ESTIMATION OF THE INFLUENCE OF PROFILE ERROR ON AERODYNAMIC PERFORMANCE FOR LOW-REYNOLDS-NUMBER AIRFOILS

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Abstract

In this study, we estimated the influence of profile error on the aerodynamic performance for Low-Reynolds-Number airfoils by numerical analysis. We used two airfoils; DAE21, which is widely used for Human Powered Aircraft (HPA) and NACA 4412. To simulate the profile error, we used sine function with maximum height of 0.1% of the chord on the upper surface. The results show that, at Re=529100, the lift-to-drag ratio (L/D) decreased by about 40% in the case of DAE21 with wave-like profile error originated from sine function on the upper surface. It is also found that the small bump on the upper surface can reduce the laminar separation bubble (LSB) and the drag by about 20% in the case of DAE21 at Re=300000. At Re=529100, however, the profile error can enhance the drag by about 20%.

To investigate the characteristics of the distributions of the actual errors, we made two wooden airfoils(DAE21) with our manufacturing process of our HPA, measured their profiles of upper surfaces and compared them with the "genuine" profiles. In addition, DFT analyses were performed and it is found that the profiles of the actual errors could be modeled by the wave-like profile errors like sine function.

1 Introduction

The wing of a Human-Powered Aircraft (HPA) is so flexible that it can easily be deformed in flight. Furthermore, in manufacturing process of HPA, manufacturing errors on its airfoils is inevitable. Hence, in design process of HPA, estimating the influence of the error on aerodynamic performance for its airfoils is very important.

In this study, we selected two low-Reynolds-number airfoils; DAE21, which is widely used for HPA, and NACA4412. To estimate the influence of these errors, we simulated the two types of errors; wave-like and bump-like profile error, by using sine function and the numerical analyses were performed at Re≈10^5 which corresponds to the flight environment of HPA. In order to investigate the characteristics of the "actual" profile errors, we made two wooden airfoils with our manufacturing process for HPA, measured their profiles over the upper surfaces, and performed DFT analyses for evaluating the distributions of the profile errors.

2 Method of analysis

In this study, we selected two airfoils; DAE21 and NACA4412. For numerical analysis, we used XFOIL [1], which is a software for solving a subsonic flow around an airfoil using panel method. Some studies and experiments using wind tunnel show that the results of XFOIL agree well with the experimental results at Re≈10^5 [2]. Reynolds numbers are set to be Re=529100 and 300000, whose correspond to Reynolds number based on the wing root chord and the wing tip chord of our HPA on steady flight, respectively.

3 Results and discussions

3.1 Influence of the profile error by sine function

The wing of HPA is so flexible that many wrinkles can be created on its upper surface in flight (Fig.1). To simulate the wrinkles, we regard them as periodic waves and simulate them by using sine function in the following form;

$$E_{\text{sin}} = e_{\max} \sin\left(C \cdot \pi x\right) \qquad (1)$$

, where $e_{\max}$, C, x are the maximum value of the profile error, wave number and x-coordinate, respectively. Figure 2 shows the schematic profile of the simulated airfoil with the wave-like profile error on its upper surface. In the case of our HPA, $e_{\max}$ is estimated to be about 0.001. Figure 3 shows that the relationship between the lift-to-drag ratio (L/D) calculated by XFOIL and angle of attack for DAE21 and NACA4412. From this figure we can observe that the L/D decreased significantly in the case of DAE21. On the other hand, in the case of NACA4412, the L/D decreased by about 20, which is much smaller than that of DAE21.

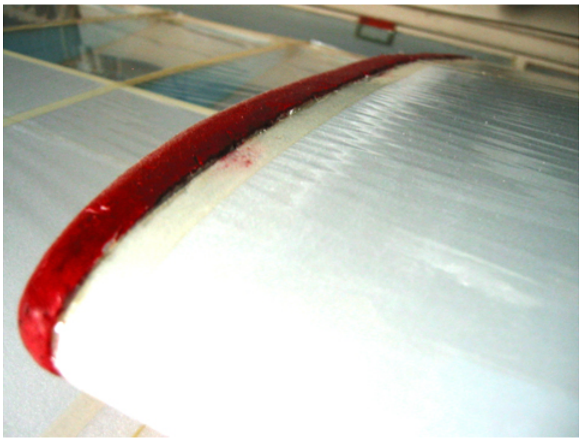

Fig.1. The wrinkles found on the upper surface of the wing of HPA.

