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ANALYSIS OF THE VARIATIONS OF THE WING LIFT COEFFICIENT OF UNMANNED AERIAL VEHICLES WITH INCREASING REYNOLDS NUMBER OF AIRFLOW

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Abstract
Unmanned aerial vehicles (UAVs) are one of the fastest growing segments of the aviation market. The concept of UAV development includes military and civilian applications. According to these objectives, the criteria for selecting parameters for micro and mini-UAVs are primarily range and flight duration. Consequently, micro and mini-UAVs should have a high level of aerodynamic quality. The usual behavior of the maximum lift coefficient (CL) of wing profiles with increasing Reynolds number is an increase. However, in some cases, the wing profiles may show the opposite - a decrease in the maximum lift coefficient (CL) with increasing Reynolds number (Re). We have analyzed this effect for a finite span wing and for a wing profile segment.

Keywords*: wing profiles, lift coefficient, UAV development, boundary layer, Reynolds number*

1. INTRODUCTION

In the design of UAVs, in general, the well-known principles set forth in [1-5] are used, but it is necessary to consider the peculiarities inherent in unmanned vehicles. The class of unmanned aerial vehicles differs from manned vehicles, first, in the absence of the need to ensure the safety of a person (pilot) on board. In addition, the absence of a pilot allows the aircraft to be miniaturized [6]. Miniaturization is possible for many tasks where the mass and dimensions of the payload are smaller than the mass of a human, such as surveillance and reconnaissance missions. The transition to smaller size and lower mass allows us to reduce the cost of the task compared to the use of traditional manned aircraft.

Many works devoted to various peculiarities of aerodynamics of small-sized drones confirm the relevance of the discussed topic. In [6], the separation of the boundary layer at a relatively small Reynolds number ($Re = 1.7x10^5$) is considered, and the essential influence of the degree of turbulence of the onrushing flow on the formation of the detachment flow and on the integral aerodynamic characteristics is emphasized. In [7], a comprehensive study of a small-size unmanned aerial vehicle including calculation, wind tunnel experiment and flight experiment was carried out. In continuation of this topic, the authors of [8] carried out a more detailed computational study of the layout of a small-sized unmanned aerial vehicle of small elongation.

In general, it is well known that the Lift force is a component of the total aerodynamic force perpendicular to the velocity vector of the airflow, resulting from the asymmetry of the flow around the airfoil. The total aerodynamic force is the integral of the pressure around the contour of the wing profile. As the angle of attack increases, the lift coefficient increases, but only up to a value of Critical Angle of Attack. At Critical Angle of Attack vortices disrupt the airflow from the wing, preventing lift from occurring and causing a stall.

The usual response of the lift coefficient (CL) of profiles with the increasing Reynolds number (Re) is an increase. However, in some cases, wing profiles may induce the opposite, i.e., a decrease in the maximum lift coefficient (CL) with increasing Reynolds number (Re). This effect can be obtained experimentally on a finite span wing or on a wing profile segment.

We have analyzed data for variable wing profiles and for flat wings of constant symmetric cross-section and summarized a huge number of experimental materials obtained by us earlier and by other authors in aerodynamics wind tunnels with a low degree of flow turbulence, in the range of Reynolds numbers $7x10^5 – 25x10^6$.

2. ANALYSIS OF THE CHANGE IN LIFT COEFFICIENT WITH INCREASING REYNOLDS NUMBER

The type of airflow separation from the wing surface depends on the airfoils' profile, thickness-to-chord ratio, leading edge radius, and Reynolds number (Re**)**. In this paper we are investigating only the factor of Reynold's number (Re**)**. On profiles for cruising flights at low subsonic speeds and low Reynolds numbers (Re**)** (e.g., for unmanned aircraft layouts), the following main types of wing boundary layer separation [9, 10] are possible in the general case:

- separation of the laminar boundary layer at the leading edge or further downstream;
- separation of a turbulent boundary layer at the trailing edge;
- a combination of these.

2.1 Separation of the laminar boundary layer at the leading edge

The separation of laminar flow is usually combined with the subsequent attachment of a free viscous layer, where the transition to turbulent flow regime takes place. A local closed zone of detachment flow (detachment flow bubble) is formed. The laminar bubble can be "short" *(0.5 - 1.0% of the chord)* or "long" *(>2% of the chord)* depending on the value of the Reynolds number (Re**)** and the pressure gradient. It should be noted that the velocity profile in the boundary layer at the attachment point corresponds to the profile at the separation point. Therefore, the boundary layer immediately after attachment is neither typically laminar nor typically turbulent and only at further motion of the attachment point does the flow regime approaches turbulent.

Typically, increasing the angle of attack after the formation of a short bubble results in a shift of the attachment point upstream to a region of greater surface curvature. Starting at some Angle of Attacks (AOA), the turbulent free viscous displacement layer no longer attaches to the surface, and there is a sharp drop in lift and an increase in drag (Stall) (Figure 1A).

This "explosion" of a laminar breakaway bubble is commonly referred to as a leading-edge detachment (short bubble detachment). Separation with formation of a short bubble can occur on the most common profiles with moderate thickness-to-chord ratio ***(0.09<t/c<0.15)***. The formation of a short bubble has practically no effect on the aerodynamic performance until the flow is abruptly disrupted by its "collapse".

When a long bubble is formed, an increase in the angle of attack causes the point of attachment of the free viscous layer to move downstream. The length of the bubble increases and at some angle of attack the bubble stretches to the trailing edge and there is a complete separation of the laminar flow.

