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NUMERICAL STUDY OF THE AERODYNAMIC CHARACTERISTICS OF AIRFOIL WITH HIGH-LIFT DEVICES

The ***subject matter*** *of this article is the aerodynamic profile of the wing with high-lift devices in the aircraft transport category. When high-lift devices are released, the aerodynamic flow of the wing changes significantly, this changes the stress-strain state of the wing. This relates not only to an increase in lift force due to a change in the curvature of the wing and an increase of the wing area, but also due to a change of the position of the center of pressure relative to the chord of the wing. The* ***goal*** *is to study the influence of wing high-lift devices on the aerodynamic characteristics of the profile during take-off, cruise, and landing cases using numerical methods. The obtained data will be used to determine the loads on the wing in various flight cases. The* ***task*** *is to determine the aerodynamic coefficients of lift and drag forces, changing the position of the pressure center during flight cases: take-off, cruise, and landing. The aerodynamic profile b737c-il was used in the analysis. The single-slot slat and double-slots flap were used in the analysis model. The numerical* ***methods*** *with the CAE system ANSYS Fluent were used. The solver models k-epsilon and transition SST were used for comparison. The use of numerical methods in the process of designing aircraft structures is widely used to accurately determine the aerodynamic parameters of the wing in various flight cases. The following* ***results*** *were obtained: the dependence of the lift coefficient on the angle of attack, the lift coefficient on the drag coefficient, and the position of the center of pressure along the chord of the profile for cruise, take-off, and landing flight cases.* ***Conclusion.*** *The scientific novelty of the results obtained is as follows: the use of numerical methods for determining the aerodynamic characteristics of a wing with high-lift devices in particular, determining the dependence of the position of the center of pressure relative to the chord and at different angles of attack. The obtained results will be used to determine the load on the wing, in particular the distributed load on the slats and flaps, to clarify the torque moment in the wing section where high-lift devices are used.*

Keywords: *high-lift devices; airfoil; numerical methods; center of pressure; aerodynamic characteristics; Reynold's number.*

1. Introduction

Despite the fact that the high-lift devices of the wing have existed for a long time, but its research and modifications continue to nowadays. The development of modern methods of analysis allows us to study in more detail the one of most important elements of the wing as high-lift devices. The design of an efficient high-lift system is a challenging task in the aerospace industry. For example, Qiang Ji and the others authors, in the article [1], performed aerodynamic optimization design of an ADHF (Adaptive Dropped Hinge Flap) high-lift system. The Adaptive Dropped Hinge Flap (ADHF) is a novel trailing edge high-lift device characterized by the integration of downward deflection spoiler and simple hinge flap, with excellent aerodynamic and mechanism performance. In this paper, aerodynamic optimization design of an ADHF high-lift system is conducted considering the mechanism performance. Another study of high-lift devices was done by Zhenhao ZHU and other authors, which examined numerical investigations [2] are conducted to explore the aerodynamic characteristics of three-dimensional Co-Flow Jet (CFJ) wing with simple high-lift devices during low-speed takeoff and landing. These articles show considerable interest in the high-lift devices.

When an aircraft is designed, it is necessary to have the aerodynamic characteristics of the wing during various flight cases, in particular, takeoff and landing. Using of high-lift devices of the wing can significantly reduce the length of takeoff ground roll and the length of landing ground roll, as well as reduce one of the most important characteristics of the aircraft - takeoff weight, which ultimately affects the economic efficiency of the operation of the aircraft. A modern wing with high-lift devices is shown in Figure 1. Takeoff and landing speeds increased on early jet airplanes, and as a result, runways worldwide had to be lengthened.

There are economical limits to the length of runways; there are safety limits to takeoff and landing speeds; and there are speed limits for tires. So, in order to hold takeoff and landing speeds within reasonable limits, more powerful high-lift devices were required. Wing trailing-edge devices evolved from plain flaps to Fowler

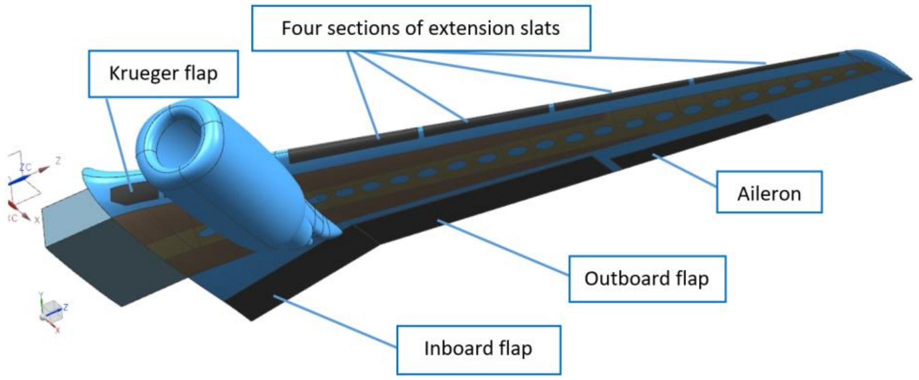


Figure 1. Modern wing with high-lift devices

flaps with single, double, and even triple slots. Wing leading edges evolved from fixed leading edges to a simple Krueger flap, and from fixed, slotted leading edges to two and three-position slats [3].