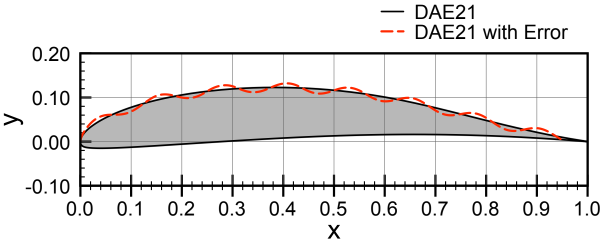

Fig.2. Schematic profile of the simulated airfoil with the wave-like profile error

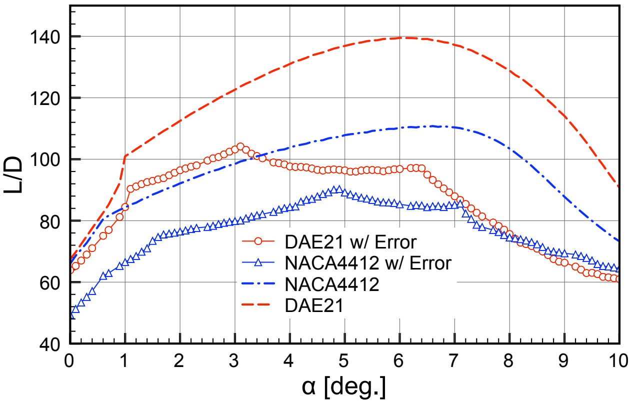

Fig.3. Relationship between the L/D and angle of attack ($e_{\max}$=0.001, C=16, Re=529100)

3.2 Influence of the bump-like profile error

In flight, droplets or insects can hit and attach to the wing. In addition, bumps can be created on the wing surface by being manufactured with poor workmanship. To simulate these bump-like profile errors, we regard them as the convex superior portion of sine function as follows;

$$E_{\text{bump}} = e_{\max} \sin\left\{\frac{\pi}{2}\left(\frac{2\left(x-p\right)}{l}+1\right)\right\} \qquad (2)$$

, where $e_{\max}$, p, l, x are the maximum value of the profile error(or the height from the upper surface of airfoil), location of the apex of the bump from the leading edge (L.E.), length of the bump and x-coordinate, respectively (Fig.4). These values are ratios of the root chord of about 1000 [mm]. In the case of our HPA, $e_{\max}$ and l are estimated to be about 0.002 and about 0.010, respectively. In this analysis, we evalu-

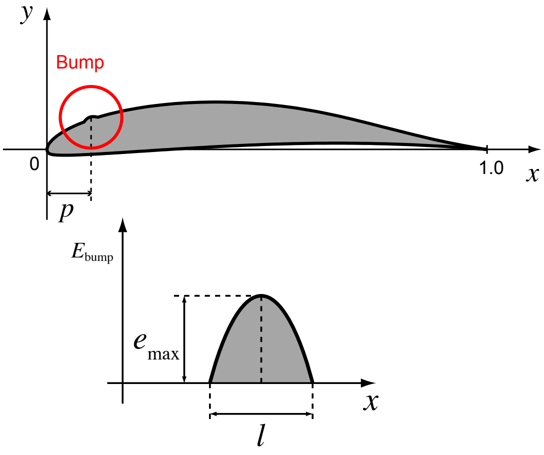

Fig. 4. Simulation of the bump-like profile error

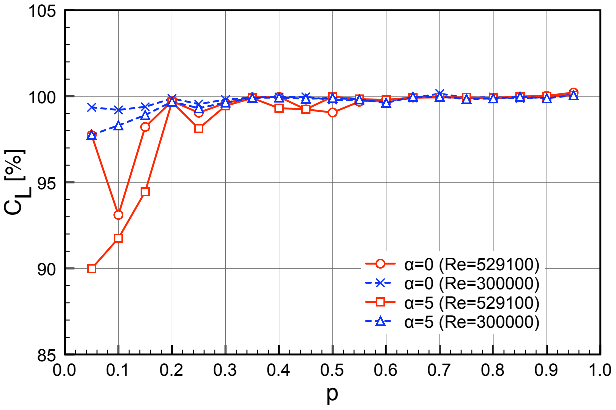

Fig.5. Relationship between the C_L and the location of the bump, at Re=529100 and 300000

