AIRFOIL DESIGN OF TAILLESS UNMANNED AIR VEHICLE (UAV)

SI Jiangtao*, ZHAN Hao, Bai Junqiang****
***The First Aircraft Design and Research Institute of AVIC-I, Xi'an 710089, China**
****Northwestern Polytechnical University, Xi'an 710072, China**

Keywords: *airfoil; design; tailless; Unmanned Air Vehicle (UAV); pitching moment*

Abstract

Comparing with conventional configuration, Tailless Unmanned Air Vehicle (UAV) has shown apparent difference on aerodynamic design. The difficulties in the aerodynamic design of tailless configuration are discussed. Based on the analysis of airfoils, which have the same 16% relative thickness and are designed with three different philosophies, this paper presents the usage of airfoil compromise design to improve pitching moment performance of tailless statically stable aircraft and the discussion of possible problems involved. According to experience, the XFOIL program is accurate enough for low Mach number problems with Reynolds number ranging from 1×10^6 *to* 2×10^6 *, which are exactly the problems this paper deals with, therefore all the analysis and computations of aerodynamic performance of the airfoils are fulfilled by the XFOIL software.*

1. Introduction

Since 1917 when the first unmanned air vehicle (UAV) was developed successfully in England, UAV has been progressing through several stages, which are target drone, recon- naissance aircraft and multi-role UAV. And heretofore, it has been successfully used for military purpose in four local wars, which has come to the attention of the world. Consequently UAV gains great promotion for a rapid development.

There are hundreds of kinds of UAV for various purposes presently. Their aerodynamic configurations can be categorized mainly into three kinds: conventional, unconventional and that with rotor. The former two kinds are adopted by most UAV. Compared with tailless configuration, conventional configuration has been studied quite broadly and thoroughly and techniques related have achieved quite a high level. Meanwhile, the development of UAV with tailless configuration has also obtained an obvious progress, such as "Dark Star".

With the rapid development of airborne weapon recently, the living environment of UAV has been getting worse, thus improving the survival capability of UAV is getting more important in the study of UAV. Many approaches can work, as to aerodynamic aspect, mainly are to improve stealth performance and increase flight altitude. Comparing with conventional configuration, tailless UAV has less radar reflection planes, so there are great advantages in stealth; "B-2" is a successful example. Although the development of "Dark Star" didn't get along well, tailless configuration will be widely adopted in the design of UAV. In addition, when the aircraft flies at an altitude of 20'000m, it will be securer from ground air defense weapons and fighters, but, there will be some problems with aerodynamics because the air density at an altitude of 20'000m is only about 7.2% of that at sea level thus the Reynolds number is very low.

2. Difficulties in aerodynamic design

Unlike conventional configuration, tailless aircraft has no horizontal tail to trim the pitching moment, (only longitudinal problems concerned in this paper) so for the aircraft there are only the control surfaces of the wing which can be utilized to achieve balance. The arm of force of control surfaces in the wing is much shorter than that of horizontal tail, so the control efficiency is much lower. Thereby, the pitching moment at the design point has to be a very small value close to zero, which means that the flight of aircraft almost needs no pitching control. In order to control the aircraft properly when it departs from the design point, there are high requirements for static margin. Usually, the absolute value of static margin is no more than 5%, which is less than 10%~ 15% of that of blended wing body of conventional configuration. The value of static margin reflects the distance between moment reference point and aerodynamic center, and does not influence the characteristic of flow separation over airfoil, but the influence of the variation of aerodynamic center on moment shows different degrees when dealing with different static margin. Therefore, for tailless UAV the angel of attack corresponding to moment divergence is much less than that corresponding to stall, which is a unique characteristic of tailless UAV.

