Optimization Criteria and Sailplane Airfoil Design

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Abstract

This paper describes procedure of sailplane airfoil optimization with the use of available numerical and experimental methods. The calculation of boundary layer transition, integral parameters, the measurement of the maximum lift coefficient, flow visualization and flow control are discussed. Results concerning airfoil design for training and club class sailplanes are presented.

Introduction

The initial stage of sailplane design, as with every aircraft, forms a pronounced need for fast and reliable analysis methods to use in the optimization process. Although wind-tunnel testing can offer all the required parameters, cost effective numerical methods are of paramount importance to airfoil design.

Optimization

Training and club class gliders represent the most numerous portions of sailplanes in use. There are several single seat types that can be included into the club class; however, only those which are primarily designed for heavy club use, such as for transition from training gliders, for pilots with relatively low flight time, will be considered. Docile stall behavior and ease of winch launch and aero tow are favorable characteristics of these types of sailplanes. Hence both categories are similar, in that performance aspects are not the primary objectives. The classical airfoil optimization approach based on cross-country speed maximization is not suitable for this application.

The requirements for an airfoil can be divided into three regimes,[1] their importance established from a questionnaire circulated among flight instructors and club pilots (throughout the experience and age spectra):

Regime	Club class
Low-turbulent free stream	31 %
Increased level of turbulence	35.7 %
Insect contamination of leading edges	33.3 %

Regime	Training cl.
Low-turbulent free stream	36.7 %
Increased level of turbulence	29.3 %
Insect contamination of leading edges	34 %

Further details of these pilot's desired design features concern interthermal glide, circling and low-speed handling. Resolved into the consideration of coefficients, at given positions along wingspan, the minimum drag coefficient c_D at 10 given lift coefficients c_L (circling and glide), maximum c_L at prescribed angle of attack (landing), and value of c_{Lmax} itself (stall) are sought. Furthermore docile stall characteristics are important; all of this information should be obtained for the three mentioned regimes. The requirements f_j and their importance v_j are summed up in a target function F, which is to be maximized.

$$F = \sum f_j v_j \qquad (1)$$

Parameters acquired by numerical modeling

Using the XFOIL airfoil analysis code, [2] considered to be a standard tool, the ratios of drag coefficients concerning the investigated, $_i$ and reference, $_{ref}$ airfoil are determined:

$$f_{cD} = \frac{c_{D\sim ref}}{c_{D\sim i}} \qquad (2)$$

Applied to experimental, $_{\exp}$ and numerical, $_{num}$ data, the principal objective is: $f_{cD\exp} / f_{cDnum} = 1$. A sufficient amount of proven wind tunnel data is available for comparison.[3,4] Considering the NACA 63-618, the Wortmann FX66-S-196 and the Eppler E603 airfoils, with reference Wortmann FX61-163, we can obtain values of mentioned ratio, with varying values of the n-factor in e^n transition prediction method. Agreement between experimental and numerical c_D values, range $c_L = 0.2 \div 1.05$, statistical confidence interval 95%, $f_{cD\exp LWK} / f_{cDnumXfoil}$:

N	Re = 10^6	Re = $3 \cdot 10^6$
5	0.973 ± 0.029	1.034 ± 0.038
9	0.993 ± 0.014	1.041 ± 0.019
11	1.010 ± 0.020	1.054 ± 0.024

The agreement with the standard $n = 9$ is acceptable for this investigation. Similar results have been obtained for NACA 6-series, altering the thickness distribution from 63-415 to 66-415, as well as for family of Wortmann airfoils FX 63-145/158/147/143. The location of the end of transition process is also computed correctly. Although the augmented level of outer flow turbulence has been the objective of numerous studies, the data concerning the effects on a laminar wing sections are scarce. The findings on a E603 wing section[5] have been used for *n*-factor adjustment in the formulation of the transition criteria.

