Design and Test Verification of Hybrid Airfoil Based on Multi-objective Genetic Algorithm

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Abstract. Certification of modern aircraft requires the manufacturers to demonstrate flight safety within the flight envelope, including icing conditions. Icing wind tunnel test is an important way for flight safety and certification. However, the size of aircraft models that can be tested in icing wind tunnels is limited by the dimensions of the facilities. It is an effective method to replace the large model with a hybrid airfoil to carry out the experiment. If properly designed, these hybrid airfoil models can generate the full-scale ice accretion on the leading edge and reduce blockage. Based on the similarity of flow field in the leading edge, a multi-objective genetic optimization algorithm is proposed to design the hybrid airfoil under different conditions. The pressure tests are carried out and compared with the leading edge pressure coefficient of the corresponding full-scale airfoils. The design and experimental results show that the pressure coefficient deviation between the hybrid airfoils designed and the corresponding full-scale airfoil in the 15% chord length range of the leading edge is within 3%. Finally, icing wind tunnel test is used to inspect the ice shape of full-scale and hybrid airfoils, and the results shows that ice accretion process have good agreement of hybrid and full-scale airfoils.

1. Introduction

Icing will change the flow field of aircraft and deteriorate the aerodynamic sharply. Therefore, to improve flight safety [1], it is important to understand the aerodynamic performance of the iced airfoil. Evaluate the iced airfoil and the wing’s performance to insure they can operate safely even in the worst icing conditions as set forth by the FAA [2]. Icing wind tunnel test is a cost effective and useful method to study icing mechanism and ice accretion process, as it can provide a wide range of meteorological conditions, and simulated a wide range of icing conditions.

However, icing wind tunnels in present are too small to test full-scale airfoils or wings, even for a moderate or small sized model, it may cause tunnel blockage [3] and affects the test accuracy. Hybrid airfoil is a useful option to deal with this problem [4]. Hybrid airfoil is designed with full-scale leading edge, but with a redesigned aft section. With properly design, the hybrid airfoil generate the full-scale ice accretion, and reduce the blockage [5].
In this paper, multi-objective genetic algorithm (MOGA) [6] is used to design the hybrid airfoils. In order to improve the design precision, a high-fidelity flow solver based on 2D Reynolds averaged Navier Stokes (RANS) equations were employed in the design method. Finally, pressure coefficient and ice accretion were tested in Low Turbulence Wind Tunnel (LTWT) and FL-16y icing wind tunnel. The test results of the hybrid airfoil are consistent with the full-scale airfoil, which prove the validity of the proposed design methodology.

2. Hybrid airfoil design based on MOGA

2.1. Definition of hybrid airfoil

As shown in Fig.1, dashed line represents the full-scale airfoil NACA0012, and the solid line is the hybrid airfoil, clearly, they have the same leading edge with 25% chord, then the aft-section of hybrid airfoil is controlled by eight points, which are (UX1, UY1), (UX2, UY2),...,(DX4, DY4). UX represents the x-coordinate of the upper surface and UY represents the y-coordinate of the lower surface, 1,2,3,4 is the number of different control point, as the control points varies in the optimization process, the shape of hybrid airfoil also changes.

Scale factor (SF) of hybrid airfoil is defined as the full-scale chord divided by the hybrid airfoil chord. As shown in Figure 1, a full-scale airfoil NACA0012 with a dimensionless chord length 1, and the hybrid airfoil has a chord length of 0.5, thus, the SF of hybrid airfoil is 2.

2.2. Hybrid airfoil optimization method

2.2.1. Definition of the optimization problem. Hybrid airfoil is optimized by of MOGA. Genetic algorithm (GA) is a random search method based on random operator, which is widely used in engineering and science because they can easily solve complex problems such as optimization of external geometry. MOGA is the development of sorting GA, it supports multiple objectives and constraints, and aims to find the global optimal value, and it is a global parallel stochastic optimization search algorithm in the sense of probability, which is convenient and fast for the optimization problems with discrete design variables [7]. In the optimization of hybrid airfoils, the leading edge of the full-scale airfoil is taken as the hybrid airfoil’s leading edge and connected with an arbitrary aft section. The flow field of hybrid and full-scale airfoil is obtained by a RANS solver, compared the pressure coefficient of these two airfoils, there must has difference as shown in Figure 2. The design objectives are to minimize the pressure coefficient (Cp) difference and stagnation point (SP) difference between full-scale and hybrid airfoil in the reference area.

The definito of multi-objective optimization can be summarized as follows:

Objective 1: \[ \min f(\varphi) = \int_{\omega} (C_{p_f} - C_{p_h})^2 \, d\omega \] (1)

Objective 2: \[ \min f(\xi) = (S_{p_f} - S_{p_h})^2 \] (2)

Subject to:
\[ 0.25 \leq x_{u} \leq 0.5 \]
\[ 0.25 \leq x_{l} \leq 0.5 \] (3)
Where, $f(\varphi)$ and $f(\xi)$ represent the pressure coefficient (Cp) difference and stagnation point (SP) difference between full-scale and hybrid airfoil in the reference area in optimization; $\omega$ is reference area, subscript of $f$ and $h$ represent full-scale and hybrid airfoil, respectively. $x_u$ and $x_d$ represent x position at upper and lower surface, respectively, $y_u$ and $y_d$ represent y position at upper and lower surface, respectively.