The difficulty with tailless UAV design is to figure out a way to compromise between lift-drag ratio and early emergence of nonlinear problem with pitching moment caused by too small static margin. Too small lift-drag ratio is not favorable for the performance of aircraft while too short linear section of moment is not favorable for flight safety. For aircraft with no sweepback or small sweepback, its characteristic is mainly determined by the characteristic of airfoil. During the process of airfoil design, large lift-drag ratio is desired. At the same time, it should be guaranteed that in a wide range of angle of attack flow separation won't occur so that the aerodynamic center won't move too fast. It is important to increase the angle of attack corresponding to moment divergence and prolong the linear section of moment. For Re=$1\sim2\times10^6$, the flow over airfoil tends to maintain laminar at a low Reynolds number. But it is difficult to obtain an excellent lift performance (or moment performance) because for the Reynolds number mentioned above, large flow separation on the airfoil surfaces occurs early and as soon as large flow separation occurs, moment divergence would happen.

For low Reynolds number and low Mach number airfoil flows, the XFOIL program which is based on panel methods with the fully-coupled viscous/inviscid interaction method is accurate enough. The calculated results by XFOIL and the experimental results from wind tunnel for a certain airfoil are illustrated in Figures 1 and 2. It can be seen that the lift coefficient, drag coefficient and pitching moment are accurately predicted; the pressure distribution is also accurately predicted. So in this work it is reliable to use XFOIL for analysis.

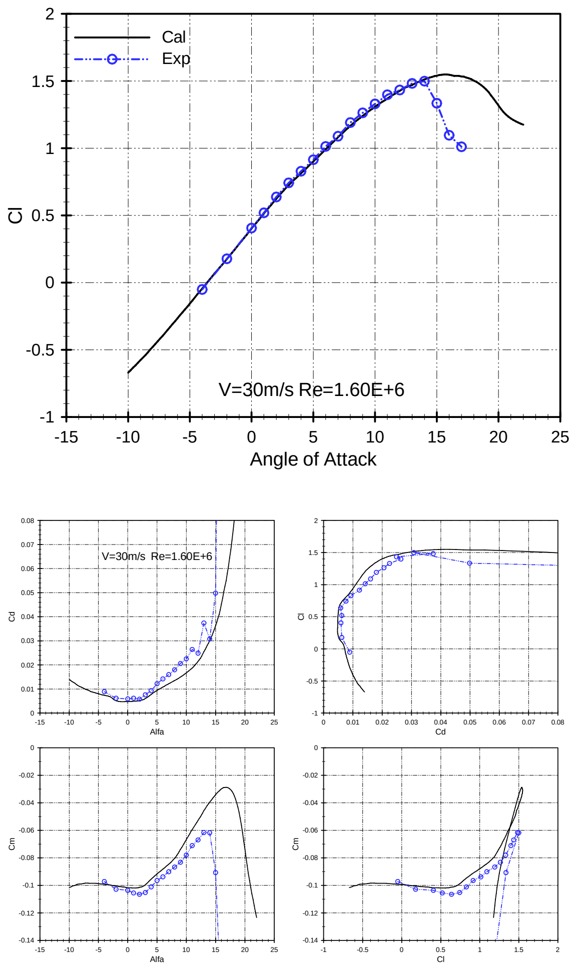

Fig. 1 Calculated lift curve, drag polar and moment curve for a certain airfoil compared with experimental data