Studies on roughness due to insects [6, 7, 8] with 130 and 20 bugs/meter are not fully consistent with one another, at least quantitative agreement can be obtained with the latter, setting the transition to 0.05 x/c on upper surface.

Parameters acquired by wind-tunnel measurement

Maximum lift coefficient and behavior in the stalled regime must be obtained from experimental investigation in all three regimes.

If we require accuracy common for preliminary conceptual design of sailplanes only, we can draw few reasonable assumptions and reduce test programme into one regime. A wide range of turbulence in the outer stream intensity was examined with defined intensity of turbulence Tu at the plane of airfoil leading edge.[9] For considered $n = 9 \sim Tu = 0.070$ % and $n = 6 \sim Tu = 0.245$ %, the effect on maximum lift coefficient can be neglected. The same simplified approach can be used for roughness due to insects, which is in agreement with general experience from flight test evaluation – a small effect on stall speed is observed on most sailplanes.

Lift curve measurements have been carried out on reference airfoil, the Wortmann FX66-17AII-182, and two new PW series airfoils, the PW212-163 and 311-161, in the two-dimensional 1200x400mm CTU FME wind tunnel. The geometries of the airfoils tested are given in Fig. 1. Again, we define criteria:

$$f_{cL\max} = \frac{c_{L\max\sim i}}{c_{L\max\sim ref}} \tag{3}$$

The following ratios have been obtained: for the PW212-163, $f_{cLmax} = 1.00$ and for the PW311-161, $f_{cLmax} = 1.04$.

A reduced Reynolds number enhances the extent of separation bubbles, which can be easily detected on static pressure measurement and visualization.

For these lower Reynolds number conditions, pressure distributions have been obtained and presented in Fig. 2. Smoke-wire techniques have been performed in 750x550mm CTU FME wind tunnel and the digital photographs, shown in Fig. 3, acquired. The PW212-163 and PW311-161 airfoils have demonstrated a longer run of laminar flow and a smaller amount of local separation than is observed on the FX66-17AII-182 airfoil.

Since the PW series airfoils are designed for boundary layer control, positions of standard zig-zag tape have been established in order to finish transition process upwind of the start of steep recovery gradient, as shown in Fig. 4.

Results

Target functions have been obtained for the wings of club class and training sailplanes in conceptual studies. The best of the published airfoils was set to $F = 100$ % and comparisons with other well-known and widely used wing sections has been carried out. The PW series airfoils,[10] which were designed for the mentioned categories of sailplanes using of the inverse methods QDES and MDES in XFOIL, were also taken into consideration.

The values presented in following tables emphasize the importance of the appropriate airfoil selection and the possibility of the considerable gains might be achieved:

Airfoil	F
PW212-163	103.3 %
FX61-163	100 %
E603	98.6 %
FX66-17AII-182	94.4 %
FX S 02-196	93.7 %

Target functions for wing root of conceptual study B, a club class sailplane, wing loading $m/S = 32$ daN/m^2

Airfoil	F
PW212-163	104.3 %
NACA 63A615	100 %
E603	99.7 %
FX73-170	95.4 %
FX S 02-196	94.5 %

Target functions for the mean aerodynamic chord of wing; conceptual study L, a training sailplane, $m/S = 28$ daN/m^2

Future work

The presented aerodynamic methods have shown their eligibility and beneficial role in the feasibility studies associated with experimental projects currently of interest. For example, the methods are applicable to research concerning the implementation of a synthetic jet actuator into a flapped sailplane airfoil, for determining test-case locations of turbulators, and the effect of free-stream turbulence on the airfoil drag coefficient.

Summary

This paper has shown details dealing with the procedure of wing section design, and with the use of experimental and numerical methods. The methodology is easily extended to other classes of sailplanes, as well as to other categories in sport aviation.

