MULTI-OBJECTIVE OPTIMIZATION DESIGN OF LOW-REYNOLDS-NUMBER AIRFOILS S1223

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Keywords: *multi-objective optimization, low Reynolds number airfoil, EXTREM, S1223*

Abstract

For the design of a high-performance propeller for low-dynamic aircraft in Near Space, it is very important to have low-Reynolds-number airfoils which are supposed to have high lift-drag ratio at cruising attack angle along with a good property of stall characteristics. The paper is having a hierarchical multi-objective optimization on the basis of the high-lift airfoil S1223 by combing direct search optimization algorithm EXTREM and airfoil flow field solver XFOIL to automatically and quick calculate aerodynamic performance function of airfoil by computer. The aerodynamic characteristic results of the optimized airfoil S1223_OPT2 meet the design requirements. So the optimized airfoil presented here is propsed as the selected airfoil reference for the high-efficiency propeller of low dynamic vehicles in stratosphere.

1 Introduction

Nowadays, a new research focus arises in the aircraft family members which is the low-dynamic vehicle in stratosphere at the height of 10km to 50km from the ground. When the low-dynamic vehicle flies in stratosphere, it shows the advantages of long endurance and the functions of large transport aircraft, so it is widely used in the place of military surveillance, communications support and antisubmarine warfare[1] [2]. Research shows that the propulsion system for the advanced low-dynamic vehicles is generally high-power DC motor-driven propeller system[3][4].

The performance of airfoil has a decisive impact on propeller aerodynamic performance. Increased payloads, shortened takeoff and landing distances, reduced aircraft noise, and lowered stall speeds can all be derived from the beneficial effects of improved high-lift airfoil aerodynamics. It is, therefore, not surprising that the classic problem of high-lift airfoil design has been and remains a topic of considerable interest[5-8]. Only single-element airfoils are considered in the current work. Compared with aerodynamic parameters at low altitude, there are great differences when an aircraft operates in stratosphere, such as the smaller atmospheric density, the lower air pressure, the larger air kinematic viscosity coefficient and the smaller speed of sound, etc. Airfoils for such propeller in stratosphere typically operate in the Reynolds number range 2×10^5 to 5×10^5, which belongs to the scope of low Reynolds number. In the low Reynolds number condition, the aerodynamic characteristics of an airfoil shows some new characteristics, such as the rapidly descending maximum lift-to-drag ratio of common airfoils[17] and the non-linear phenomena of the symmetrical airfoils at small attack angles especially near 0^{o}[18][19], etc. A lot of researches show that the above phenomena are closely related with the laminar flow separation phenomenon[20][21]. For subsonic flows, the laminar boundary layer over an airfoil at low Reynolds number has been observed to separate and reattach to the airfoil surface forming a laminar separation bubble even at small attack angles, which would decrease the efficiency of propeller decreases sharply and reduce aerodynamic performance of propeller dramati-cally. Therefore, one of the challenges to propeller designers for low-dynamic vehicle in stratosphere is to design a high-performance low-speed low-Reynolds- number airfoil.

A great deal of existing data reveals[23] that instead of using current existing airfoils, many aircrafts have utilized special airfoils which are more adequate to their functional requirements. For the low-dynamic vehicles at high altitude, the requirements are listed as follows:

1) High operational lift coefficient $C_l \geq 1$;
2) High lift-to-drag ratio C_l / C_d;
3) High endurance factor $C_l^{1.5} / C_d$;
4) High maximum lift coefficient C_{lmax};
5) Very mild stall characteristics for enough safety margins;
6) Limited pitching moment coefficient C_m;
7) Large relative thickness T/C;
8) Wide range of low resistance;

However, in the absence of experimental data in Low Reynolds number, the means of wind tunnel tests to design a new airfoil is very difficult, which always needs a long period, a high cost and a rich experience[24]. Fortunately, with the emergence of the high-speed electronic computers, numerical simulation technology is applied to airfoil design more frequently. Computational Fluid Dynamics (CFD) is one effective method of studying fluid dynamics, which could describe the complex flow of geometric boundary, evaluate the preliminary airfoil design rapidly and make prompt changes which not only can greatly reduce the cost, time and the risks of repeated experiments，but also can improve the airfoil design quality. So it becomes a kind of important design and calculation method and is used in the airfoil design and the flow field analysis more frequently in recent years[12].

The aerodynamic optimization design method[23-25] is a combination of aerodynamic analysis and optimization method, which achieves the best aerodynamic performance under given constraint conditions by changing the aerodynamic shape of design target by using the computer. Every constraint algorithm can be applied directly in the optimization process, while constrained problem can also be conveniently converted to unconstrained problem. So the optimization design method brings more flexibility and use value.

When conducting single-objective optimization design to improve the performance of a certain state of aircraft; it is often difficult to ensure the performances of other states. It is necessary to do the multi-objective optimization design which is aimed to improve the performance of one major state, at the same time giving consideration to improve the performance of other states or keep the performance of other states without reduction. To design such a good high-lift low-Reynolds–number airfoil for the propeller of low-dynamic vehicles in stratosphere, the paper is presenting a hierarchical multi-objective optimization on the basis of the high-lift airfoil S1223 by combing direct search optimization algorithm EXTREM and airfoil flow field solver XFOIL to automatically and quick calculate aerodynamic performance function of airfoil by computer.

