Design Characteristics of an Airfoil for Flying/ Tailless Wings: A Study

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Abstract— The primary complications in the conventional aircraft are the aerodynamics at the interference between fuselage, wing and tail, profile drag and structural complexity in the joints. With the application of flying wing, interference between different members has been almost completely eliminated. The main objective of the present work is to study requirements of tail in conventional aircraft and design requirements of an airfoil for flying wing. Stability of an airfoil with reflex camber line and their disadvantages has also been discussed.

Key words: Flying Wings, Reflex, Stability and its Curve, Angle of Attack, Tail, Coefficient of Moment

I. INTRODUCTION

Flying wing configuration is a new concept in aircraft design which expects to offer great potential to substantially reduce operating costs while improving an aerodynamic performance and flexibility by integrated the propulsion systems, wings, and the body into a single lifting surface both passenger and cargo mission.

Flying wings has shown promise in terms of aerodynamic efficiency, in particular for very large transport aircraft because the configuration has a single lifting surface that means an aerodynamically clean configuration and very less parasite drag. After more than a century of research and development the flying wing is still viewed as a unique and unconventional aircraft concept. From a technical point of view, the dominant issue has been stability and control, which to this day continues to affect this class of vehicle. As a result, flying wing aircraft continue to be limited to missions comprised of only low lift (cruise) conditions.

It is clear that the realization of the flying wing concept is benefiting from recent technological advances in aerodynamics, flows control, flight control systems, materials, structures, and propulsions systems. Today such a concept has only been applied to military aircraft to obtain a low radar cross-section. United States of America, Germany and several investigators tried to produce an aerodynamically efficient aircraft in past, such as tailless aircraft and Flying Wing. Northrop Corporation (USA) introduced the YB-49 (Fig. 1) in 1947 which proved to be the most successful Flying-Wing aircraft.

The most famous Flying-Wing is the Northrop-Grumman B-2 Spirit Stealth Bomber (Fig. 2) made in 1981 which had sophisticated modern computer control systems installed, and the 21 of these planes were in service in the 1999 bombing of Yugoslavia.


Fig. 1: YB-49


Fig. 2: Northrop-Grumman B-2 Spirit Stealth Bomber

Horten Brothers (Germany) in 1988 designed Ho III (Fig. 3) successfully soared to 7,000 meters altitude.

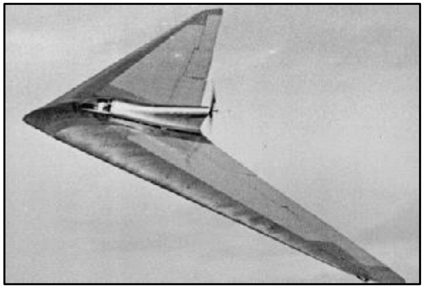
Fig. 3: Ho II

The most famous project is the X-48 project (Fig. 4) with both NASA and the Boeing Company designs suggesting the concept configuration for passenger flight could carry from 450 to 800 passengers and achieve fuel savings of over 20 percent compared to the same flight missions of conventional aircraft. It can house a wide double-deck passenger compartment that actually blends into the wing. Adjacent to the passenger section is ample room for cargo. It is predicted to enter service between 2010 and 2020, and to carry 800 passengers with mixed classes over a range of 8,000 nautical miles at a cruise Mach number 0.85.


Fig. 4: X-48

II. REQUIREMENT OF TAIL

Longitudinal stability states that aircraft should be able to return to its trimmed flight condition after a disturbance by a gust or a control input. For a stable aircraft, the coefficient of moment about centre of gravity should be zero in trimming condition (Eq. 1) but it is negative when there is no tail (Eq. 2)

$$C_M = 0 \qquad (1)$$

$$C_M = C_{Mac} \qquad (2)$$

Also, at the condition of no lift when there is only wing, the total moment about C.G. is:

$$C_{M0} = C_{Mac} \qquad (3)$$

Where, subscript 0 represents no lift condition and C_{Mac} is coefficient of moment about aerodynamic centre.

We know that C_{Mac} is always negative, so will be C_{M0} according to equation 3. Therefore, for a wing with positive camber, C_{M0} is negative and we can say that wing by itself is unbalance. To rectify this situation, a horizontal tail must be added behind wing (Fig. 5).

