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To cite this article: Haibo Jiang *et al* 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **310** 032040

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Method for fitting wind turbine blade airfoil profile with function curve

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Abstract. This paper analyzed the characteristics of a midline -thickness function, and gave the influence of the change of the constant value in the function on the change of the function graph. A method for fitting a wind turbine blade airfoil profile with a midline -thickness function curve was demonstrated by three examples, and some limitations of this method were pointed out. Studies have shown that the airfoil profile can be generated by using the midline -thickness function. The shape of the airfoil profile can also be changed in the desired direction by adjusting the constant value in the function. As a result, new airfoil profiles can be created, and the airfoil design can be improved. For existing wind turbine airfoil profiles, the midline -thickness function can be used for fitting. The main method is to adjust the constant value in the function to compare with the airfoil profile bitmap. Since the constants have a clear geometric meaning, the fitting process is relatively simple, but there are minor errors.

1. Introduction

The wind turbine blade airfoil profile is usually determined by a coordinate database, or with which an airfoil profile can be generated by sequentially connecting the airfoil profile bitmap with a smooth curve. In addition, the geometric shape of airfoil can be described by a variety of methods, mainly including the shape parameterization method, the shape function perturbation method and the analytic function method. The shape parameterization method uses several parameters to describe the geometric dimensions of each part of the airfoil. The design variables have clear geometric meaning, but do not give analytical expressions [1] [2]. The shape function perturbation method adds a perturbation shape function to the original airfoil to linearly superimpose to determine the shape [3], and the shape function mostly uses the Hicks-Henne function [4]. But this method has strong dependence on the original airfoil. If the original airfoil shape is not smooth, the shape of the airfoil is not smooth, and it will directly affect the smoothness of the pressure coefficient curve. In addition, this method cannot change the geometric parameters such as the leading edge radius and the trailing edge angle of the initial airfoil [5,6]. The analytic function method directly uses the analytic function to directly generate airfoil profile. For example, the NACA 4-digit and 5-digit series airfoil expressed by polynomial in the early stage, and the method of expressing the airfoil by the series recently [7]. These methods are more suitable for representing the static airfoil. Since the parameter changes have a great influence on the overall shape, the fine adjustment effect is not good. Only a few airfoils can be approximately expressed by polynomials. But since the constants in the polynomial have no clear geometric meaning, when the constant value changes, the image will undergo unpredictable changes, so one polynomial can only represent one airfoil, which cannot represent an airfoil family.

This paper takes the wind turbine blade airfoil as an example to explore the method of fitting its



profile with a simple function expression. Since the parameters in this function have clear geometric meaning, the fitting process is relatively simple, and it is convenient to improve the airfoil.

2. Airfoil profile function and its characteristics

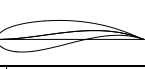
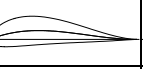
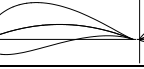
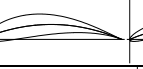
Simplifying Joukowski airfoil expression and extending definition for it, an airfoil profile represented by a midline -thickness function is obtained, and the function expression is [8]

$$y = px^a(1-x)^b \pm qx^c(1-x)^d \quad (1)$$

Where p , a , b , q , c and d in the formula are constants greater than 0. The first term of the formula represents midline of airfoil, which is controlled by 3 constants: coefficient p controls height of the whole midline; a , exponent of x , controls height of front-end midline; b , exponent of $(1-x)$, controls height of back-end midline. The second term of the formula represents airfoil thickness whose tendency is controlled by 3 constants: coefficient q controls the tendency of thickness; c , exponent of x , controls front-end thickness; d , exponent of $(1-x)$ controls back-end thickness.

Increase or decrease of these 6 constants will have impact on shape, and impact trends relative to datum graph are shown in Table 1, here constants that are used to compare with datum graph are $p=0.4$, $a=1$, $b=1$, $q=0.3$, $c=0.5$, $d=1.5$ (Joukowski airfoil).

