INVESTIGATION OF HIGH-LIFT, MILD-STALL WINGS

F.M. Kong, J. Hua, J.W. Xiang
Beijing University of Aeronautics and Astronautics, 100083 Beijing, China
Z.Y. Zhang
Northwestern Polytechnical University, 710072 Xi'an, China

Keywords: *Wing, Maximum lift coefficient, Mild-stall, Endurance*

Abstract

The design research of wings featuring high-lift, mild-stall characteristics for long-endurance air-vehicles is presented. The main purpose is to investigate the design concept, methods and technology of the particular wing sections. Wind-tunnel measurements show that the maximum lift coefficient and the maximum endurance factor of a sample wing equipped with the new BUAA-K1/-K2 airfoils have been increased considerably, compared with another wing using the well-known GAW-1/GAW-2 airfoils. The aerodynamic features of high-lift and mild-stall have been realized.

1. Introduction

Since the first manned flight a hundred years before, the main goals of flying have long been faster, higher and farer, so as the wings of different aspect ratio and swept angle equipped with conventional, high lift, supercritical and laminar flow airfoils, thick and thin, have been continuously studied and developed.

For some of the more recent applications of air-vehicles, manned and unmanned, long-endurance has become the new goal. Examples include high altitude communication relay aircraft, natural environmental protection survey flights and even the sport sailplanes. This gives rise to a R&D boom in the aerospace world in the last few years and there appear a number of projects and tests, concerning models from turbo-charged piston low-speed unmans, turbofan powered high altitude transonic manned/unmanned composites, up to more venturing solar–electric plastic cruisers. For each of those new airplanes, a creative high performance wing other than the wings above mentioned is the most essential component. This forms the background of the present study.

In this paper the target Cp (pressure coefficient) distribution of an ideal low-speed, low Reynolds number, high-lift and very mild-stall wing section is prescribed, as part of the conceptual study. The CFD (Computational Fluid Dynamics) design method used to generate the wing sections is shortly described. The design results of the new BUAA K1 & K2 airfoils and K12 wing are presented, and compared with a wing using the well-known GAW-1 & -2 airfoils. Wind tunnel measurements of both wings show that the research target has been fulfilled.

2. Conceptual Study

2.1 The required wing to "Hang" the airplane

The general goal of the aerodynamic design is to increase the lift to drag ratio CL/CD. But for different airplanes the emphasis may also be different. For example, the most important parameter for a subsonic passenger jet is the Aerodynamic Efficiency ML/D, which reflects the role of the cruise Mach number to effectively cover a certain distance at reasonable time and fuel expense. A supersonic jet, on the other hand, requires minimum zero-lift drag CD_0 for higher speed, and maximum lift coefficient CL_{max} for better maneuverability. In order to realize long-endurance flight, the wing should provide higher endurance factor $CL^{3/2}/CD$. Notice the increased importance of

CL here and it should be kept greater than 1 in such a function, the flight concept of "hanging" the aircraft in the sky could herein be put forward, which implies to fly at almost maximum lift and lowest cruise speed with engine power just good enough to maintain the altitude and against the wind, so as to reach the minimum fuel consumption and longest endurance. This is particularly true when the aircraft is making a stationary circle-route for communication relay.

Such a "near stall" flight asks the challenge to develop new wings with the following requirements:

- High operational lift coefficient, CL>1;
- High endurance factor $CL^{3/2}/CD$;
- Very mild stall characteristics for enough safety margins;
- Limited pitching moment coefficient CM;
- To realize the above features at low Reynolds numbers ($Re \sim 10^6$);
- High relative thickness ratio T/C, particularly near the front and rear beam chord locations for larger aspect ratio, reduced wing weight, increased fuel-tank volume and more convenience for control surfaces installation.

It is clear that none of the existing airfoils in handbooks could provide the above features and this explains why the wing and wing section research has been kept a forever project.

2.2 The design philosophies

For endurance of a few hours, such as sailplanes being normally operated in fine atmosphere, the Nature Laminar Flow (NLF) airfoils could provide very high CL/CD and also $CL^{3/2}/CD$ values, mainly by reducing CD. Successful examples include DLR-HQ airfoils for a lot of sailplane applications; the Drela's airfoils for Reynolds numbers as low as to the man-powered airplanes; and also the work of Maughmer et al. for high altitude laminar wing sections [1].

For longer endurance flight up to a day or more in multiple weather conditions, keeping laminar flow over the wing becomes difficult. Koss [2] and Zhang [3] developed different high-lift mild-stall airfoils for long endurance aircraft applications. These wing sections feature special upper surface Cp distributions to postpone separation, and strong rear loadings to retain high lift.

