The Influence of Airfoil Shape on The Aerodynamic Characteristics of Aircraft Wings

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***Abstract*— Airfoil geometry plays a key role in determining an aircraft wing's aerodynamic performance. Parameters such as camber, thickness, and profile shape strongly affect lift, drag, and operating limits under different flight conditions. This study examines the impact of airfoil shape through three aspects: comparing symmetric and cambered airfoils in terms of maximum lift, evaluating the effect of thickness on drag and critical Mach number, and analyzing three typical airfoils across various speeds. Results indicate that cambered airfoils provide higher maximum lift, while thickness significantly influences drag and critical Mach number, with each airfoil showing distinct performance in different flight regimes.**

Keywords*— *airfoil; lift coefficient; drag coefficient; critical Mach number.

I. INTRODUCTION

In aircraft aerodynamic design, the airfoil geometry plays a crucial role in determining the lift generation capability and aerodynamic efficiency the wing. The shape of an airfoil directly affects the pressure distribution over the wing surface, which consequently determines key aerodynamic coefficients such as the lift coefficient C_L, drag coefficient C_D, and pitching moment coefficient.

Throughout the development of aviation technology, various airfoil families have been developed and widely used, including the NACA airfoil series in the United States and the airfoils designed by the Central Aerohydrodynamic Institute (TsAGI) in Russia. Each airfoil type is optimized for specific flight conditions and aircraft missions.

The most important geometric parameters defining an airfoil include:

- camber of the mean camber line;
- relative thickness of the airfoil;
- overall profile geometry.

These parameters determine the maximum lift capability, aerodynamic drag characteristics, and the allowable flight speed range of the aircraft.

This paper focuses on analyzing the influence of airfoil shape on aerodynamic characteristics by examining representative airfoil configurations and key geometric parameters.

II. THEORETICAL BACKGROUND

The aerodynamic forces acting on an aircraft wing are commonly expressed using dimensionless aerodynamic coefficients.

Lift coefficient

$$C_L = \frac{L}{\frac{1}{2}\rho V^2 S} \tag{1}$$

Drag coefficient

$$C_D = \frac{D}{\frac{1}{2}\rho V^2 S} \tag{2}$$

where

L- lift force,[N];

D - drag force, [N];

ρ - air density, [kg/m^3];

V - flight velocity, [m/s];

S- wing area, [m^2];.

Another important parameter in transonic aerodynamics is the **critical Mach number M_{CT}**, defined as the Mach number at which the local airflow over the wing first reaches Mach 1.

III. INFLUENCE OF SYMMETRIC AND CAMBERED AIRFOILS ON THE MAXIMUM LIFT COEFFICIENT

Double-curved airfoils can be categorized into **symmetric airfoils** and **cambered airfoils**, depending on the position of the mean camber line relative to the chord line.

Symmetric airfoils

For symmetric airfoils, the mean camber line coincides with the chord line, resulting in identical upper and lower surfaces. When the angle of attack is zero, the pressure distribution is symmetric and therefore the lift force is zero.

According to thin airfoil theory, the lift coefficient of a symmetric airfoil is mainly dependent on the angle of attack:

$$C_L = a \cdot \alpha \tag{3}$$

Where: a - represents the lift - curve slope.

To generate significant lift, symmetric airfoils must operate at relatively high angles of attack. However, when the angle of attack reaches a critical value, flow separation occurs and the lift decreases rapidly.

As a result, the maximum lift coefficient of symmetric airfoils typically ranges between: $C_{Lmax} \approx 1.1 \div 1.4$ depending on the airfoil thickness and flow conditions.

Cambered airfoils

Cambered airfoils have a mean camber line that deviates from the chord line, creating a curved geometry. Due to this camber, even at zero angle of attack the airfoil can generate positive lift.

The cambered geometry accelerates the airflow over the upper surface more strongly than over the lower surface, resulting in lower pressure above the wing and a larger pressure difference between the two surfaces.

Consequently:

- the lift coefficient at zero angle of attack is positive;
- lift increases more rapidly with increasing angle of attack;
- the maximum lift coefficient becomes higher.