Unfortunately, the existing theoretical methods for calculating the aerodynamic characteristics of wing with high-lift devices are very laborious and cannot always be implemented [4].

In order to obtain reliable data of wing with high-lift devices, one has to perform laborious, expensive experiments. As an example, we can consider aerodynamic research performed in the aerodynamic wind tunnel T-3 KhAI (Kharkiv Aviation Institute). During the experiment, the aerodynamic characteristics of a scale model of a rectangular wing with mechanical high-lift devices and considering a flat interface were obtained. The experiment was performed in the aerodynamic wind tunnel with work area 1.5x1.5 meters and Re = $3 \cdot 10^5$. More details about the experiment are described in the works [5] and [6].

During the design process, wing parameters may change, or multiple wing configurations may need to be researched to select the optimal configuration. Unfortunately, full-scale tests are not always reasonable. Therefore, at present time, numerical simulation is being used more and more. Numerical simulation is increasingly used in the design of aircraft structures to determine the optimal parameters for given operating conditions. This makes it possible to create more advanced aircraft designs that meet modern requirements for safe operation and economic benefit. As an example of the using numerical simulation ANSYS for the study of aerodynamic characteristics of the wing is presented in the article [7].

In this article, the aerodynamic characteristics of the wing with extended high-lift devices (slats and flaps in the take-off and landing positions) was obtained and compared with a pure airfoil (cruise case). All analysis was accomplished using numerical simulation in ANSYS. In this article, presents the results of a numerical analysis of the aerodynamic characteristics of a wing with two slots flap at landing edge and simple extension slat at trailing edge. Analyses were performed at three flight cases: takeoff, landing, and cruise mode.

2. Materials and Methods

In the article, the finite element method based on the ANSYS Fluent program was used. The ANSYS Fluent Tutorial Guide [8] was used to perform analysis of aerodynamic characteristics of the wing section for takeoff, landing and cruse flight cases with appropriated flight parameters (speed, flight altitude, high-lift devices position).

The airfoil Boeing 737 Midspan b737c-il was used, with maximum thickness 10 % at 39.9 % chord [9]. The airfoil chord is 1000 mm (airfoil with retracted slats and flaps). The airfoil models were created using the CAD SIEMENS NX system and imported into ANSYS DesignModeler, where the angle of attack of the airfoil was subsequently set in the parametric mode. The angle of attack varied from -10 to 39 degrees. The step of the angle of attack was reduced depending on the area of interest at a given angle of attack (at small angles, the step was 5 degrees, at large 2 degrees). The calculation environment has dimensions of 20x45 meters. To obtain more accurate data, the mesh size, around the airfoil, was reduced at area with a radius of 4 and 1.5 meters. The calculation area, mesh and boundary conditions are shown in Figure 2.

In the ANSYS Mesh module, the boundary layer and mesh parameters were set. The results of the mesh are shown in Figure 3.

3. Results

3.1. Calculation model validation

First of all, aerodynamic characteristics were obtained for clear airfoil for validation calculation model in ANSYS. Obtained results were compared with public sources from [9] for Reynold’s number is 10^6.