Selig and Gugleilmo [4] developed high-lift airfoils for low Reynolds numbers around 2.0E5, by adopting concave pressure recovery and great amount of rear loading.

As a pure scientific research of Design Aerodynamics, more severe requirements are targeted in this paper for both aerodynamic characteristics and geometry convenience.

The design point of the baseline airfoil is chosen as: M=0.16, CL=1.0 and Re=2.0E6. The new wing section is supposed to have comparable thickness distributions with the GAW-1 profile [5], especially near the wing beam locations. The absolute pitching moment CM is no larger than GAW-1 at design point. Meanwhile, the endurance factor should be greatly increased.

2.3 Prescribing the target Cp distributions

The well-known GAW-1 airfoil, designed at CL=0.4, T/C_{max}=17% and Reynolds numbers for low-speed general aviation airplanes, adopts the Cp distribution and rear loading like the supercritical airfoils. At M=0.16 and Re=2.0E6, this airfoil is analyzed by using a reliable Euler plus Boundary Layer solver.

The GAW-1 generates CL=1.0 at angle of attack α=4°, under this low Reynolds number. The leading edge suction peak has already started to rise, as shown in Fig. 1. At α=12°, the suction peak is so high that adverse pressure gradient makes boundary layer separate from 80% chord. The separation point moves upstream shiftily towards the leading edge when α further increases and CL drops dramatically when the stall occurs.

The prescription of the target Cp distribution of the new airfoil focuses on the following:

- The correct Cp type in the front part of the upper side;
- The shape of the Cp curve for the upper surface pressure recovery;
- The correct extension of the laminar flow in the upper side;
- The correct strength of the rear loading, because rear loading will increase |CM| and make the aft-airfoil too thin to be considered applicable.

Repeated investigation leads to a final optimized target Cp distribution as shown in Fig. 1, together with that of GAW-1. The target features the following:

- CL=1.0;
- A round front upper Cp shape up to 30% chord, one key to mild-stall;
- A weak Stratford type upper surface pressure recovery for preventing the fast upstream movement of the separation, which is important for maintain high lift in low Reynolds numbers;
- Certain amount of front loading in the lower surface for compensation of the lift and also for making the airfoil nose-down, another key to mild-stall.
- Reduced rear loading for the pitch moment and aft-airfoil thickness control;
- The upper surface transition occurs at 30% chord under the design Reynolds number, but the target Cp features will not be changed in full turbulent flows.

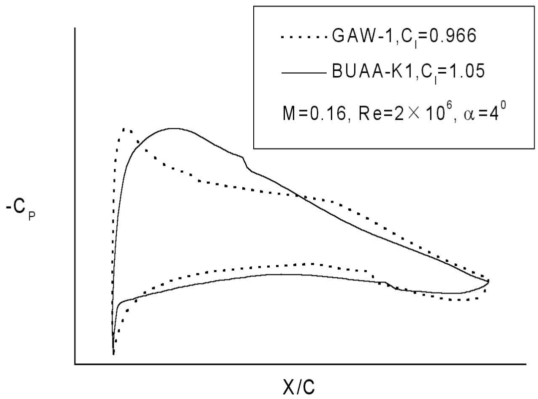

Fig. 1. Target Cp distribution of the new airfoil and the comparison with that of the GAW-1

3. Design Software and 2D/3D Results

3.1 Design software

In order to realize the carefully specified Cp distribution, the 2D/3D Transonic Design CFD software NPU-TDTDTD has been used which includes 2D/3D inverse codes and airfoil/wing analysis codes based on FP/Euler + Boundary-Layer methods and NS solvers. This software utilizes a modified "iterative residual correction" principle and is able to generate new airfoils and wings within a few design iterations with the Cp converged very satisfactorily to the targets, even when strong discontinuities like shock waves exist. The software has been continuous upgraded and used for a number of 2D/3D designs of supercritical and laminar flow configurations [6] [7].

3.2 Design of the wing sections

From the target Cp prescribed in section 2.3, the new airfoil, BUAA-K1 is generated, as show in Fig. 2, together with the GAW-1 contour. The airfoil has the maximum relative thickness 17.2%, the wall heights at front and rear beam locations, say 15% and 80% chord, are close to that of the GAW-1, the fuel-tank volume comparable, and the trailing edge thickness ratio is a standard value 0.5%.