2 Optimization Design Method

The shape optimization design procedure for an airfoil comprises four important steps. The first step is how to describe or parameterize airfoil shape in optimization design. The second is concerning an appropriate aero-dynamic analysis method. The third is concerning an effective optimization algorithm based on CFD. The last is choosing an multi-objective optimization method. As the above mentioned steps play the key role in the shape optimization design process which can control the optimization quality and efficiency, they will be discussed in detail in the following sections.

2.1 Airfoil Shape Parameterization Method

As airfoil shape parameterization method has a direct impact on the results of airfoil optimization design, it could directly affect airfoil aerodynamic characteristics. The optimization design procedure starts with a chosen initial airfoil. The new airfoil shape is represented in the program by the following equations:

$$y_{upper}(x)=y_{ou}+\sum_{k=1}^{7}c_k f_k(x)$$
$$y_{lower}(x)=y_{ol}+\sum_{k=1}^{7}c_{k+7} f_k(x) \quad (1)$$

where y_{ou} and y_{ol} are the ordinates of the upper and lower surface of the initial airfoil, k is number of the design variables, f_k represent the shape functions and c_k represent the design variables. The new airfoil contour is determined by the value of the design variables and the shape functions. The communication between the flow solver and the optimization program is established through the objective function and the design variables.

The performance of optimization design is related to the selection of the shape functions. Different types of functions could affect the quality and efficiency of optimization design[27]. There are three common shape functions including polynomial function[28], Hicks-Henne function[24] and Wagner function[25]. Hicks-Henne function, shown in the Formula (2), is adopted in this paper.

$$f_k(x)=\begin{cases} x^{0.25}(1-x)e^{-20x}, & k=1 \\ \sin^3(\pi x^{e(k)}), & k>1 \end{cases} \quad (2)$$

Where $e(k)=\dfrac{\log 0.5}{\log x_k}$, $0\le x_k \le 1$.

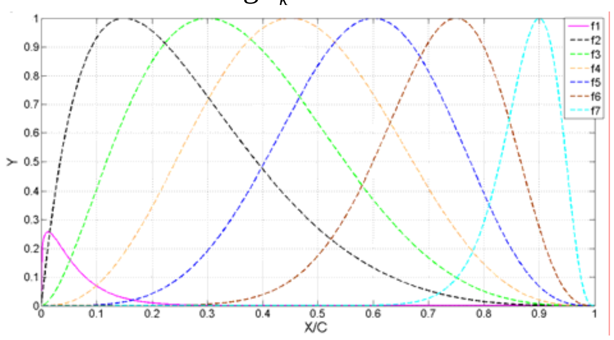


Fig. 1. Hicks-Henne shape function.

In the above functions, for k = 1~7, the peak position is shown in Table.1.

Table 1 Peak Position for Hicks-Henne shape function

k	1	2	3	4	5	6	7
Peak Position	0.012	0.15	0.30	0.45	0.60	0.75	0.90

When x=0 and x=1, $f_k(x)$=0, to satisfy the design requirement that is fixed positions of leading edge and trailing edge of airfoil. During applying parameterization of Analytic Function Linear Superposition Method, the coefficients of Hicks-Henne shape function defined as the design variables would determine the airfoil shape combined with the baseline airfoil and its leading edge and trailing edge.

2.2 Flow Solver for Subsonic Airfoil

Drela's XFOIL uses a linear-vorticity panel method for inviscid analysis coupled with an integral boundary-layer method for viscous analysis, for the design and analysis of subsonic isolated airfoils which has been evaluated by many designs[39]. It is widely-used in academia and parts of industry for quick preliminary estimates of airfoil performance due to its ease of use and versatility. The suitability of XFOIL for quick preliminary estimate of transition position has been demonstrated[39].So in the optimization design process, XFOIL(version 6.94) is employed for the calculation of the airfoil aerodynamic characteristics at low-speed and low Reynolds numbers, and estimate the chord-wise location of transition from laminar to turbulent flow x_{tr} using an envelope e^n-type method. For the current work, a value of $n_{crit}=9$ has been assumed for the critical transition amplication factor, which is typical for a smooth blade surface in a low-turbulence environment and all of the analyses have been conducted using the free-transition option in which the code computes the transition location as a part of the solution procedure. Each airfoil was represented in XFOIL using 230 panels distributed using XFOIL's default paneling routine.

2.3 Numerical Optimization Algorithm

Optimization algorithm is an important part in the aerodynamic shape optimization design system. The individual objective function in this paper is minimized by the direct search optimization algorithm EXTREM which is developed by H.G. Jacob, because of its quick convergence and no derivation[38]. The EXTREM optimization algorithm is a direct search method which can be used effectively for solving the multi-variable constrained optimization problem without calculating the derivative of object function. The search direction is determined just the same as Rosenbrock's method. If it is a constrained optimization problem with N variables, the first main search direction is determined by the initial value $\vec{C}$ and the initial search step $\vec{DC}$ (manually input according to the requirements) in the following manner:

$$\vec{S} = \vec{C} + \vec{DC} \tag{3}$$

By means of a Gram-Schmidt orthogonalization, *N-1* secondary search directions are determined. After along every secondary search directions search, the extremum of $(k+1)th$ optimum is attained. The optimization process in one direction is implemented by a parabolic extrapolation, shown in Fig.2, just like Powell's method:

$$\vec{C}_4 = \vec{C}_1 + \frac{\vec{DC}}{|F_3 - 2F_1 + F_2|} \times \frac{F_2 - F_3}{2 \times N} \tag{4}$$

where the maximum is obtained when $N = +1$ and the minimum is obtained when $N = -1$.