For many cambered airfoils, the maximum lift coefficient typically lies within the range:$C_{Lmax} \approx 1.4 \div 1.8$

Therefore, cambered airfoils are widely used for the main wings of transport and trainer aircraft where high lift capability is required at relatively low flight speeds.

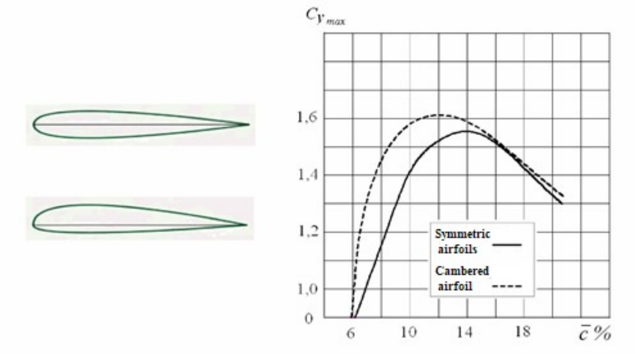

Fig. 1 The influence of symmetric and cambered airfoils on the maximum lift coefficient

IV. INFLUENCE OF RELATIVE THICKNESS ON DRAG COEFFICIENT AND CRITICAL MACH NUMBER

The relative thickness of an airfoil is defined as

$$\bar{c} - \frac{c_{max}}{b} \tag{4}$$

Where: c_{max} - is the maximum thickness of the airfoil and ccc is the chord length.

Influence on drag coefficient

As the relative thickness increases, the frontal area exposed to the airflow also increases. This leads to an increase in form drag and therefore a higher overall drag coefficient.

Additionally, thicker airfoils tend to exhibit stronger adverse pressure gradients near the trailing edge, which increases the likelihood of flow separation and contributes to higher aerodynamic drag.

For this reason, aircraft designed for high-speed flight generally employ thinner airfoils to reduce aerodynamic drag.

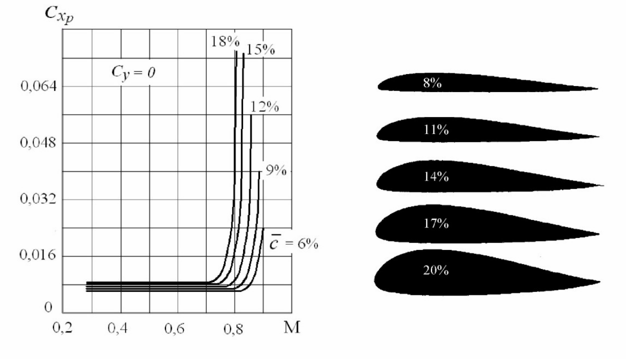

Fig. 2. Influence of airfoil relative thickness on the drag coefficient

Influence on the critical Mach number

Relative thickness also significantly affects the critical Mach number of an airfoil.

For thicker airfoils, the airflow acceleration over the upper surface becomes stronger, causing the local Mach number to reach unity at a lower freestream Mach number. Consequently, thicker airfoils generally have lower critical Mach numbers.

This implies that:

- thicker airfoils are more suitable for low-speed aircraft;
- thinner airfoils are preferable for high-speed or transonic aircraft.

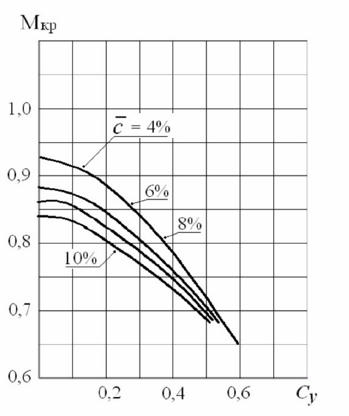

Fig 3. Influence of airfoil relative thickness on the critical Mach number

V. AERODYNAMIC COMPARISON OF NACA 23012, NACA 0012, AND TSAGI P-57-9 AIRFOILS

Three representative airfoils are analyzed in this study:

- **NACA 0012** – a symmetric airfoil;
- **NACA 23012** – a cambered airfoil from the NACA five-digit series;
- **TsAGI P-57-9** – an airfoil optimized for subsonic flight conditions.