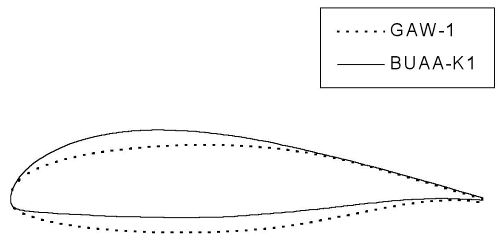

Fig. 2. Contour of the new airfoil BUAA-K1 and the comparison with GAW-1

The new airfoil is analyzed by using the same method and compared with GAW-1. At α=12°, the BUAA-K1 airfoil has no visible separation, and the leading edge suction peak is still low and blunt.

Fig. 3 plots the calculated lift curves, which shows that the slope of the lifting line of the new airfoil in the linear portion is greater than the GAW-1; the maximum CL value is increased and appears at smaller angle of attack. The most important point is that the new airfoil has a very mild-stall feature while the other suffers a sudden stall when the viscous flow computation could no longer converge.

Fig. 4 illustrates the comparison of the calculated endurance factor $CL^{3/2}/CD$, the new airfoil has a 70% increase in the maximum value in the 2D case.

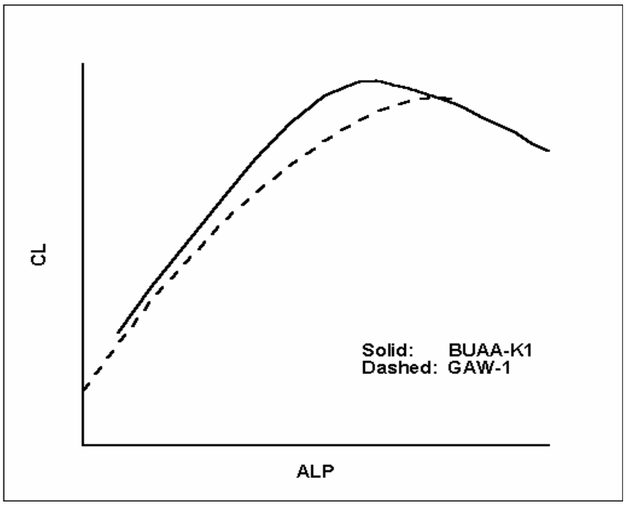

Fig. 3. Comparison of the calculated lift curves

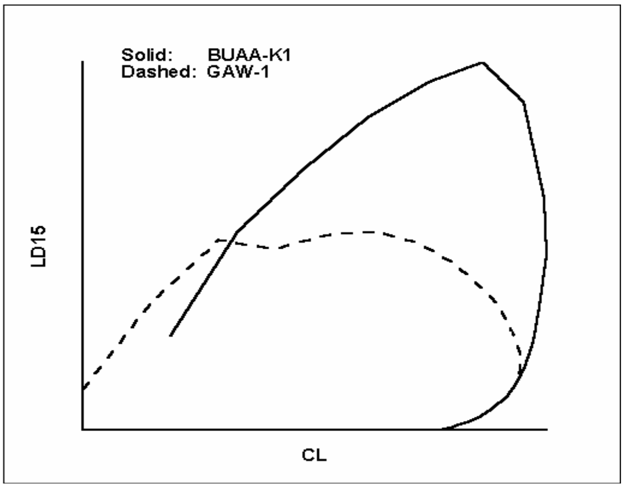

Fig. 4. Comparison of the calculated endurance factor curves

The comparison of the calculated pitching moment of both airfoils is given in Fig. 5, where the absolute values of the new airfoil keep smaller before CL = 1.22.

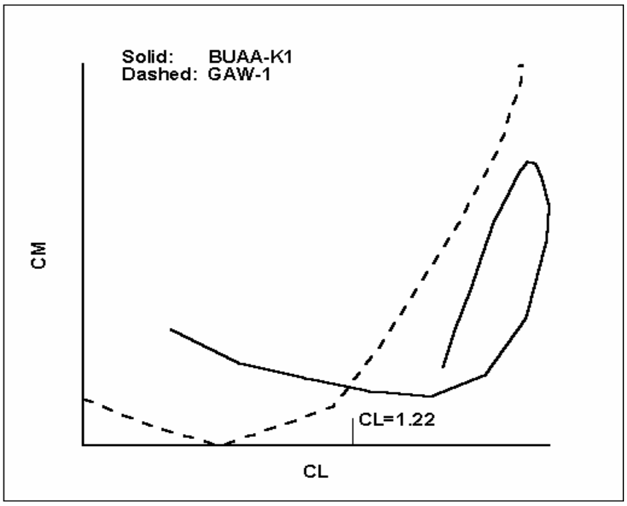

Fig. 5. Comparison of the calculated pitching moment

The above analysis suggests that the 2D design target has been successfully realized, and the new airfoil BUAA-K1 could be used as the baseline wing section. Due to the validated reliability of the analysis code, 2D wind tunnel test is considered unnecessary.