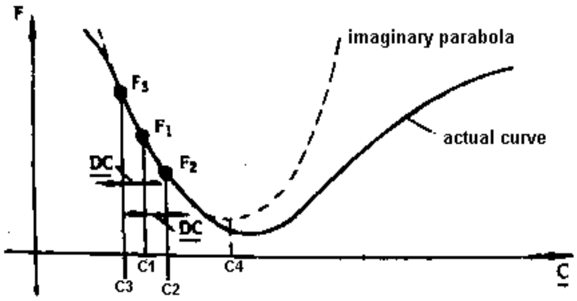


Fig. 2. Parabolic extrapolation.

The next main search direction, $\overline{S}^{(k+1)}$, always results from connecting the extremum of (k+1)*th* optimum $\overline{X}^{(k+1)}$ and the one of k*th* optimum $\overline{X}^{(k)}$:

$$\overline{S}^{(k+1)} = \overline{X}^{(k+1)} - \overline{X}^{(k)} \tag{5}$$

All kinds constraints can be take into account, but the optimization variables in each search or extrapolation process must be checked whether they have violated the given constraints. If the variables have violated, they will be managed in following two ways:

(1) In search process, if $\vec{C}_2 = \vec{C}_1 + \vec{DC}$ violates the given constraints, $\vec{C}_2$ will be changed to $\vec{C}_{2new} = \vec{C}_1 - \vec{DC}/2$;

(2) In extrapolation process, if $\vec{C}_4$ violates the given constraints, $\vec{C}_4$ will be changed to $\vec{C}_{4new} = \vec{C}_1 + \left(\vec{C}_4 - \vec{C}_1\right)/4$.

The method described as above has been shown having quick convergence[38].

2.4 Hierarchical Multi-objective Optimization Method

If one design target is involved to assess the design case in the optimization, then it is called single-objective optimization design. While in practical engineering problem, it is very often that more than one design target needs to be dealt with. The design targets are required to achieve at the same time during the optimization design. This is known as multi-objective optimization design. When conducting single-objective optimization design to improve the performance of a certain state, it is often difficult to ensure the performances of other states. Therefore, it is necessary to do the multi-objective optimization design for the optimization design of aircraft which is aimed to improve the performance of one major state, at the same time giving consideration to improve the performance of other states or keep the performance of other states without reduction. The typical form of mathematical model of the multi-objective optimization is as below.

$$\begin{cases} \min f_1(x) & x = [x_1, x_2, ..., x_n]^T \in E^n \\ \min f_2(x) \\ \cdots \\ \min f_q(x) \end{cases} \tag{6}$$

subject to: $g_i(\mathbf{x}) \le 0 \qquad i = 1, 2, \cdots, m$

In the multi-objective optimization design, it is difficult to make all sub-objectives be optimal at the same time. It occurs often that the performance of one or some sub-objectives turn worse as a result of one sub-objective minimization. That is to say, the optimizations among sub-objectives contradict each other in the process of minimizing. Therefore, it is necessary to coordinate and make some concession among the optimal values of the sub-objective functions $f_1(x), f_2(x),..., f_q(x)$ in order to obtain a better overall optimal solution. It can be seen that the multi-objective optimization design is much more complicated and more difficult than the single-objective optimization design. Although there are a lot of optimization methods for the multi-objective optimization design, most are not able to achieve ideal effect, and are not suitable for complex engineering problems. In fact, for such complex engineering problem like multi-objective aerodynamic optimization design of aircraft, it is important to make use of common multi-objective optimization methods combining with practical experience for specific problems to meet engineering needs and achieve satisfied results. Hierarchical Multi-Objective Optimization Method[41] is adopted as the multi-objective optimization method used in this paper. In the hierarchical multi-objective optimization method, objective functions are listed in order of importance. Every objective function is minimized:

$$Minimize \quad f_i\left(\vec{X}\right) \tag{7}$$

where i = 1, 2, …, k. From i=2 to i=k, $f_i\left(\vec{X}^{(k)}\right)$ subject to:

$$f_{i-1}\left(\vec{X}^{(k)}\right) \le \left(1+\varepsilon_{j-1}/100\right) \times f_{i-1}\left(\vec{X}^{(k-1)}\right) \tag{8}$$

where j =2, 3,…, i and ε_{j-1} is the given increment of (j-1)*th* objective function. So the optimum point $\vec{X}^{(k)}$ is finally obtained.