Table 1. Impact of constant changes on airfoil shape.

Constants	Constants of midline function			Constants of thickness function		
	p	a	b	q	c	d
Graph change trends when constants increase	Overall rising 	Front-end descending 	Back-end descending 	Overall extension 	Front-end narrowing 	Back-end narrowing 
Datum graph						
Graph change trends when constants decrease	Overall descending 	Front-end rising 	Back-end rising 	Overall narrowing 	Front-end extension 	Back-end extension 

The impact trend of constant changes on shape shows a strong law. p represents coefficient of midline, if p increases, airfoil midline will rise pro rata, and curvature will increase. q represents coefficient of thickness, if q increases, thickness will extend pro rata. The term that the base is x has a great effect on front-end airfoil shape, and the term that base is $(1-x)$ on back-end airfoil shape, both of which are less than 1, therefore, if the exponent increases, the affected term will decrease. Thus it can be seen that geometrical significance of each term, coefficient or exponent in the formula (1) is definite, and the expression is not complex (only 6 constants), therefore, it is easy to structure various shapes of airfoils.

Now we discuss functional construction method of complex airfoil profile. To structure more complex airfoil shapes, upward and low profiles may be separated and recombined them. Upward and low profile is shown by subscript u , l , the formula (1) can be extended to the following

$$\begin{cases} y_u = p_u x^{a_u} (1-x)^{b_u} + q_u x^{c_u} (1-x)^{d_u} \\ y_l = p_l x^{a_l} (1-x)^{b_l} + q_l x^{c_l} (1-x)^{d_l} \end{cases} \quad (2)$$

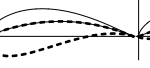
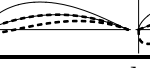
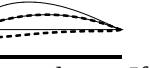
If the low profiles and their midlines always keep datum shape (solid line), the change trends (dotted line) for graphs with only upward profile constants are changed are shown in Table 2. Correspondingly, if the upward profiles and their midlines always keep datum shape (solid line), the

change trends (dotted line) for graphs with only low profile constants are changed are shown in Table 3.

Table 2. Impact of upward profile constants change on airfoil shape.

Constants	Constants of midline function			Constants of thickness function		
	p_u	a_u	b_u	q_u	c_u	d_u
Graph change trends when constants increase	Overall rising 	Front-end descending 	Back-end descending 	Overall extension 	Front-end narrowing 	Back-end narrowing 
Graph change trends when constants decrease	Overall descending 	Front-end rising 	Back-end rising 	Overall narrowing 	Front-end extension 	Back-end extension 

Table 3 Impact of low profile constants change on airfoil shape.

Constants	Constants of midline function			Constants of thickness function		
	p_l	a_l	b_l	q_l	c_l	d_l
Graph change trends when constants increase	Overall rising 	Front-end descending 	Back-end descending 	Overall extension 	Front-end narrowing 	Back-end narrowing 
Graph change trends when constants decrease	Overall descending 	Front-end rising 	Back-end rising 	Overall narrowing 	Front-end extension 	Back-end extension 

Above all examples are graph trend with adjusting single constant only based on datum shape. If several constants are adjusted, the change forms for graphs will be diverse, therefore many analytical expressions of the airfoil will be obtained by adjusting constants.

3. Function expression of wind turbine blade airfoil profile

Airfoil profile is generally described by coordinate database, and it is easy to plot coordinate data to coordinate dot matrix plot, dot matrix is connected orderly to form airfoil image by smooth curve. Approximate airfoil dot matrix by function graph, and airfoil profile integral theory [10] and analytical function linear superposition method [11] are used, the paper introduces to approximate gradually airfoil dot matrix by adjusting constant in the function based on difference between two graphs. Because geometrical significance of constant value in the function given in the paper is definite (refer to Table 2 and Table 3), approximation progress is simple and practicable, generally it takes only several minutes to obtain function expression and graph, which is simple and visual.

