaoqiang@buaa.edu.cn (X. Lu), junh@china.com (J. Huang), songlei@buaa.edu.cn (L. Song), imwoshibing@163.com (J. Li).

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Nomenclature

b_{X_C}	camber line curvature on the location of maximum camber
C	maximum camber
c_1, c_2	coefficients of camber-line-abscissa parameter equation
c_3, c_4	coefficients of camber-line-ordinate parameter equation
cov	*covariance*
k	control parameter of camber-line parameter equations
k_C	k value on the location of maximum camber
P	a new reference value for plotting (instead of R^2)
R^2	fitting correlation coefficient
T	maximum thickness
t	thickness
$t_1, \ldots, t_5$	coefficients of thickness equation
X_C	chordwise location of maximum camber
X_T	chordwise location of maximum thickness
x	abscissa (chord location)
x_C	camber line abscissa
x_l	lower surface abscissa
x_u	upper surface abscissa
y_C	camber line ordinate
y_l	lower surface ordinate
y_u	upper surface ordinate
y_{ori}	original airfoil ordinate
y_{fit}	fitted airfoil ordinate
α_{TE}	angle between camber line and chord line on trailing edge
β_{TE}	trailing edge boat-tail angle
$\overline{\beta_{TE}}$	relative quantity of β_{TE}
ρ_0	leading edge radius
$\overline{\rho_0}$	relative quantity of ρ_0
σ	variance

3) During the computation on the basis of thin airfoil theory, the camber of airfoil is the only one to be considered. If the appropriate airfoil parameterization method is applied to generate the camber and the thickness distribution functions of the airfoil respectively, only the camber is needed to be optimized in the design process, which could reduce the computational complexity and speed up the method optimization process.

Therefore, an improved geometric parameter airfoil parameterization method (the IGP method) is presented. The IGP method, as a constructive method, requires no need for the basic airfoil. In the IGP method, the camber is expressed based on the Bézier polynomial, and the thickness is expressed by the polynomial basis function. Besides the decoupling of the camber and the thickness, the IGP method is also featured with clear physical meaning and fewer control parameters compared with other methods. In addition, the control parameters of the IGP method could also be directly related to the corresponding airfoil shape parameters which are commonly used in the general aerodynamic theory.

In this paper, the part of method establishment, as the beginning part, defined the curve function parameters, geometric parameters, control parameters and the relations between them. Then by geometry fitting validation and aerodynamic validation of the 2199 airfoils in the airfoil library, the domain of the 8 control parameters was determined and the continuity of the domain above were validated to ensure the feasibility of the IGP method. In the end, the fitting of some typical airfoil was analyzed, and the applicable scope of the method was discussed.

2. Method establishment

In the conceptual design phase, during aerodynamic analysis based on the potential flow theory, it is possible to use the thin airfoil theory to simplify the calculation. The thin airfoil theory assumes that for the ideal incompressible flow of the airfoil, if the angle of attack, thickness and camber are small, then the effect of the three can be considered separately. The lift characteristic of small-thickness airfoil is determined by its camber, rather than its thickness [10]. Under the premise above, the IGP method, by decoupling the camber and the thickness, could split the aerodynamic optimization problem into two independent problem: the camber optimization and the thickness optimization. Even if the number of control parameters did not change, the IGP method could also help reduce the design space, simplify the optimization problem and speed up the optimization process. Based on that, the IGP method reduces the number of control parameters in order to further increase the computational efficiency in the process of optimization.

2.1. Parameterization expression of airfoil curves

In order to consider the camber and the thickness separately, it is necessary to determine the basis functions of both the camber and the thickness.

To avoid the appearance of the airfoil degenerate state, based on the fitting study of airfoil by various basis functions, the Bézier curve is selected to describe the camber line.

$$\begin{cases} x_C = 3c_1k(1-k)^2 + 3c_2(1-k)k^2 + k^3 \\ y_C = 3c_3k(1-k)^2 + 3c_4(1-k)k^2 \end{cases} \tag{1}$$

Among Eqn. (1), c_1, c_2 are the horizontal coordinates of the two control points of the cubic Bézier curves, and c_3, c_4 are the vertical coordinates of the two control points of the cubic Bézier curves. k is an independent parameter, whose range is $[0, 1]$.

Then, enlightened from the basis function of the thickness curve NACA "four-digit" airfoil series, the thickness expression is determined.

$$t = t_1x^{0.5} + t_2x + t_3x^2 + t_4x^3 + t_5x^4 \tag{2}$$

Based on Eqn. (1) and Eqn. (2), the airfoil expression is determined as Eqn. (3) and Eqn. (4) below.

The upper surface of an airfoil:

$$\begin{cases} x_u = x_c \\ y_u = y_C + \frac{1}{2}t(x_c) \end{cases} \tag{3}$$

The lower surface of an airfoil:

$$\begin{cases} x_l = x_c \\ y_l = y_C - \frac{1}{2}t(x_c) \end{cases} \tag{4}$$

In summary, according to Eqns. (1)–(4), 9 curve function parameters are needed to describe and construct an airfoil. As for the standard airfoil considered in this paper, trailing edge thickness is 0, then

$$t(1) = 0 \tag{5}$$