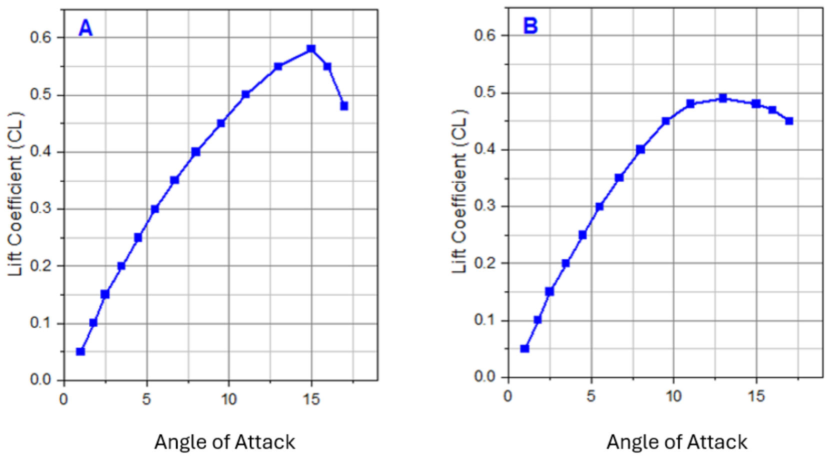

Figure 1. Airflow disruption on the profile with formation of a short bubble in the flow (A) and disruption with formation of a long bubble in the breakaway flow (B).

Further increase in the angle of attack leads to a gradual decrease in the lifting force (Stall) (Figure 1B). Such separation can occur at profiles t/c<0.9 and is commonly referred to as thin profile separation (long bubble separation). Although this bubble causes a gradual flow stall rather than a sudden one as in the case of a short bubble, it nevertheless has a significant effect on drag, lift, and longitudinal momentum over a fairly large range of angles of attack. This is because the appearance and development of a long bubble of detachment flow changes, and quite noticeably, the pressure distribution along the chord. At the trailing edge at separation of the long bubble, the pressure is positive, and the main changes in the pressure diagram occur at the front part of the profile.

2.2 Separation of a turbulent boundary layer at the trailing edge

The separation of the flow from the trailing edge (Figure 2) is typical for "thick" profiles ***t/c>0.12*** and occurs in the chord sections with a boundary layer that has already entered the turbulent state.

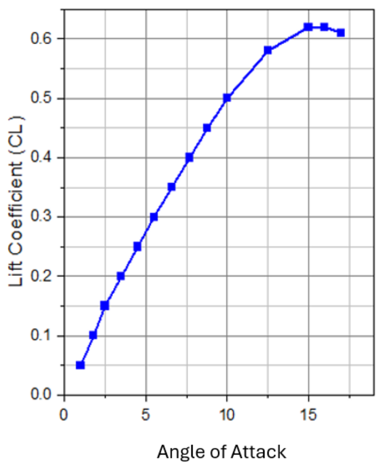

Figure 2. Airflow disruption at the trailing edge of the airfoils profile.

An increase in the angle of attack causes a constant upstream displacement of the separation point and a gradual, rather than an abrupt, decrease in lift. In this type of separation, a depression occurs at the trailing edge of the profile, and the main changes in the pressure diagram occur at the trailing edge of the profile.

2.3 Combination of Separations of boundary layer at the leading and trailing edges

On some profiles, in a certain range of Reynolds numbers (Re**)**, both breakaway flow bubbles and trailing edge separation can be observed simultaneously (Figure 3).

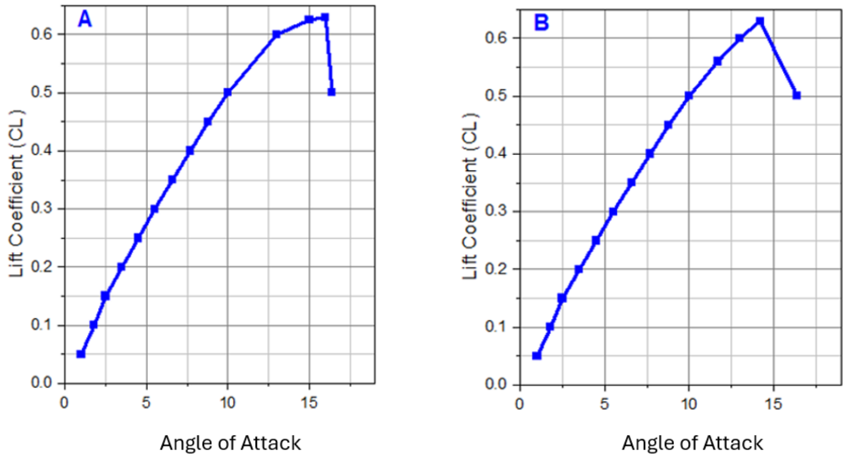

Figure 3. Combined Airflow separation: breakaway flow with bubble formation in the flow (A), and separation at the trailing edge (B).

Consequently, there can be a combination of different types of separation with features typical of both closed bubble and trailing edge separation. This intermediate type of separation is called a combined separation.

3. CONCLUSION

The effect of decreasing maximum lift force with increasing Re number is reviewed. This behavior is not typical for profiles, but there are mentions and explanations of this effect in the literature. From the point of view of the cruising flight of the vehicle, the stall speed margin is important, and hence the behavior of the maximum lift coefficient by the Reynolds number (Re**)**.

Since wing design to maximize aerodynamic quality or flight duration parameter may require a significant reduction of the chord at the wing tip, and stall at the wing tip is most dangerous in terms of stall, consideration of profiles with inverse behavior of the maximum lift coefficient with respect to Reynolds number (Re**)** may be useful.

The main conclusion is that for any profile, when changing the Reynolds number (Re**)** (flow velocity), a consistent change (and quite cardinal) in the type of flow stall and, consequently, in the values and dynamics of aerodynamic characteristics at different angles of attack is possible.

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