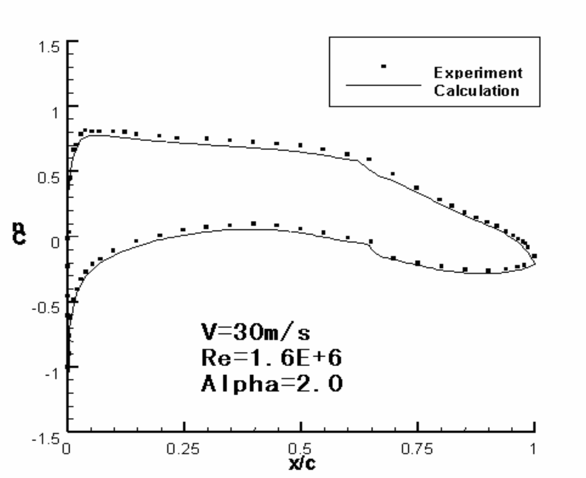

Fig. 2 Calculated and experimental pressure distributions for a certain airfoil

3. Airfoil design and analysis

The static margin of statically stable tailless UAV is negative and the pitching moment at design point is zero, so the zero-lift pitching moment is positive. According to this, it is required that the zero-lift pitching moment should be positive in airfoil design. Given that this paper is mainly to discuss the airfoil design philosophies, no exact value of zero-lift pitching moment will be specified.

Generally speaking, obvious flow separation takes place earlier when the camber of airfoil is larger in the case of low speed with a 2×10^6 Reynolds number. For example, moment divergence occurs for GAW-1 airfoil is at the angle of attack of about 5 degrees. On the contrary, airfoil with smaller camber has a larger angle of attack corresponding to obvious moment divergence. It is not known very well about the performance of airfoils with negative camber at the rear for the reason that this structure is rarely used in practice. In order to get particular knowledge about this kind of airfoil, we designed three kinds of airfoils T1601, T1602 and T1603 with different design philosophy each. ①, airfoil T1601 is designed according to the methods for typical laminar airfoils, thus it has a longer low-drag region. The rear with negative camber can produce positive pitching moment; ②, without consideration of lift-drag ratio, airfoil T1602 is designed primarily to improve moment performance, that is, the moment coefficient varies linearly in a wide range of angle of attack; ③, airfoil T1603 is designed to guarantee that the maximum lift-drag ratio appears at a high lift coefficient and the moment varies little in a wide range of angle of attack.

Shown in Figure 3 are the shapes of three airfoils. T1601 has the characteristics of typical laminar airfoils as it has a smaller leading-edge radius and a further location of maximum thickness from the leading-edge, while the leading-edge radiuses of T1602 and T1603 are relatively larger, the locations of maximum thickness are closer to the leading-edges and the rear are thinner thus laminar flow regions are shorter.

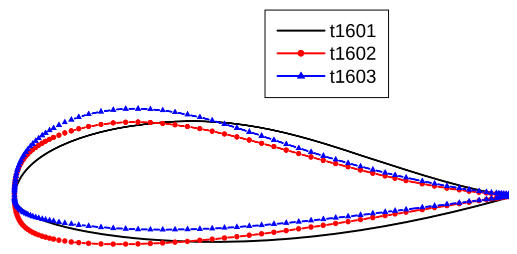

Fig. 3 Shapes of three airfoils

Figures 4−6 show the pressure distributions with different lift coefficients for the three airfoils at a Mach number of 0.2 and a Reynolds number of 2×10^6. Compared with airfoil T1602 and T1603, airfoil T1601 has longer laminar flow region at the upper surface when the lift coefficient is small. But as the lift coefficient increases the peak value of pressure increases quickly. As a result, the transition point moves forwards fast and the laminar flow region get smaller quickly. Therefore, for a laminar airfoil, although the peak value of pressure appears late, high-lift performance is worse because of the quickly increasing peak value of pressure.