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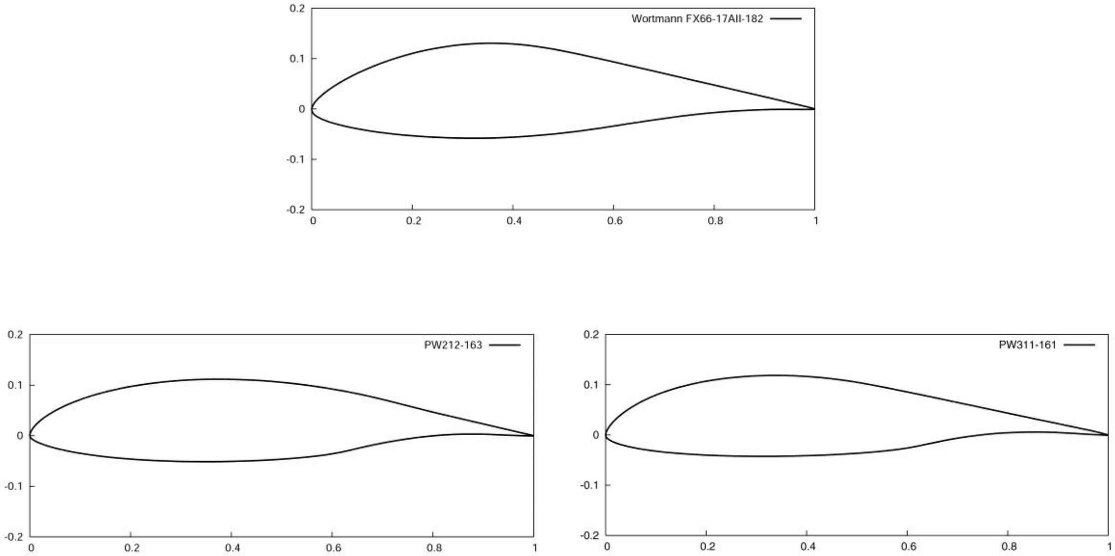

Figure 1 Contours of airfoils FX66-17AII-182, PW212-163 and PW311-161

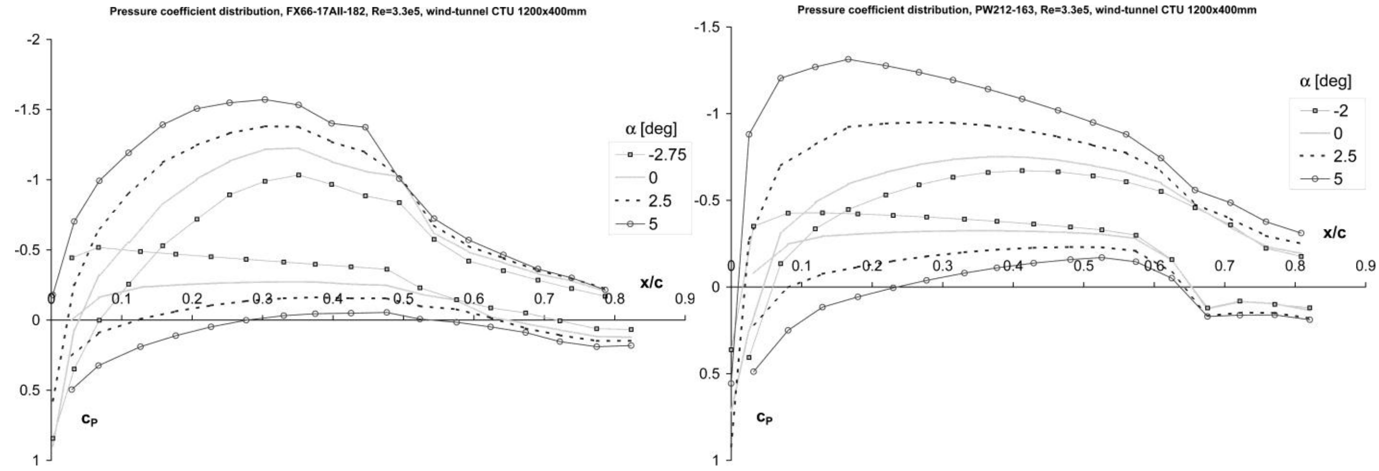

Figure 2 Measured pressure distributions, FX66-17AII-182, PW212-163, *Re* = $3.3\cdot10^5$, *Iu* = 1.2 %