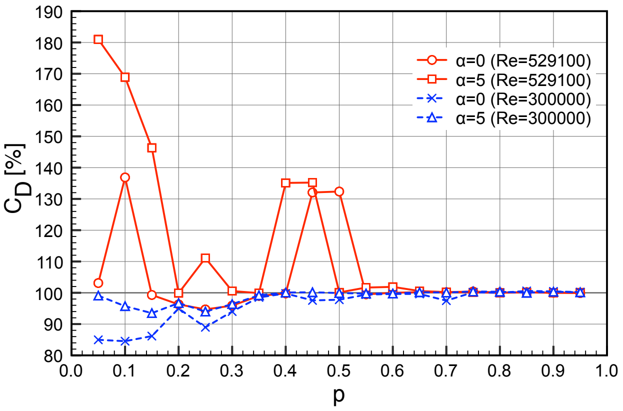

Fig.6. Relationship between the C_D and the location of the bump, at Re=529100 and 300000

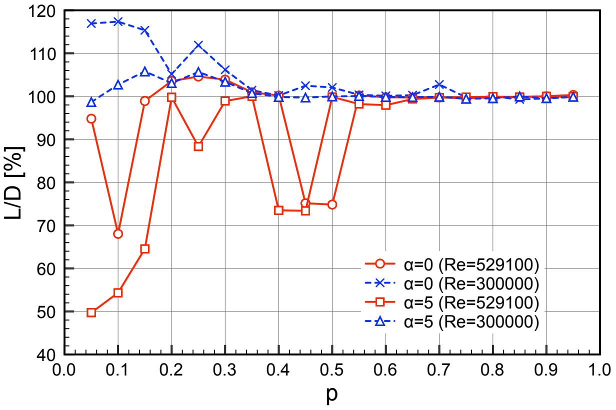

Fig.7. Relationship between the L/D and the location of the bump, at Re=529100 and 300000

ated the relationships between the location of the bump and the influences of them on aerodynamic performances for DAE21 by varying p from 0.05 to 0.95, at Re=529100 and 300000.

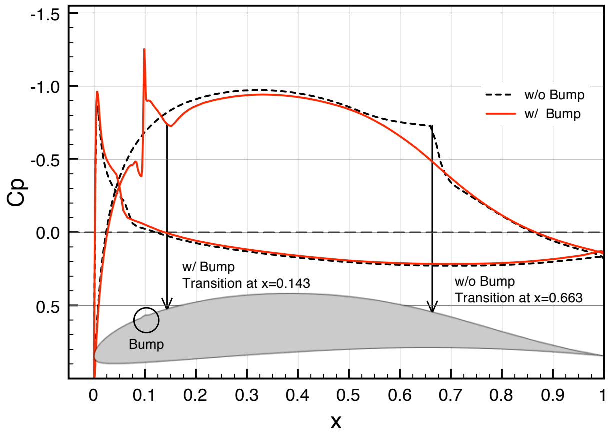

Fig.8. Pressure distributions over the airfoil surface with and without the bump, where p=0.10 and α=0 [deg.], at Re=529100

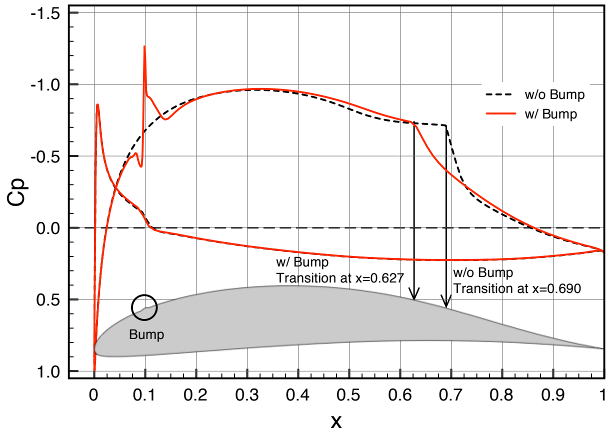

Fig.9. Pressure distributions over the airfoil surface with and without the bump, where p=0.10 and α=0 [deg.], at Re=300000

Figure 5, 6 and 7 show that the relationship between the location of the error and C_L, C_D and L/D, respectively. All results are compared with the “clean” airfoil.