Take a airfoil from NACA family airfoil of the US, FFA-W family airfoil of Sweden, DU family airfoil of Netherlands, examples for approximating these 3 wind turbine airfoils with distinct characteristics are shown in Figure1- Figure3, the dot bitmaps in the figure is original airfoil profile coordinate dot plot, and the curve is function graph of approximating original airfoil.

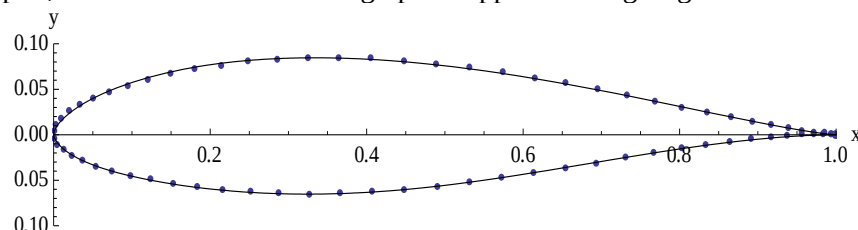


Figure 1. Function approximation curve of NACA 63(2)-215 wind turbine airfoil.

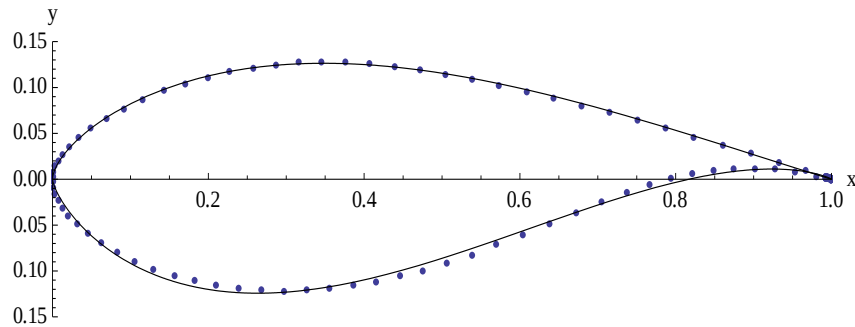


Figure 2. Function approximation curve of DU 91-W2-250 wind turbine airfoil.

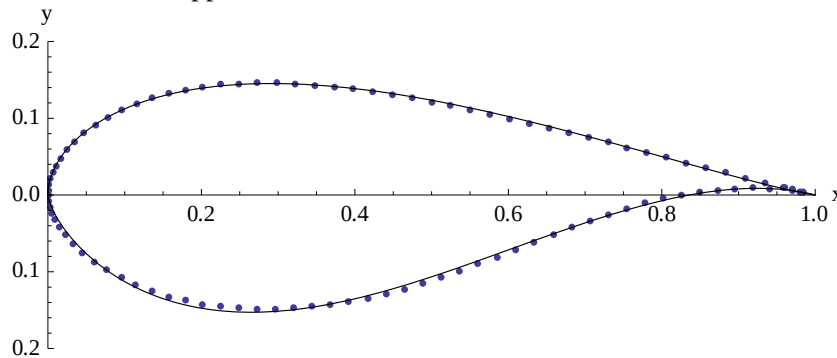


Figure 3. Function approximation curve of FFA-W3-301 wind turbine airfoil.

Plotting function of Mathematica software can be used to approximate, with the method to be show airfoil coordinate data as dot matrix image, and then generate similar airfoil curve by using parameter expression, then superpose two images together, so as to compare their difference, then the airfoil curve is approximated to dot matrix image by adjusting the coefficient and the exponent. After approximation process is completed, airfoil function expression is obtained based on the constant value, that is:

NACA 63(2)-215 airfoil

$$\begin{cases} y_u = 0.2x^{0.8}(1-x)^{1.25} + 0.11x^{0.5}(1-x)^{1.5} \\ y_l = 0.3x^{1.1}(1-x)^5 - 0.33x^{1.8}(1-x)^{0.66} \end{cases} \quad (3)$$