3 Initial Airfoil Selection for Optimization Design

Fig.3 presents the maximum lift characteristics of a number of representative low-speed airfoils taken from various sources[1, 9-16]. Although not all of these airfoils were specically designed for high-lift, a predictable and anticipated trend emerges, the lower the Reynolds number, the lower the maximum lift. In particular, in going from a Reynolds number of 10^5 to 10^6, a sharp drop in Cl_{max} is seen in the available data. The lower end of this range is of interest in the design of the high efficiency propeller in stratosphere based on current trends[6]. Due to airfoils for propeller in stratosphere typically operate in the Reynolds number range 2×10^5 to 5×10^5, the FX63-137 and the M06-13-138 are chosen first from Fig.3. From Ref.39, it shows that the S1223 has high Clmax, nearly a 25% increase compared with the FX 63-137. This characteristic is important for some UAVs that operate with the airfoil near Cl,max to achieve low-speed flight requirements for loiter, cruise, or landing. What is more, the S1223 exhibits acceptable moderate stall characteristics much like the M06-13-128. From the above mentioned, the S1223 has the aerodynamic advantages of both the FX63-137 and the M06-13-138. High lift is rarely the only desirable feature of an airfoil. The airfoil lift-to-drag ratio, endurance parameter, thickness, pitching moment, stall characteristics, and sensitivity to roughness are all important factors, among others, that must each be weighed separately when one considers selecting or designing an airfoil. This study focuses on those factors most related to enhanced high-lift low Reynolds numbers airfoil performance. From Ref.39, it presents that the S1223 has larger drag at the same time, which need improving in order to get high lift-drag ratio. So the S1223 is chosen finally as the initial airfoil for optimization design.

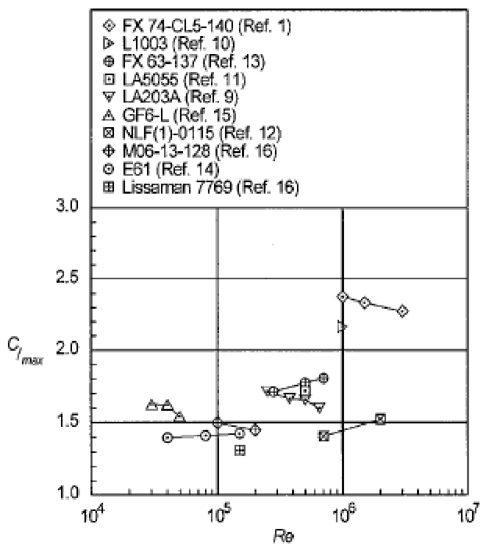


Fig. 3. Maximum lift coef. cient of several airfoils over a range of Reynolds numbers

4 Optimizaiton Design of S1223 Airfoil

In various design problems, different constraints may be applied to the airfoil geometry depending on the specific requirements. For low Reynolds number airfoils, friction drag is the main one in airfoil drags, which closely related to the transition position. Airfoils at low Reynolds numbers have low skin friction drag because of the inherent laminar boundary layer formation. The challenge in low Reynolds number airfoil optimization design is an optimization of transition position to maintain low airfoil drag. So it allows that both upper and lower surfaces vary in the different manners in airfoil optimization design to get a better aerodynamics characteristics and a suitable transition position.

Airfoils with high lift-to-drag ratios suitable for low Reynolds number applications[46]. The S1223 airfoil is chosen as a basic airfoil in the optimization design case.

General design targets are as following:

1) The lift-drag ratio C_l / C_d at cruising attack angle $\alpha = 2^{\circ}$ can reach 80 with a higher lift coefficient than S1223 at $\alpha = 2^{\circ}$;
2) Higher maximum-lift-coefficient $C_{l\max}$ at climbing attack angle $\alpha = 12^{\circ}$ than the S1223;
3) Wide range of low drag coefficient.

The design conditions of the low speed low-Reynolds-number airfoil for this investigation were chosen as: *Ma* = 0.1, *Re*= 0.2×10^{6} . In addition to providing a maximum lift-drag ratio C_l / C_d at design point, the optimized airfoil must satisfy certain maximum thickness constraint and has a good property of stall characteristics. So the optimized airfoil is supposed to have the maximum thickness and the leading edge radius unreduced (to avoid stall-incidence and $C_{l\max}$ decreasing) compared with the S1223 airfoil.

3.1 Single-Objective Optimization

The single design objective for the low-Reynolds-number airfoil S1223 is to maximize the lift-drag ratio C_l / C_d on the design condition of *Ma*=0.1, *Re*= 0.2×10^{6} and $\alpha = 2^{\circ}$ with a limitation of higher lift coefficient than the S1223 at $\alpha = 2^{\circ}$. The optimized airfoil of the single-objective optimization is described as the S1223_OPT1 airfoil. Calculation data comparison between the S1223 and the optimized airfoil S1223_OPT1 at the design attack angle $\alpha = 2^{\circ}$ are shown in Table 2, while the contour comparison between the S1223 and the S1223_ OPT1 is shown in Fig.4.