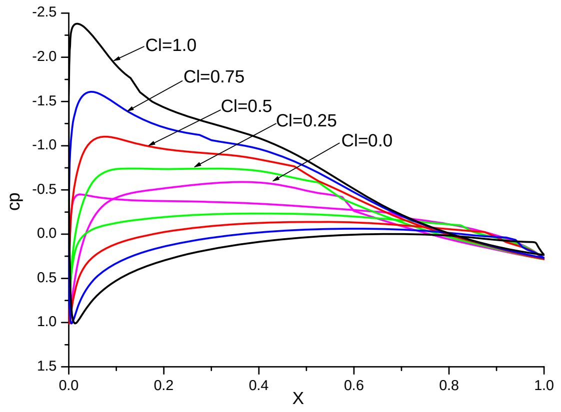

Fig. 4 T1601 Pressure distribution

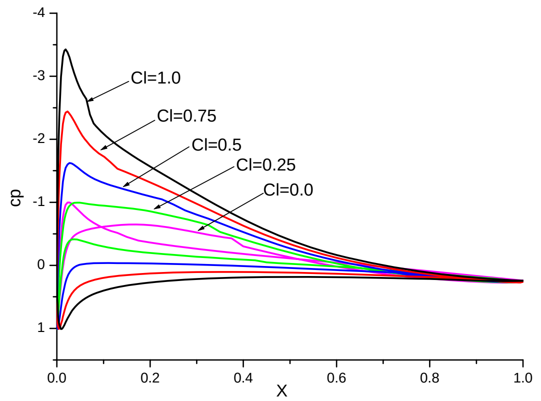

Fig. 5 T1602 Pressure distribution

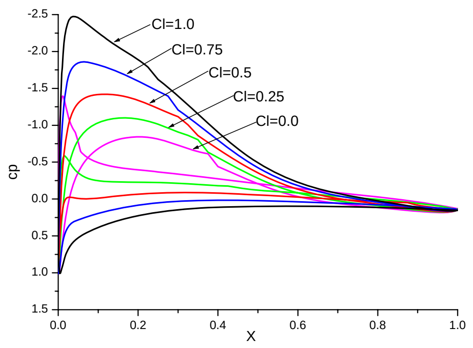

Fig. 6 T1603 Pressure distribution

Figures 7 and 8 show the calculated results for the three airfoils at M=0.2 and Re= 1-2×10^6 (N_{CR} takes 9, and the corresponding turbulence level is 0.07% in the calculation). It can be seen that, ①, for airfoil T1601, an obvious low-drag region exists with the lift coefficient ranging from 0 to 0.7 and the low-drag region decreases while the Reynolds number increases. For a Reynolds number of 1×10^6 and 2×10^6, the lift curve inflects obviously at the angle of attack of about 9 and 10 degrees respectively, and the corresponding moment coefficients take on severe nonlinearity. For Re=1 × 10^6, the linearity of moment coefficient is not good at a negative angle of attack. Further research indicates that the lift and moment performance improves as the turbulence or Reynolds number increases. ②, the lift-drag performance of airfoil T1602 is relatively poor, but its moment performance is best among the three kinds of airfoils. Its moment coefficient varies slightly when the angle of attack ranging from 6 to 11 degrees. ③, for airfoil T1603, in the situation of high lift coefficient, the corresponding drag is lower and the lift-drag ratio is higher and the linearity of the moment coefficient is better. Although there is a “step” on the curve of moment coefficient at the angle of attack of about 4 degrees, the moment performance improves as the Reynolds number increases.

Compared with airfoils T1602 and T1603, airfoil T1601 has the worst moment performance at negative angles of attack. Because the leading-edge radius of the lower surface of the airfoil is small and the rear of the lower surface of the airfoil is relatively thicker. These two characteristics make severe flow separation occurring easily at negative angles of attack when the Reynolds number is low. Attention should be paid to the point stated above when the aircraft operates at a small angle of attack, because there is always some disturbance on the aircraft by the airflow.