Geometric characteristics

- NACA 0012: symmetric airfoil with 12% relative thickness;
- NACA 23012: cambered airfoil with 12% relative thickness designed for improved lift performance;

- TsAGI P-57-9: airfoil optimized for efficient operation in the subsonic speed regime.

Influence on lift coefficient

At low and moderate flight speeds, the NACA 23012 airfoil demonstrates the highest lift capability due to its cambered geometry. Its maximum lift coefficient is significantly higher than that of the symmetric NACA 0012 airfoil.

The NACA 0012 airfoil provides lower lift but exhibits symmetric aerodynamic characteristics, making it suitable for control surfaces and maneuvering aircraft.

The TsAGI P-57-9 airfoil is designed to maintain stable lift characteristics while delaying drag rise in the transonic regime.

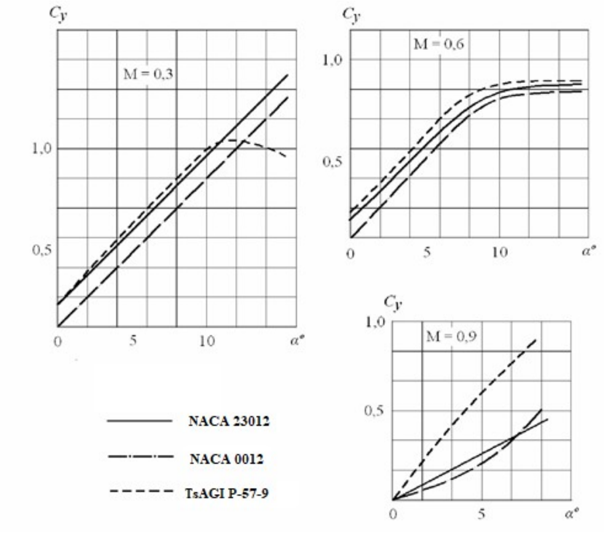

Fig 4. Dependence of the lift coefficient on airfoil geometry at different flight speeds

Influence on drag coefficient

At low flight speeds, the difference in drag among the three airfoils is relatively small. However, as the flight speed increases and the Mach number approaches the critical value, the TsAGI P-57-9 airfoil demonstrates lower drag due to its optimized aerodynamic shape.

In contrast, the NACA 0012 and NACA 23012 airfoils tend to experience earlier drag rise as the Mach number increases.

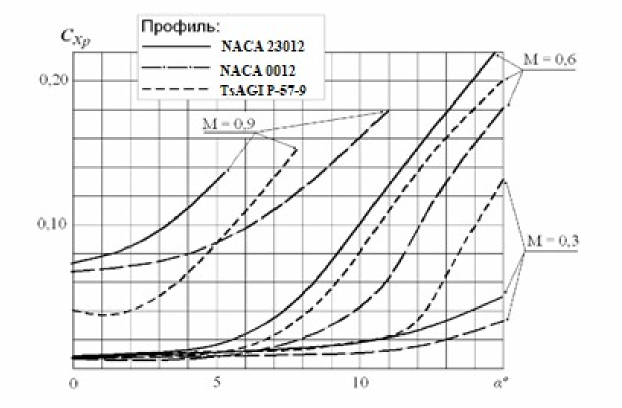

Fig 5. Dependence of the drag coefficient on airfoil geometry at different flight speeds

VI. CONCLUSIONS

This study investigated the influence of airfoil shape on the aerodynamic characteristics of aircraft wings. The main findings can be summarized as follows:

- Cambered airfoils produce higher maximum lift coefficients compared with symmetric airfoils due to more favorable pressure distributions;
- The relative thickness of the airfoil strongly affects aerodynamic drag and the critical Mach number; thicker airfoils increase drag and reduce the critical Mach number;
- Comparative analysis shows that the NACA 23012 airfoil provides superior lift performance at low speeds, whereas the TsAGI P-57-9 airfoil demonstrates better aerodynamic efficiency in the higher subsonic speed regime.

The results provide useful insights for selecting appropriate airfoil configurations in aircraft wing design to achieve optimal aerodynamic performance under different flight conditions.

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