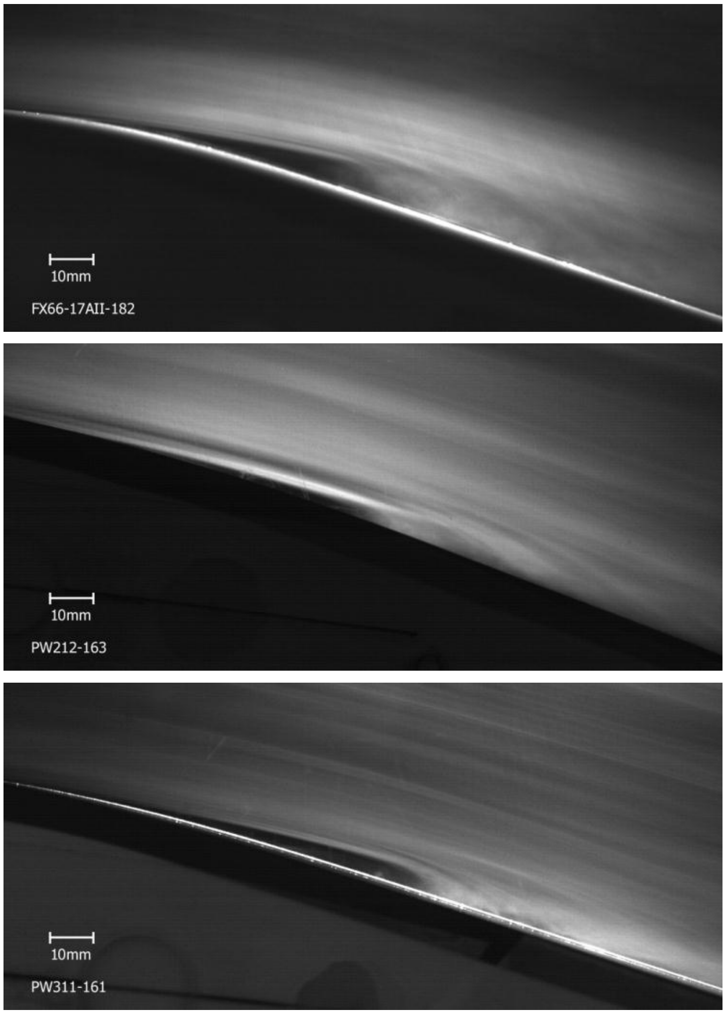

Figure 3 Airfoils FX66-17AII-182, PW212-163 and PW311-161, smoke-wire visualization on upper surface, $\alpha = 5^o$, *Re* = $1.3\cdot 10^5$, *Tu* = 0.7 %. Laminar separation of boundary layer, transition and turbulent reattachment

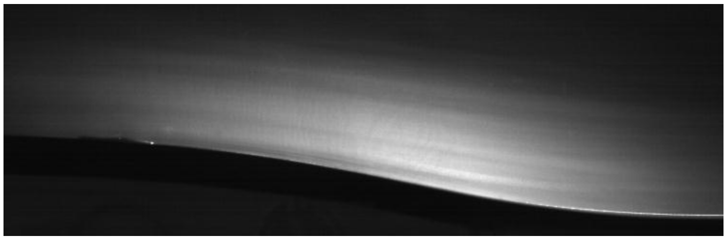

Figure 4 Passive flow control by standard ZZ turbulator on lower surface of PW311-161 airfoil; attached boundary layer, $\alpha = 0^o$, $Re = 2.1 \cdot 10^5$, $Tu = 1.3$ %