At Re=529100, results show that the value of C_L decreased by about 10% and C_D increased by about 80% at a maximum from that of the “clean” airfoil, at around p=0.10. In addition, it is also found that a bump located around the leading edge (from 0 to 0.30) reduces the aerodynamic performances more drastically than that of the trailing edge (from 0.60 to 1.00). When the bump is located near the L.E., the flow over the upper surface would be changed into turbulent flow immediately after passing through the bump (Fig.8) and this would increase the drag significantly. In the case that the bump is located in the trailing edge (T.E.), however, the influence is found to be not so significant because the thickness of the turbulent boundary layer would be thick enough that it would not change the flow significantly.

On the other hand, at Re=300000, it is found that the bump around *p*=0.10 reduced the drag by about 15% than the "clean" one. When the Reynolds number is lower than this value, the flow separation or transition would not be triggered. Fig.9 shows that the pressure distributions over the airfoil surfaces with and without the bump where AOA=0 [deg.], at Re=300000. In the case of the "clean" one, a larger LSB can be observed around *x*=0.50 to 0.70. In the case of the airfoil with the bump, however, the smaller LSB is created and the pressure jump at the transition becomes less aggressive. This "improved" pressure distribution would reduce the drag significantly.

In both Reynolds numbers, however, decreasing the values of C_L are inevitable against any values of *p*.

4 Measuring the profile of the actual airfoils

At the present, in Japan, most of HPAs are manufactured by university students and by their "hands". Hence, the manufacturing quality greatly depends on their workmanship. Thus, in order to evaluate the influence of their workmanship on the manufacturing error, we made airfoils (DAE21) with our manufacturing process of HPA and measured the profiles of their upper surface. These airfoils are made of SUNMODUR®; a kind of fiber board and the chord length is 1000 [mm]. Under the cooperation of SUAC, two members of them made two test airfoils named No.1 and No.2, respectively. We measured the 118 y-coordinates of the upper surface of the two airfoils and compared them with the "genuine" y-coordinates. Figure 10 and Table 1 show that the distributions of the profile error of the two airfoils and the summary of the values of measured errors, respectively, and note that the value of the error are normalized by the chord length.

Table 1. Summary of the distributions of the measured errors of No.1 and No.2

	No.1	No.2
Max.	$8.8\text{x}10^{-4}$	$1.48\text{x}10^{-3}$
Min.	$-2.9\text{x}10^{-4}$	$1.5\text{x}10^{-4}$
Avg.	$5.1\text{x}10^{-4}$	$7.7\text{x}10^{-4}$

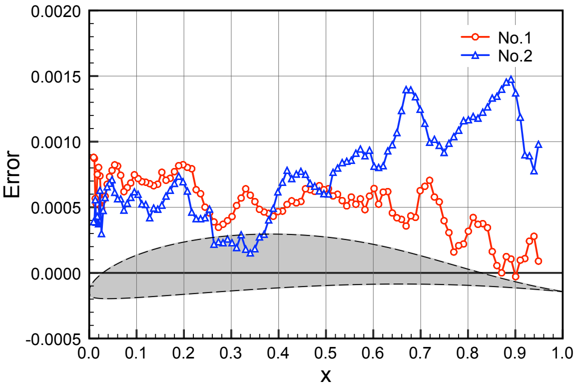

Fig.10. Distributions of the profile error on the upper surfaces of the test airfoils

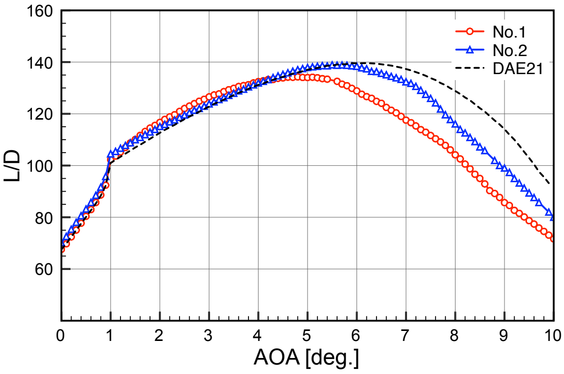

Fig.11. Comparison between the L/D characteristics for the "actual" airfoils and for the "genuine" DAE21, predicted by XFOIL at Re=529100

The result shows that the distribution of the profile error of No.1 is different from that of No.2. In the case of No.1, it is found that the errors near the L.E. are larger than that of the T.E.. On the other hand, in the case of No.2, the errors near the L.E. are smaller than that of the T.E..