2.2.2. Improved optimization algorithm. A conceptual illustration of hybrid airfoil design approach is shown in Figure 3. The specific design method is as follows: 1) taking the 25% leading edge chord length of the full-scale airfoil as the leading edge of the hybrid airfoil, called nose-section, this part of the full-scale airfoil is fixed in the hybrid airfoil optimization and is common to both the full-scale and hybrid airfoil. 2) generating the aft-section by defining the control point’s positions arbitrarily. Then combined the primitive airfoil, The aft-section is designed to provide full-scale flow field on the nose-section of the hybrid airfoil because the nose-section is fixed and cannot be changed to affect the flow field. 3) Starting the optimization process. Automatic grid generation and Cp calculation by CFD was employed to optimize the airfoil shape. 4) Comparing and output the hybrid airfoil, ensure that the flow field of the hybrid and full-scale airfoils within the reference area meet the requirements, otherwise, repeat the optimization loop.

![Figure 2. Cp difference between hybrid and full-scale airfoil.](image1)

![Figure 3. Work flow of hybrid airfoils design approach.](image2)
2.3. Optimization results of hybrid airfoil

With the method described above, different hybrid airfoils were obtained. The hybrid airfoil designed shows a good consistency of pressure coefficient with that of the full-scale airfoil, as illustrated in Figure 4 and 5. The magnified box in Figure 5 shows the reference area of interest in more detail. It is clear that the hybrid airfoil designed here has a perfect match in stagnation point as well as pressure coefficient with the full-scale airfoil.

![Figure 4. Profile of designed hybrid airfoil.](image)

![Figure 5. Cp comparison of hybrid and full-scale airfoil.](image)

3. Test of Aerodynamic Characteristics and ice accretion

3.1. Comparison of flow characteristics and Cp.

In order to validate the design performance of hybrid airfoils, flow characteristics and pressure distribution experiments were carried out. The test model is NACA0012, with a chord length of 300 mm and the corresponding hybrid airfoil with a chord length of 150 mm. Tests conditions are shown in Table 1.

| Test Cases | Airfoils | AoA (°) | V (m/s) | P (pa) |
|------------|----------|---------|---------|--------|
| Case1      | Hy00     | 0       | 30      | 98,193 |
|            | NACA0012 | 0       | 30      | 95,406 |
| Case2      | Hy04     | 4       | 30      | 98,672 |
|            | NACA0012 | 4       | 30      | 95,404 |

As we can see from Figure 6 and 7, the pressure coefficient distribution of the hybrid and full-scale airfoils at the leading edge are essentially the same, the difference are less than 3%.
3.2. Ice accretion tests on hybrid and full-scale airfoil

The pressure coefficient has been checked for hybrid and full-scale airfoils. Then, the ice accretion experiment is carried out in FL-16y icing wind tunnel of CARDC. The icing test parameters are shown in Table 2.

| Parameters | AoA (°) | $V_\infty$ (m/s) | $T$ (℃) | MVD (μm) | LWC (g/m$^3$) | Icing time (s) |
|------------|---------|-----------------|--------|----------|--------------|---------------|
| Hy04       | 4       | 85              | -7.5  | 23       | 0.55         | 180           |
| NACA0012   |         |                 |        |          |              |               |
| Hy08       | 8       | 85              | -7.5  | 25       | 0.5          | 180           |
| NACA0012   |         |                 |        |          |              |               |

The airfoils were tested in the icing wind tunnel. After the experiment, the ice was cut by a hot plate, and drawn on the coordinate paper. Finally, the shape were digitized and as shown in Figure 8 and 9. Figure 8 is the ice shape for hybrid and full-scale airfoil of Hy04, as we can see, the ice limits, ice range on upper and lower surface, and maximum ice thickness are all close to that of full-scale airfoil. The maximum ice angle position has a slight difference, but the ice angle height and the overall range have no difference, and the ice range of the lower surface is also relatively consistent. Figure 9 is the comparison of the test results of Hy08 airfoil and corresponding full-scale airfoil. Also, the ice range, ice angle, ice position, height on the leading edge of the hybrid airfoil are close to that of the full-scale airfoil, and there are only slight differences at the stagnation point.

In general, the ice shape of the hybrid airfoil is close to that of the full-scale, and the similarity of the ice shape is more than 85%. For the most important position of the ice angle centre and the overall shape, the hybrid airfoil can produce the icing results basically consistent with the full-scale airfoil.

Figure 8. Ice shape for full-scale and Hy04 airfoil
4. Conclusion
The use of hybrid airfoil is an attractive way for icing wind tunnel tests of large models. In this paper, a design method for hybrid scale airfoil based on MOGA is proposed. Hybrid airfoils under different design conditions were obtained and tested. From the simulation and test results, it can be understood that the RANS solver provided a high-precision flow field of airfoils. For the hybrid airfoils design by this method, the flow field characteristics, pressure coefficient distribution and the final icing shape in the leading edge of the hybrid and full-scale airfoil all have good similarity, which proves the effectiveness and accuracy of the design method.

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References
[1] Bragg M B, Broeren A P and Blumenthal L 2005 Prog. Aerosp. Sci. 41 323-62
[2] Liu T, Qu K, Cai J S and Pan S C 2019 Aerosp. Sci. Technol. 93 105328
[3] Bragg M B and Wells S L 1994 J. Aircr. 31 175-80
[4] Saeed F, Selig M S and Bragg M B 1997 J. Aircr. 35 233-9
[5] Fujiwara G E, Bragg M B 2019 J. Aircr. 56 137-49
[6] Sumnu A, Guzelbey I H and Ogucu O 2020 Int. J. Aerosp. Eng. 1528435
[7] Keita K, Nozomu K, Takayuki Y, Kazuhiro I, Shinji N and Masato T 2020 Trans. Japan Soc. Aero. Space Sci. 63 90-100