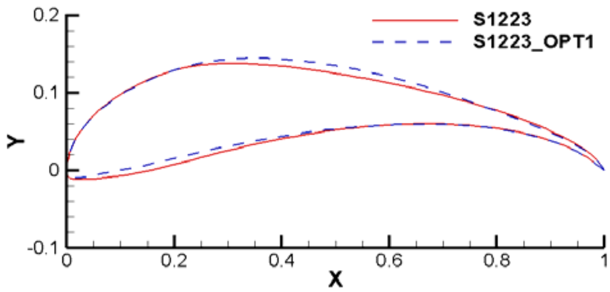
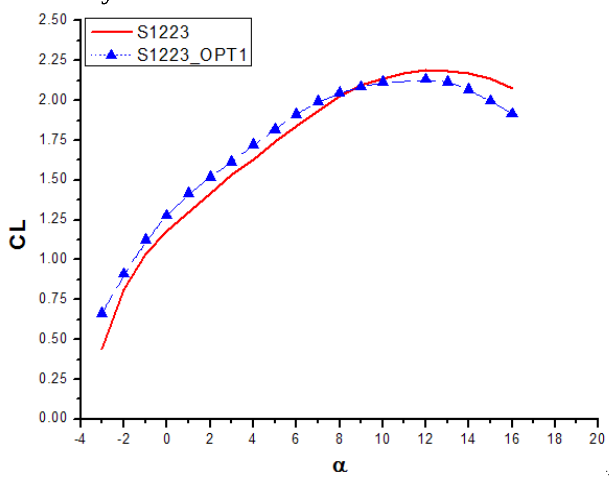


Fig. 4. Contour comparison between S1223 and S1223_OPT1

Table 2 Aerodynamic results comparison between S1223 and S1223_OPT1 at the design attack angle $\alpha = 2^{o}$

	C_l	ΔC	C_d	ΔC_d	$\frac{C_l}{C_d}$	$\Delta\left(\frac{C_l}{C_d}\right)$
S1223_2°	1.417		0.2016		70.29	
S1223_OPT1_2°	1.520	**7.3%**	0.01737	**-9.14%**	83.87	**19.32%**

Where ΔC_l , ΔC_d and $\Delta(C_l/C_d)$ represent the change percentage of lift coefficient, drag coefficient, lift-drag ratio compared with the S1223 by XFOIL calculation.



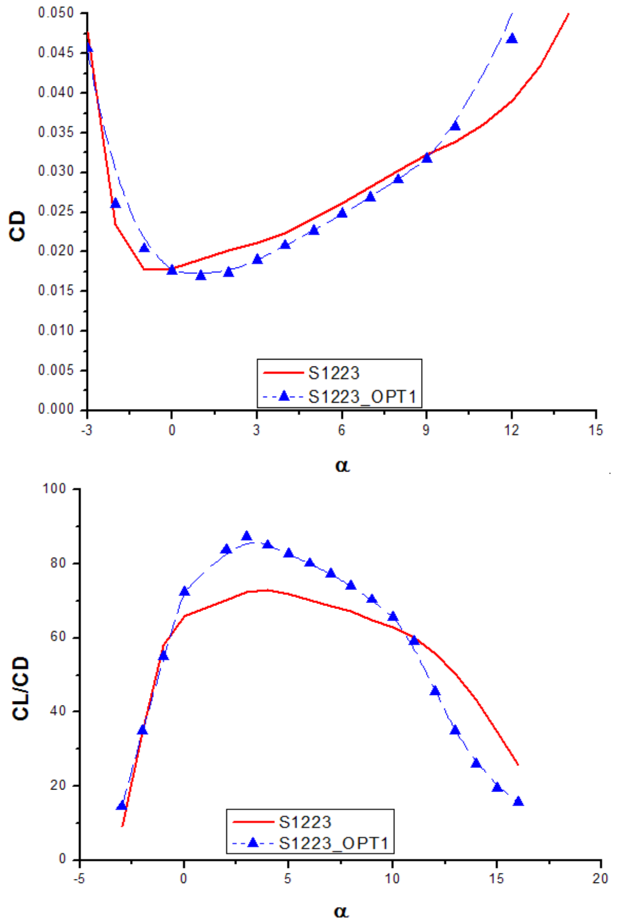


Fig. 5. Aerodynamic calculation results comparison of S1223 and S1223_OPT1.

As shown in Table 2 and Fig.5, it can be seen clearly that S1223_OPT1 has a better aerodynamic performance at the design attack angle $\alpha = 2^o$ than the S1223, whose lift-drag ratio rises from 70.29 to 83.87, an increase of 19.32%, compared with the S1223. The lift coefficient increases 7.3% and the drag coefficient decreases 9.14%. It is well known that the single-objective optimization can easily lead to a local extreme. This phenomenon can also be seen from Fig.5. From the curve diagram of lift coefficient in Fig.5, it can be seen that S1223_OPT1 has a smaller lift coefficient (reaching 2.135) compared with the S1223 (2.188), an decrease of 2.4% has been achieved. While from the curve diagram of drag coefficient in Fig.5, it can be seen that the S1223 performs badly at the off-design attack angles $\alpha > 9°$, which bring a rapidly corresponding decrease in the lift-drag ratio curve. So the single-optimization airfoil S1223_OPT1 is not suitable for practical use. Therefore, a multiple design-point multi-objective optimization has been conducted, whose results are presented below.