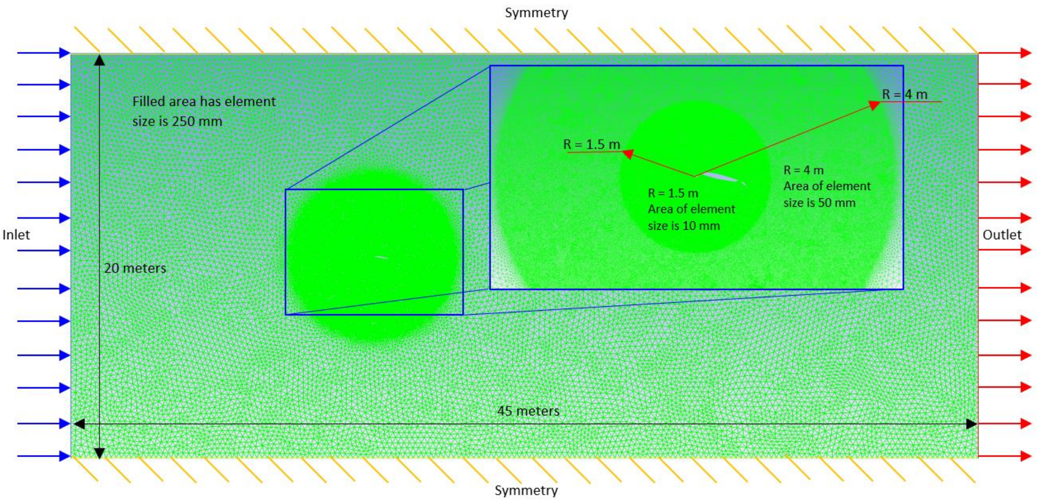
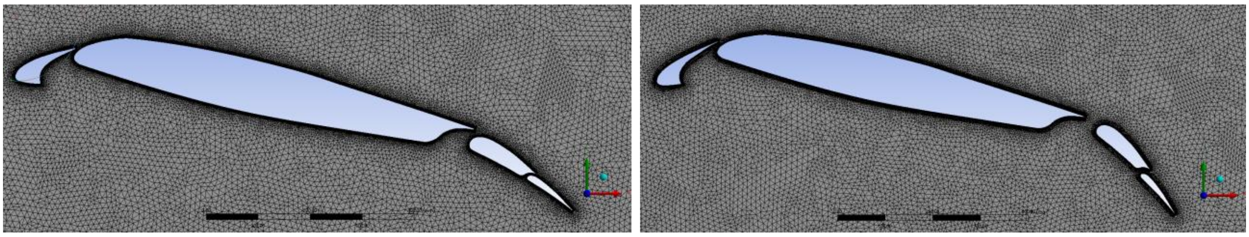


Figure 2. Calculation area, mesh and boundary conditions



(a) Nodes: 248799, Elements: 463064

(b) Nodes: 252977, Elements: 465760

Figure 3. Mesh of analyzed airfoil with takeoff (a) and landing (b) positions of slat and flap

The Reynold's number is a dimensionless value (similitude parameter) that measures the ratio of inertial forces to viscous forces and describes the degree of laminar or turbulent flow. Systems that operate at the same Reynold's number will have the same flow characteristics even if the fluid, speed and characteristic lengths vary [10].

The Reynold's number is calculated like:

$$R_e = \frac{\rho \cdot \nu \cdot l}{\mu}, \quad (1)$$

where ρ – density of the fluid;

ν – velocity movement of the fluid;

l – characteristics length, the chord's width of an airfoil;

μ – dynamic viscosity of the fluid.

To obtain more accurate results, different mesh shapes (quadrilateral - Quad4 and triangular - Tri3) and different solvers models (k-epsilon [11] and transition SST [12]) were used. The result of analyses is shown in Figure 4. As shown on lift coefficient vs angle of attack dependence, best results (the greatest agreement between the result ANSYS and the experimental public sources) are the calculation performed with solver model k-epsilon. Both mesh shapes Tri3 and Quad4 have good results.

As a result, for analysis of aerodynamic characteristics of the airfoil in cruise, takeoff and landing flight cases, calculation model with solver model k-epsilon and mesh shape Tri3 was chosen. The mesh shape Tri3 was chosen because such type of mesh is easier to build difficult airfoil shape/geometry (in particular airfoil with extended slats and flaps, see Figure 3) and this type of mesh has less number of nodes, that will reduce the calculation time.

3.2. Expected results

Based on literature review of public sources of wing with extended high-lift devices, with the extended high-lift devices, a significant increase lift force is expected as a result of a change in curvature and an increase in wing area.

The similar research was accomplished in study [13]. Based on the data in this study, conclusions can be performed about the reliability of the calculations obtained by the numerical method in this article.

The study used a system of two profiles simulating a wing and a flap «NACA 2142» and «B – 14%» with chords b1 = 0.015 m and b2 = 0.005 m, with stream speed V∞ = 1 m/s, kinetic viscosity at temperature T=25 °C. The Reynold's number is 1000. The scheme of the calculation model is shown in Figure 5.