Figure 11 shows that the comparison between the L/D characteristics for the "our" airfoils and for the "genuine" DAE21, predicted by XFOIL at Re=529100. From this figure, we found that the L/D decreased by about 20% in the case of No.1. On the other hand, in the case of No.2 which has the larger error, moderate decrease of L/D is observed. In the case of No.1, larger errors mainly distributed near the L.E. and they

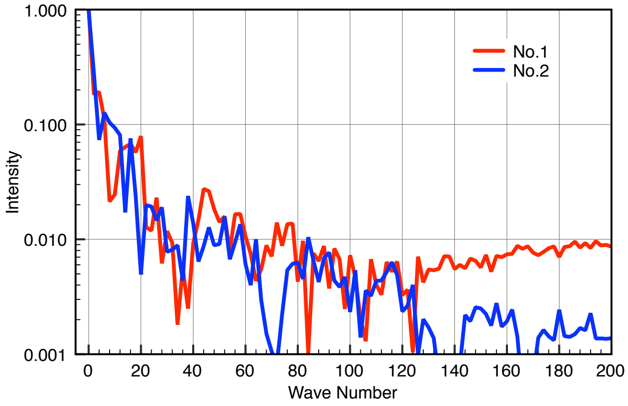

Fig.12. Comparison between the result for the DFT analysis for No.1 and that for No.2

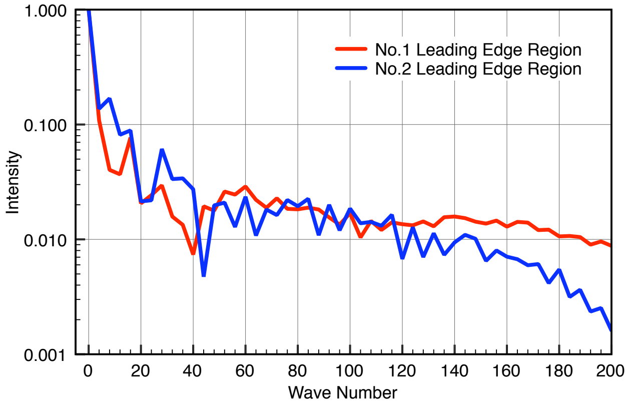

Fig.13. Comparison between the result for the DFT analysis for No.1 and that for No.2, near the L.E. ($0 \le x \le 0.500$)

would change the flow into turbulent flow earlier. This would decrease the aerodynamic performances drastically. In the case of No.2, however, larger errors mainly distributed near the T.E. and they would not changes flow significantly. In both cases, the aerodynamic performances decreased at relatively high angle of attack (α>6 [deg.]).

In order to investigate the characteristics of the distributions of each error, spectrum analyses were performed by using discrete Fourier transform (DFT). In order to perform the analysis, the measured profile errors were divided equally into 200 points by using linear interpolation. For two airfoils, the analysis were conducted all over the airfoils and around the L.E. domains (x=0 to 0.500), respectively. Figure 12 and 13 show that the comparisons between the results for the analysis for No.1 and that for No.2 for all over the airfoils and for the L.E. domains, respectively. These figures show that the actual profile errors consist of relatively low-wave-number periodic waves (C<20) and this indicates that the actual profile error could be modeled by series of low frequency wave originated from sine function. In the L.E. domain, the intensities of low wave numbers (C<20) for the No.2 are higher than that for the No.1. This means that the profile of the upper surface of No.2 is piecewise smoother than that of No.1, near the L.E. (Fig.13). This smooth surface would maintain the aerodynamic performance high.

5 Conclusion

The influences of the profile error on aerodynamic performances were estimated by numerical analysis for low-Reynolds-number airfoils. It is found that the errors near the L.E. could reduce the aerodynamic performance drastically. In some cases, small bumps located near the L.E. could reduce the drag by about 15%. In all cases, however, decreasing the lift performance is inevitable. Hence, the care should be taken for the influences of these errors created by the manufacturing process when designing a low powered aircrafts such as HPA.

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