3.2 Multi-Objective Optimization

According to the Hierarchical Multi-Objective Optimization Method, the primary objective function of bi-objective optimization design here (at the basis of the S1223_OPT1) is $\min Cd$ at the primary design attack angle $\alpha = 10^0$, while the secondary objective function here is $(C_d/C_l)_{S1223\_OPT2} \leq 1.1\times(C_d/C_l)_{S1223\_OPT1}$ at the secondary design attack angle $\alpha = 2^o$, subject to:

1) $(C_l)_{S1223\_OPT2} \geq (C_l)_{S1223}$ at the primary design attack angle $\alpha = 10^o$;
2) $(C_l)_{S1223\_OPT2} \geq (C_l)_{S1223}$ at the secondary design attack angle $\alpha = 2^o$;
3) $(C_d)_{S1223\_OPT2} \leq (C_d)_{S1223}$ at the secondary design attack angle $\alpha = 2^o$.

The optimized airfoil of the multi-objective optimization is described as the S1223_OPT2 airfoil. Calculation data comparison between the S1223 and the S1223_OPT2 at the primary design attack angle $\alpha = 10^o$ and the secondary design attack angle $\alpha = 2^o$, shown in Table3. The contour comparison among S1223, S1223_OPT1 and S1223_OPT2 are shown in Fig.6.

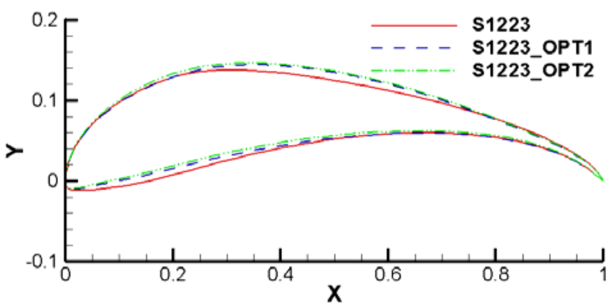


Fig. 6. Contour comparison among S1223, S1223_OPT1 and S1223_OPT2

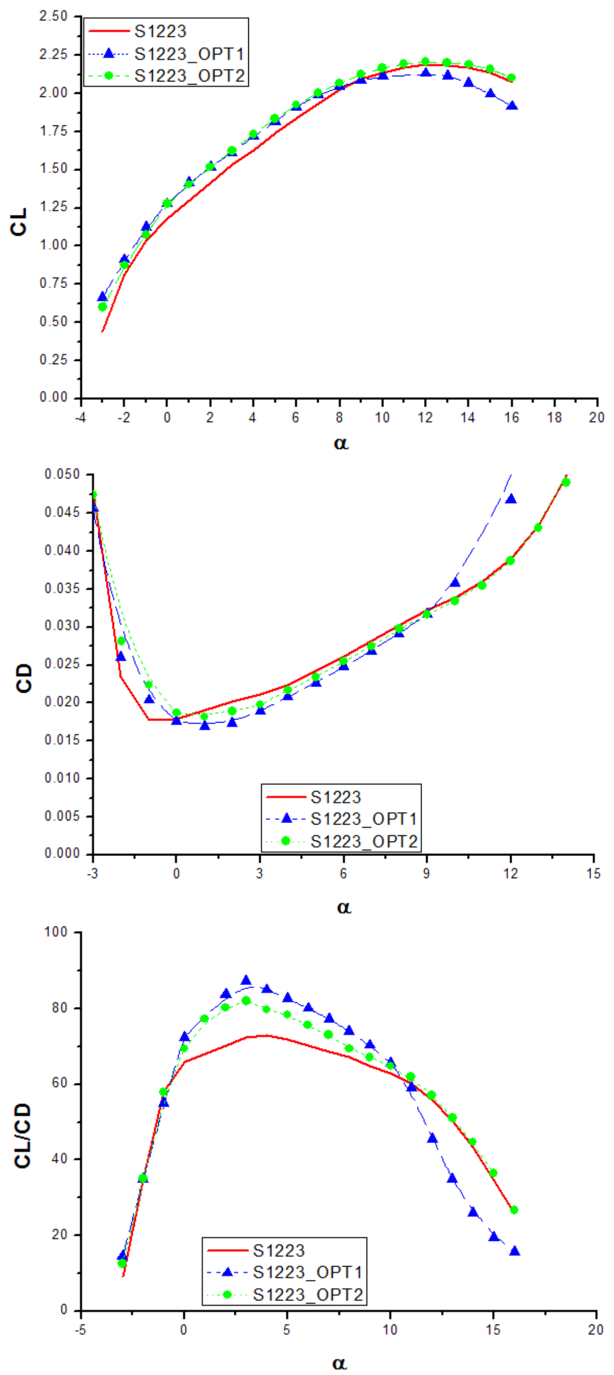


Fig. 7. Aerodynamic calculation results comparison of S1223, S1223_OPT1 and S1223_OPT2

Table 3 Aerodynamic results comparison between S1223, S1223_OPT1 and S1223_OPT2 at multiple design-points

	C_l	ΔC_l	C_d	ΔC_d	$\frac{C_l}{C_d}$	$\Delta\left(\frac{C_l}{C_d}\right)$
S1223_10°	2.138		0.034		63.05	
S1223_OPT2_10°	2.168	**1.4%**	0.033	**-3%**	64.80	**3%**
S1223_2°	1.417		0.0202		70.29	
S1223_OPT2_2°	1.520	**7.3%**	0.0189	**-6.4%**	80.33	**14.3%**