Following the same procedure, another airfoil of smaller thickness ratio 13.5%, named BUAA-K2, is designed to serve as the wing tip section, and it has very similar aerodynamic characteristics.

3.3 Design of the high-lift mild-stall wing

Mounted to an existing passenger jet fuselage, in order to save the wind tunnel model cost, two wings with the same planform are constructed. The BUAA-K12 wing has the K1 airfoil as the root section and K2 as the tip section. While the G12 wing uses GAW-1 and a 13% thick GAW-2 at the root and tip sections.

Both wings are analyzed by using a reliable Full Potential + Boundary Layer code, and the twist angle is afterwards determined to be 2 degrees.

The side view of the BUAA-K12 wing is illustrated in Fig. 6. The calculated surface Cp contour in Fig. 7 shows straight isobars over the wing upper surface, implying that the carefully prescribed 2D Cp distribution has been well retained over the span.

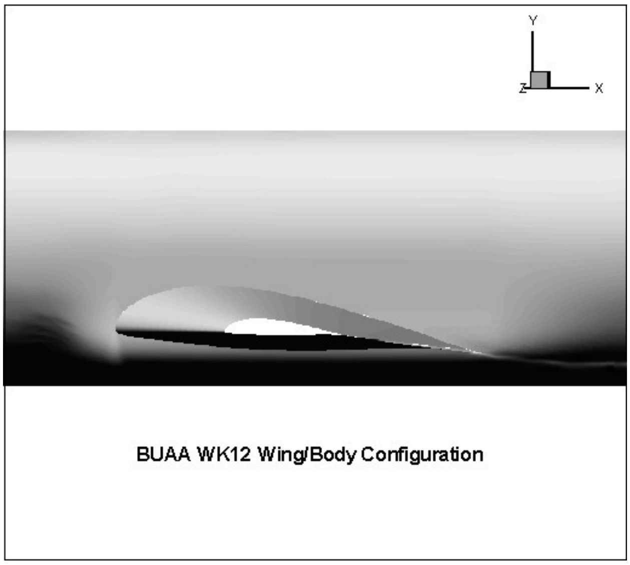

Fig. 6. Side view of the BUAA-K12 wing/body combination, CFD model

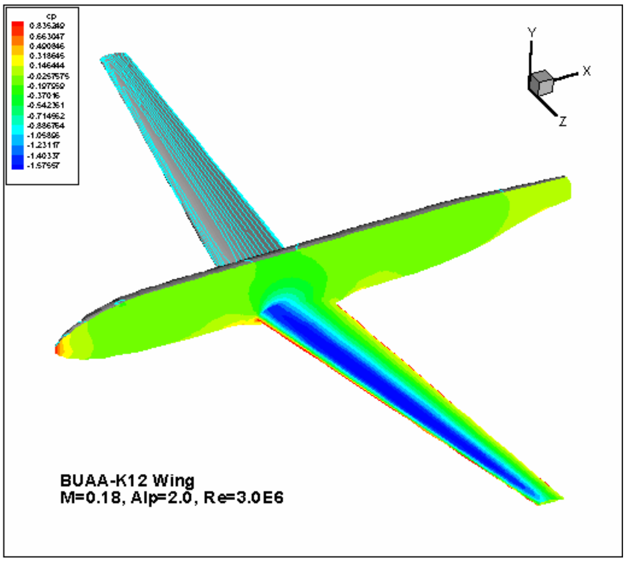

Fig. 7. Calculated surface Cp distribution and isobars of the BUAA-K12 wing/body configuration

4. Experimental Verification

Both wings are tested with the same fuselage in the 3.5m x 2.5m low speed wind tunnel of the Chinese Aeronautical Aerodynamics Institution.

Fig. 8 is the measured CL~α curve, which not only demonstrates the calculated feature of Fig. 3, but also shows an even mild stall characteristics and an 15% increase in the maximum lift coefficient.