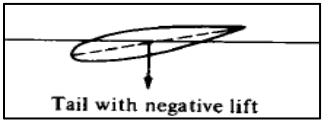

Fig. 5: Tail behind wing

The incidence of tail must be negative so that it can produce negative lift and clockwise moment about centre of gravity and will overcome the negative C_{Mac}. Now C_{M0} for wing tail designed will become positive and the airplane is balanced. Hence tail is required to balance the aircraft.

The criterion for longitudinal stability states that if airplane is travelling at equilibrium angle (α_e) and due to sudden disturbance its angle of attack momentarily decreases, the moment about centre of gravity should be positive and if angle of attack increases then moment about centre of gravity should be negative, only then aircraft is able to go back to its initial trimmed position. Fig. 6 represents change in C_M as angle of attack changing.

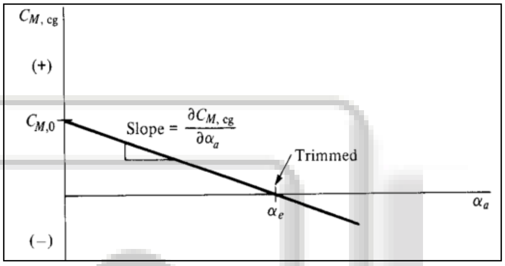

Fig. 6: Stability curve between coefficient of moment vs. angle of attack

So the conditions to maintain longitudinal stability are, C_{M0} should always be positive and the slope between C_M and angle of attack should always be negative.

The total pitching moment about C.G. for wing tail combination is:

$$C_M = C_{Mac} + a\,\alpha\,[(h-h_{ac})-V_H\,a_t\,(1-d\varepsilon/d\alpha)\,/\,a)] + V_H\,a_t\,(i_t+\varepsilon_0) \quad (4)$$

Where,

α= angle of attack

a= slope between lift and angle of attack for wing

at= slope between lift and angle of attack for tail

h= centre of gravity position from leading edge of wing

h_{ac} = position of aerodynamic centre from leading edge of wing

V_H = volumetric ratio between tail volume and wing volume

ε= downwash angle

ε_0= downwash angle at zero lift condition

i_t = incidence angle of tail

At zero lift condition, equation of C_M will be:

$$C_{M0}= C_{Mac} + V_H\, at\, (i_t + \varepsilon_0) \quad (5)$$

The equation for moment coefficient slope is:

$$dC_M/d\alpha = + a[(h- h_{ac})- V_H\, at\, (1-d\varepsilon/d\alpha)/a)] \quad (6)$$

Equation 5 and 6 suggesting that C_{M0} is positive and slope is negative when there is a tail behind wing and aircraft is balance and stabile. So the main problem in tailless aircraft is that there is no tail to provide longitudinal stability. Therefore, to design an airfoil for tailless aircraft, always choose an airfoil which gives positive value of C_{M0} and negative value of slope of moment coefficient curve.

III. SHAPE OF AIRFOIL

The shape of an airfoil being composed of two parts: a camber distribution and a thickness distribution along the camber line. The only way to achieve a positive moment coefficient and the required amount of lift is to use S-shaped camber line and the airfoil with this camber line is known as reflexed airfoil. It is possible to adjust the shape near the trailing edge to achieve the moment coefficient necessary to stabilize tailless plane. To understand, why a reflexed airfoil is able to provide longitudinal stability to a wing, let's compare a conventional, cambered airfoil with an airfoil with a reflexed camber line.

A. *Cambered Airfoil*

As we know that in conventional airfoil moment about C.G. is equal to moment aerodynamic centre at zero lift condition and position of aerodynamics centre is c/4 of cord line from leading edge. Therefore there is always a negative moment present on wing airfoil. To counteract this moment or to maintain the equilibrium position shifts the C.G. position behind centre of pressure where total lift is acting. Now, this moment which is the product of lift and distance between centre of pressure and C.G. will counteract the negative moment and aircraft will achieve equilibrium position (Fig. 7) The distance between C.G. and c/4point is depending on the negative moment. A symmetrical airfoil has no zero lift moment, so C.G. position is exactly at c/4 distance from leading edge.

Due to some disturbance if angle of attack is increased, the lift force L increases and now airfoil has more lift than the previous one which is required to counteract the negative moment at c/4. The result is pitch up moment which further increases the angle of attack (Fig. 8). This behaviour is instable and a tail is needed to stabilize the airfoil.