Fig.7 presents that the aerodynamic character of the S1223_OPT2 is significantly better than the S1223 and the S1223_OPT1. From Table 3, it can be clearly seen that the S1223_OPT2 has a good aerodynamic performance at multiple design-points $\alpha = 2^o$ and 10°. The drag coefficient of the S1223_OPT2 declines from 0.034 to 0.033 at the primary design attack angle $\alpha = 10^o$, a decrease of 3%, along with an increasing lift coefficient of 1.4% (reaching 2.168) , compared with the S1223, which is obviously better than the S1223_OPT1 at off-design attack angles $\alpha > 9°$. The lift-drag ratio rises from 70.29 to 80.33 at the secondary design attack angle $\alpha = 2^o$, an increase of 14.3%, compared with the S1223, along with an increasing lift coefficient of 7.3% (reaching 1.52) and a decreasing drag coefficient of 6.4% (reaching 0.0189). At the same time, you can see that the S1223_OPT2 have satisfied the requirement of higher lift coefficient on the climbing attack angle $\alpha = 12^o$ as well, whose lift coefficient raises from 2.2077 to 2.188, compared with the S1223, along with a wide range of low drag.

As will be readily seen, the multiple design-points multi-objective optimization example produces a satisfactory result. So the bi-objective optimization example presented here is resultful.

5 Conclusion

The high-lift low-Reynolds-number airfoil plays a decisive role for the success or failure of the propeller design of low-dynamic aircraft in Near Space. To such a good low-speed, high-lift and low-Reynolds-number airfoil, the paper demonstrates a hierarchical multi-objective optimization platform on the basis of the high-lift airfoil S1223 by combing direct search optimization algorithm EXTREM and airfoil flow field solver XFOIL to automatically and quick calculate aerodynamic performance function of airfoil by computer, with analytic functions linear superposition method used for establishing the shape of airfoils. From the optimization design results of the S1223 above, it can be clearly seen that the optimized airfoils S1223_OPT2 on the basis of high-lift and low-Reynolds-number airfoil S1223 can sufficiently meet the optimization design requirements, which have good aerodynamic characteristics at the design and off- design conditions. Thus, the multi-optimized airfoil and the hierarchical multi-objective optimization platform presented here can be supported as the airfoil technology reference for the high-efficiency propeller of low-dynamic vehicles in stratosphere.

References

[1] Lewis Jamison, Geoffrey S. Sommer and Isaac R. Porche III. *High-Altitude Airships for the Future Force Army*, published 2005 by the RAND Corporation.

[2] Pengfei Hao. *The Future Stratospheric Airships*, Chinese Newlore Magazine , 2006.12.

[3] Marcus Young and 2d Lt Stephanie Keith. *An Overview of Advanced Concepts for Near-Space Systems*, AIAA 2009-4805.

[4] Anthony Colozza and Geoffrey A. Landis. *Long Duration Solar Flight on Venus*, AIAA 2005-7156.

[5] Wortmann, F. X. *The Quest for High Lift*, Proceedings of the AIAA/MIT/SSA 2nd International Symposium of the Technology and Science of Low-Speed and Motorless Flight, Soaring Society of America, Los Angeles, CA, 1974, pp. 97-101; also AIAA Paper 74-1018, Sept. 1974.

[6] Liebeck, R. H.. and Ormsbee, A. I. *Optimization of Airfoils for Maximum Lift*, Journal of Aircraft, Vol. 7, No. 5, 1970, pp. 409- 415.

[7] Miley, S. J. *On the Design of Airfoils for Low Reynolds Numbers*, Proceedings of the AIAA/MIT/SSA 2nd International Symposium of the Technology and Science of Low-Speed and Motorless Flight, Soaring Society of America, Los Angeles, CA, 1974, pp. 82 - 96; also AIAA Paper 74-1017, Sept. 1974.

[8] Eppler, R. *Airfoil Design and Data*, Springer-Verlag, New York, 1990.

[9] Liebeck, R. H. *Low Reynolds Number Airfoil Design at the Douglas Aircraft Company*, Proceedings of the Aerodynamics at Low-Reynolds Numbers $10^4 < Re < 10^6$ International Conference, Vol. 1, The Royal Aeronautical Society, London, 1986, pp. 7.1 - 7.24.

[10] Liebeck, R. H. *Design of Subsonic Airfoils for High Lift*, Journal Aircraft, Vol. 15, No. 9, 1978, pp. 547 - 561.

[11] Van Ingen, J. L., and Boermans, L. M. M. *Aerodynamics at Low Reynolds Numbers: A Review of Theoretical and Experimental Research at Delft University of Technology*, Proceedings of the Aerodynamics at Low Reynolds Numbers $10^4 < Re < 10^6$ International Conference, Vol. 1, The Royal Aeronautical Society, London, 1986, pp. 1.1 - 1.40.

[12] Maughmer, M. D., and Somers, D. M. *Design and Experimental Results for a High-Altitude, Long-Endurance Airfoil*, Journal of Aircraft, Vol. 26, No. 2, 1989, pp. 148 - 153.

[13] Althaus, D. and Wortmann, F. X., *Stuttgarter Profilkatalog I*, Vieweg, Brunswick, Germany, 1981, ISBN 3-528-08464-2.