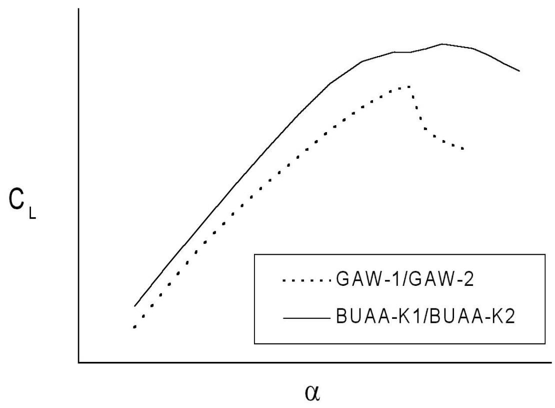

Fig. 8. Comparison of the measured wing/body lift curves

Fig. 9 shows the improvement of the endurance factor. There is a 25% increase in the maximum value, and even more in higher lift coefficients, for the 3D wing/body which promise more loads, higher altitude, lower fuel consumption and longer flight time. The achievement of the design target has then been clearly verified.

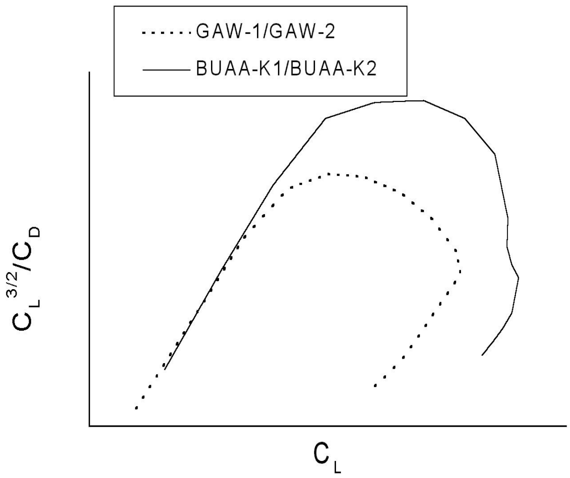

Fig. 9. Comparison of the measured wing/body endurance factor curves

5. Conclusions

- Long endurance flight could be realized by the concept to "hang" the aircraft in the sky, which means to operate the vehicle at the "near stall" boundary.

- Such a flight could be possible with the help of a high-lift, mild-stall wing.
- Design research of such a wing is conducted in this paper with the special effort on the prescription of the target Cp distributions of the baseline airfoil.
- Each portion of the target Cp is responsible for a certain aerodynamic feature, such as the mild-stall, the slow development of the separation, the reduction of the absolute pitching moment, and the airfoil thickness control, as detailed in section 2.3.
- The design software and CFD analysis codes used in this study are all validated, effective and reliable.
- The baseline airfoil BUAA-K1 and K2 have satisfied geometry and required aerodynamic characteristics.
- The BUAA-K12 wing designed well retains the features of the 2D research.
- The wind tunnel experiment shows that the new K12 wing could provide a 15% increase in maximum CL and 25% in $CL^{3/2}/CD$, compared with the reference G12 wing. This ensures more loads, higher altitude and longer endurance.
- The design concept, methods, technology and results are successfully verified and the target of the present investigation has been fulfilled.

Acknowledgement

The authors are grateful to Prof. B.J. Fei of BUAA and the Chinese Aeronautical Aerodynamics Institution for their advise and help to this research.

References

[1] Maughmer M. D and Somers D. M. Design and Experimental results for a High-Altitude, Long-Endurance Airfoil. *Journal of Aircraft*, Vol. 26, 1989.

[2] Koss D, Steinbuch M and Shepshelovich M. Design and Experimental Evaluation of a High-Lift, Mild-Stall Airfoil. *AIAA 94-1867*, 1994.

[3] Zhang Z. Y, Hua J, Zhan H. and Wang J.P. NPU-ANS-1 Airfoil for Long –Endurance Aircraft. *Journal of NPU*, Vol. 17, 1999.

[4] Selig M.S and Guglielmo J.J. High-Lift Low Reynolds Number Airfoil Design, *Journal of Aircraft*, Vol. 34, No. 1, 1997.

[5] McGhee R. J and Beasley W. D. Low-Speed Aerodynamic Characteristics of a 17-Persent-Thick Airfoil Section Designed for General Aviation Applications, *NASA TN D-7423*, 1973.

[6] Hua J and Zhang Z.Y. Transonic Wing Design for Transport Aircraft. *ICAS 90-3.7.4*, 1990.

[7] Hua J, Yang Q.Z, Xi D.K, Zahng Z.Y, Fu D.W and Zhang Z.L. Design and Experimental Investigation of Transonic Natural Laminar Flow Wings. *ICAS 94-4.7.3*, 1994