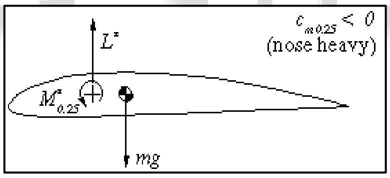

Fig. 7: Conventional airfoil with camber in equilibrium condition

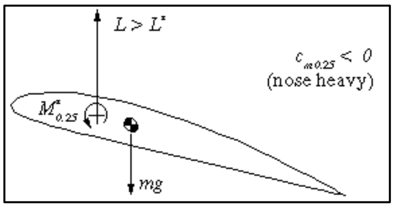

Fig. 8: Conventional airfoil with camber in disturbance

B. *Reflexed Airfoil*

When the amount of reflex is increased, flow will move with low velocity on upper surface of trailing edge and with high velocity on lower surface of trailing edge. This will modified the direction of pressure force from upper to lower surface, hence negative lift near the trailing edge which will driving the moment coefficient towards positive values.

Therefore, reflexed camber line makes the moment coefficient at c/4 positive because of the modified pressure distribution towards the trailing edge. Maximum coefficient of pressure will shift toward trailing edge due to the more curvature there, this defines the position of lift i.e., behind

C.G. Now, the moment which is the product of lift and distance between centre of pressure and C.G. will counteract the positive moment at c/4 and aircraft will achieve equilibrium position (Fig. 9). The larger the moment at c/4, larger will be the distance between c/4 and the C.G. for equilibrium.

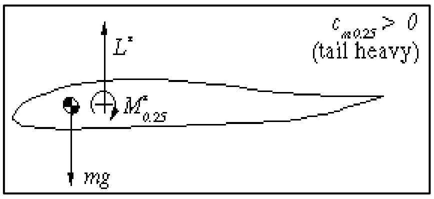

Fig. 9: Reflexed airfoil with camber in equilibrium condition

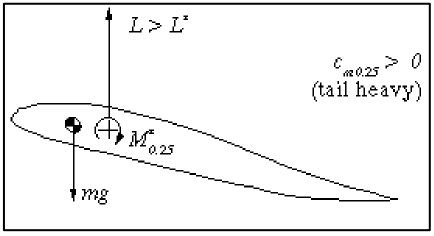

Fig. 10: Reflexed airfoil with camber in disturbance

If angle of attack is increased due to disturbance, the lift force L increases and now airfoil has more lift than the previous one which is required to counteract the negative moment at c/4. The result is pitch down moment which decreases the angle of attack until the equilibrium state is reached again (Fig. 10). Therefore reflexed airflow is itself stable and tail is not required to provide stability.

IV. DISADVANTAGES OF REFLEXED AIRFOIL

In general, the velocity distributions of the upper surfaces show high velocities in the first third of the chord length, steadily decreasing as the flow reaches the trailing edge. As the flow decreases pressure increases according to Bernoulli's equation. When the pressure rise is too strong, the flow separates, causing loss of lift and increasing drag. Similarly, there is the possibility of stalling on the lower surface of trailing edge due to abrupt pressure loss.

Due to modified pressure distribution over a reflexed airfoil, generated lift will be less as compare to conventional airfoil. Increased amount of camber can be suggested to compensate for the lift loss and Increasing the camber will increase the velocity on the upper surface and decrease the on the lower surface. The enclosed area of positive lift in the front half of the airfoil also increases, contributing to the lift. But when the camber is increased too much, the maximum lift may decrease, because the camber has to be compensated by a larger amount of reflex, putting more stress on the boundary layer. Typically, the maximum lift can be increased to a certain amount, by increasing camber and reflex, but at the cost of a harder stall, which might be dangerous during take-off and landing.

V. CONCLUSION

Depending on the type of tailless airplane, stability requirements lead to different criteria for airfoil selection. For most tailless planes, airfoils with low moment coefficients yield the best performance. Low moment coefficients and high lift coefficients can be achieved by using reflexed camber lines, but the corresponding velocity distributions are sensitive to low Reynolds numbers, and may result in problems with stall behaviour. The best compromise for tailless airplane seems to be a moderately reflexed camber line, combined with the maximum camber shifted towards the leading edge and a rather blunt nose.

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