DU 91-W2-250 airfoil

$$\begin{cases} y_u = 0.2x^{1.1}(1-x)^{2.3} + 0.295x^{0.58}(1-x)^{1.03} \\ y_l = 0.26x^{0.75}(1-x)^{0.9} - 0.85x^{0.73}(1-x)^{1.6} \end{cases} \quad (4)$$

FFA-W3-301 airfoil

$$\begin{cases} y_u = 0.2x^{0.61}(1-x)^{1.6} + 0.24x^{0.48}(1-x)^{1.1} \\ y_l = 0.27x^{2.6}(1-x)^1 - 0.68x^{0.7}(1-x)^{1.7} \end{cases} \quad (5)$$

Similarly, function expressions for other airfoils can be obtained, and adjusting constant value in the expression may adjust the shape slightly so as to design a new airfoil.

In designing airfoil, an existing airfoil is referenced generally, shape adjustment and performance calculation are made by various methods to determine new airfoil based on optimal performance under constraint condition.

4. Limitation of airfoil expression

Airfoil expression established in the paper may express many airfoils by using limited constant, geometrical significance for constant is very definite, thus it is easy to adjust local airfoil shape and whole shape, holding certain advantage in parameterization design. Because the function expression is simple and can be used to generate airfoil image, which allows approximation to existing airfoil to become simple and lay foundation on drawing three-dimensional image of the blade.

However, airfoil expression also has certain limitations. Airfoil function comes from simplification and expansion definition of Joukowsky airfoil, therefore it brings common features of Joukowsky airfoil family inevitably. Joukowsky airfoil family can be obtained by conformal transformation, and studied deeply in potential flow theory, which has very high theoretical value, but seldom applied in engineering practice, with main reason is the airfoil family has thick leading edge and sharp trailing edge; the former meets most airfoil design requirements, but the latter is not allowed for almost all types of fluid machinery. In respect to sharp trailing edge, function structure method for smooth trailing edge airfoil profile has been given, but with the one more thickness term for airfoil function, which becomes complex. Although airfoil expression has some characteristics of Joukowsky airfoil family, the definition is extended to broaden value range of constant, shake off some characteristics of Joukowsky airfoil family, thereby increasing the range of sub-airfoil family.

Another limitation for airfoil expression is that it is only a sub-airfoil family of total airfoil family. In this sub-airfoil family, although infinite number of forms of airfoils can be obtained by change of constant value, it is difficult to express precisely airfoils of another sub-airfoil family, including wind turbine airfoil. For all sub-airfoil families, this problem is inevitable, for example, aforementioned NACA airfoil family of the US, FFA-W airfoil family of Sweden and DU airfoil family of Netherlands have their own series, with obvious characteristic. For over 100 years since generation of airfoils, human being fails to express all airfoils by using one parametric expression, although efforts have been made by multinomial and series method, approximate expression has been only given; however, this expression is difficult to play a role in airfoil design, because constant in the expression has no definite geometrical significance, constant value changes will cause airfoil shape to change unpredictably and wholly, therefore, this airfoil, even “static”, is seldom applied.

In short, airfoil expression given in this paper can easily and quickly generate precious airfoil profile in its own airfoil family, but generate approximate expression in approximation manner only for airfoils in other sub-airfoil families; degree of approximation will have great difference for different types of airfoils.

5. Conclusions

(1) The airfoil profile can be generated using a regular midline -thickness function, and the shape of the airfoil profile can also be changed in the desired direction by adjusting the constant value in the analytic function.

(2) For the existing wind turbine airfoil profile, the regular analytic function can be used for fitting. The main method is to adjust the constant value in the analytic function against the airfoil profile bitmaps. Since the constants have clear geometric meaning, the fitting process is relatively simple.

(3) Using the midline -thickness function to fit the existing wind turbine blade airfoil profile, there are minor errors, and the fitting curve cannot pass all profile bitmaps.

(4) Using the obtained wind turbine airfoil profile function, by adjusting the constant value, a series of new airfoil profile functions can be generated to improve the airfoil design.

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