[14] Althaus, D. *Profilpolaren fur den Modellflug*, Neckar-Verlag, Villingen-Schwenningen, Germany, 1980.

[15] Althaus, D. *Profilpolaren fur den Modellflug*, Vol. 2, Neckar- Verlag, Villingen-Schwenningen, Germany, 1985.

[16] Mueller, T. J. *Low Reynolds Number Vehicles*, AGARDograph 288, Feb. 1985.

[17] MUELLER T. J. *The Influence of Laminar Separation and Tran-sition on Low Reynolds Number Airfoil Hysteresis* (Translation Journals style), Journal of Aircraft, vol.22, 1985, pp. 764-770.

[18] Michael S. Selig, James J. Guglielmo and Andy P. Broeren. *Experiments on Airfoils at Low Reynolds Number* (Translation Journals style), AIAA-1996-62, 34th Aerospace Sciences Meeting and Exhibit, NV, Jan.1996, pp. 15-18.

[19] Peng Bai, Erjie Cui, Feng li and Weijiang Zhou. *Symmetrical airfoil low Reynolds number of small attack angle lift coefficients nonlinear phenomena research* (Journals style), Chinese Journal of Theoretical and Applied Mechanics, vol.38, 2006, pp. 1-8.

[20] Ziqiang Zhu, Xiaolu Wang and Zongcheng Wu. *Aerodynamic Characteristics of Small/Micro Unmanned Aerial Vehicles and Their Shape Design* (Journals style), ACTA Aeronautica ET Astronautica Sinica, vol.27, 2006, pp. 353-364.

[21] Donald Greer and Phil Hamory. *Design and Predictions for High-Altitude (Low Reynolds Number) Aerodynamic Flight Experiment*, Journal of Aircraft, Vol. 37, No. 4. July-August 2000.

[22] L. Danielle Koch. *Design and Performance Calculations of a Propeller for Very High Altitude Flight*. NASA/TM, 1998-206637, 1998.

[23] Zhou Liu, Ziqiang Zhu, Hongyan Fu and Zongcheng Wu. *Design for the high lift-drag ratio*, The 12th Chinese national computational fluid dynamics conference.

[24] Hicks R and Henne P. Wing *Design by Numerical Optimization*. Journal of Aircraft, 1978, 15(7): 407-413.

[25] Ramamoorthy P, Padmavathi K. Airfoil *Design by Optimization*. Journal of Aircraft, 1977, 14(2), 219-221.

[26] Z. X. Xia, Z. Q. Zhu, L. and Y. Wu. *A Computational Method for Inverse Design of Transonic Airfoil and Wing*. AIAA-93-3482-CP, 1993.

[27] Eyi S, Lee K D. *Inverse Airfoil Design Using the Navier-Stokes Equations*. AIAA 93-0972, 1993.

[28] Lee K D, Eyi S. *Aerodynamic Design via Optimization*. ICAS90-6.9.1, 1990.9. 1808-1818.

[29] Volpe G, Melnik R E. *The Design of Transonic Airfoils by a Well-posed Inverse Method, International Conference on Inverse Design Concepts in Engineering Sciences*, Austin, TX, October 1984.

[30] Giles M B, Drela M. *Two-dimensional Transonic Aerodynamic Design Method*. AIAA Journal.Vol.25, No.9, September 1987, pp1199-1205.

[31] Mani K K. Design *Using Euler Equations*. AIAA 84-2166, August 1984.

[32] Hirose N, Takanashi S, Kawai N. *Transonic Airfoil Design Procedure Utilizing a Navier-Stokes Analysis Code*. AIAA journal, Vol.25, No.3, 1987, pp353-359.

[33] Malone J B, Narramore J C, Sankar L N. *Airfoil Design Method Using the Navier-Stokes Equations. Journal of Aircraft*. Vol.28, No.3, March 1991, pp.216-224.

[34] Kim H J, Rho O H. *Aerodynamic Design of Transonic Wing Using the Target Pressure Optimization Approach*. AIAA 98-0599.

[35] Zhu Z W, Chan Y Y. *A New Genetic Algorithm for Aerodynamic Design Based on Geometric Concept*. AIAA 98-2900. 1998.

[36] Dulikravich G S. *Aerodynamic Shape Design and Optimization*. AIAA 91-0476, 1991.

[37] Mosetti G, Poloni C. *Aerodynamic Shape Optimization by Means of a Genetic Algorithm*. proc.of the 5th Int. Symp. On Computational Fluid Dynamics, Sendai. 1993.

[38] H. G. Jacob. *Rechnergesutzte Optimierung statischer und dynamischer systeme*, Springer Verlag, 1982.

[39] Drela. XFOIL: *An Analysis and Designing System for Low Reynolds Number Airfoils. In Low Reynolds Number Aerodynamics*. Proceedings of the Conference in Notre Dame, Indiana, Springer-Verlag, 1989. New York: Springer-Verlag.

[40] Michael S. Selig and James J. Guglielmo. *High-Lift Low Reynolds Number Airfoil Design*, Journal of Aircraft, Vol. 34, No. 1, Jan-Feb 1997.

[41] Zhong Bowen, Qiao Zhide. *Multiobjective Optimization Design of Transonic Airfoils*, ICAS-94-2.1.1.

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