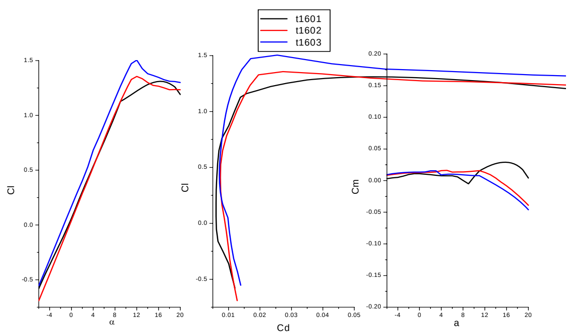

Fig. 7 Calculated results for the three airfoils at M=0.2，Re=1×10^6

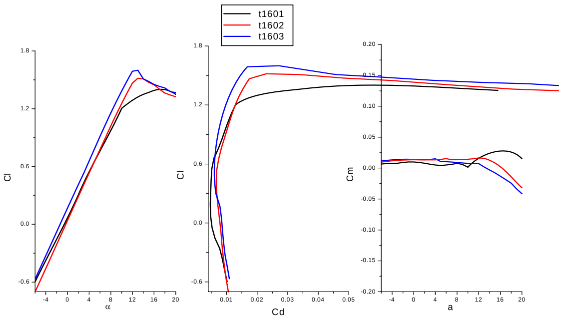

Fig. 8 Calculated results for the three airfoils at M=0.2，Re=2×10^6

To sum up, these three kinds of airfoils represent three different design philosophies. Airfoils T1602 and T1603 are superior at moment performance and can meet the special requirement for pitching moment of the Tailless Unmanned Air Vehicle (UAV).

The “inflection” and “step” on the moment curves are related to the flow separation around airfoil. Comparing with airfoil T1601, the flow separation of airfoils T1602 and T1603 occurs earlier, but develops slower. Additionally, the lift contribution of the airfoil rear part is relatively small, so the flow separation has less influence to the moment. At low lift coefficient, these two kinds of airfoils cannot guarantee long laminar flow regions, and furthermore they have higher drag coefficients. When adopting the airfoil to the wing, the lift coefficient corresponding to maximum lift-drag ratio should increase remarkably. This phenomenon should be paid attention in the design procedure. The lowness of the control surface efficiency of the tailless UAV determines that the aircraft has low designing lift coefficient. Therefore, an excellent lift-drag ratio performance at a high lift coefficient does not mean much to aircraft. In addition, high lift coefficient corresponds to large attack angle. However neither of the attack angles of two airfoils corresponding to moment divergence exceeds 13 degrees.

The moment performance of airfoils T1602 and T1603 is improved at the price of losing thickness of the rear part, which probably will bring difficulties to the configuration of control surfaces. Thus a compromise way in design is required. With large leading edge radiuses for airfoils T1602 and T1603, there are advantages to controlling flow separation over the airfoils one hand, but disadvantages to stealth the other hand.

4. Conclusions

Comparing with conventional configuration, tailless Unmanned Air Vehicle (UAV) has shown apparent difference on aerodynamic design. Without horizontal tail to operate longitudinal pitching control, tailless configuration requires highly for stability margin and pitching moment at design point. Thereby, it is important and also difficult to guarantee a satisfying moment performance in aerodynamic design. In this paper, the aerodynamic performance of three different kinds of airfoils, representing three design philosophies each, is analyzed. The method to improve airfoil moment performance is studied and satisfying results are obtained. Meanwhile, possible problems involved in practice are also discussed.

References

[1] V.E.Denisov,A.L.Bolsunovksy,N.P.Buzoverya,B.l.Gurevich,L.M.Shkadov. Conceptual Design For Passenger Airplane Of Very Large Passenger Capacity In Flying Wing Layout. *ICAS-96-4.6.1*.

[2] D.Roman,J.B.Allen,and R.H.Liebeck. Aerodynamic Design Challenges Of The Blended-Wing-Body Subsonic Transport. *AIAA-2000-4335*.

[3] Libeck,R.H., Page, M.A.and Rawdon,B.K. Blended-Wing-Body Subsonic Commercial Transport”. *AIAA-98-0438,January 1998.*

[4] Kasim Biber and Carl P.Tilmann. Supercritical Airfoil Design For Future Hale Concepts. *AIAA 2003-1095,41st Aerospace Sciences Meetings and Exhibit*,6-9 January 2003.6.