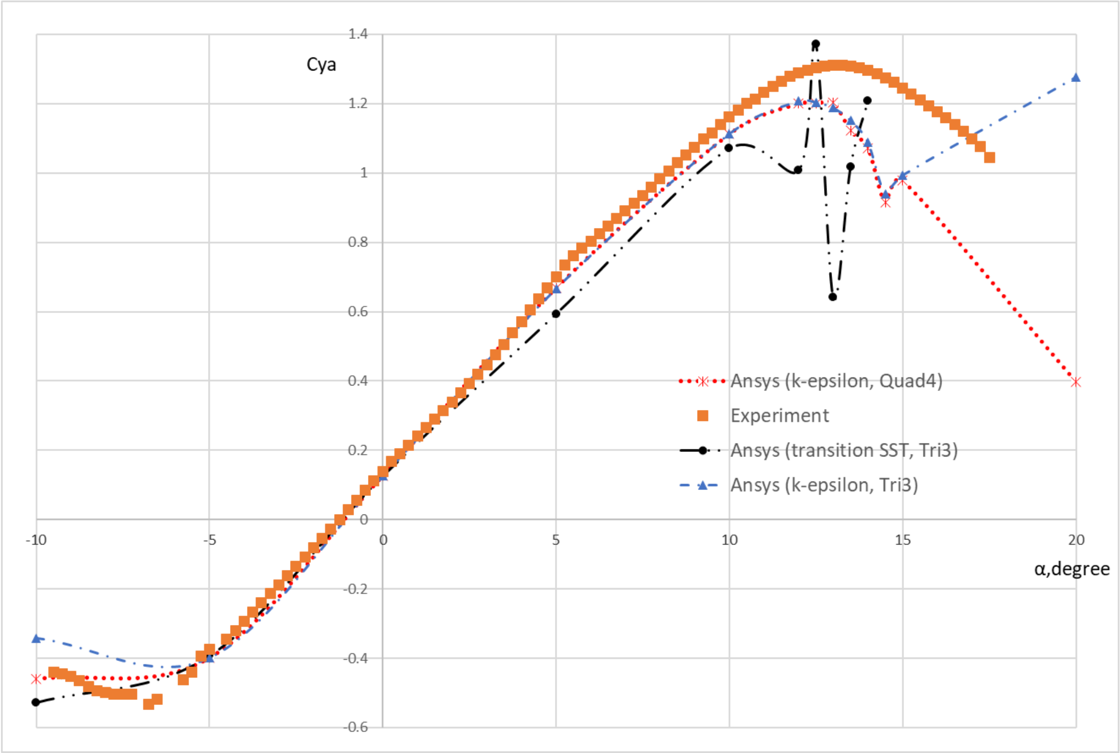
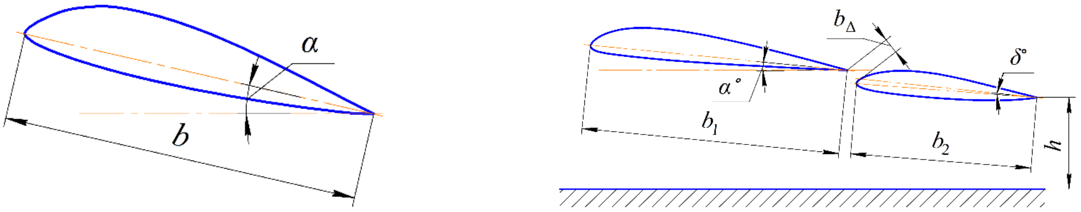


Figure 4. Lift coefficient vs angle of attack for different mesh types and models of solver



a

b

Figure 5. Airfoil (a) and its modification in the system of two separate airfoils (b)

The angle of deflection (δ) of the airfoil that imitates a flap, varied from 0 to 15 degrees with a step of 5 degrees.

It is expected that the dependence of the lift coefficient vs the angle of attack will shift upwards with an increase in the deflection of flap (Figure 6). Also, according to the dependence of the lift coefficient vs the drag coefficient, it will be possible to observe an increase in the drag force, which, as a result, leads to a decrease aerodynamic efficiency (Figure 7).

It should be noted that the leading edge slat was not used in the study [13]. The slat provides a more stable flow around the wing at high angles of attack. The slat forms a aerodynamics downwash of the flow and an increase in the speed of the boundary layer, which prevents the flow from shock stall and leads to an increase the maximum lift coefficient and an increase the critical angle of attack [14].

Therefore, the evaluation of the obtained results can be performed at small angles of attacks (see Figure 6 and Figure 7).

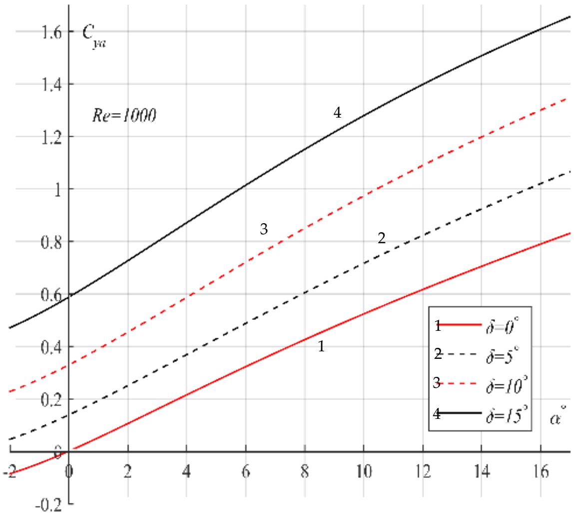


Figure 6. The dependence of the lift coefficient vs the angle of attack at different angles of deflection of the flap

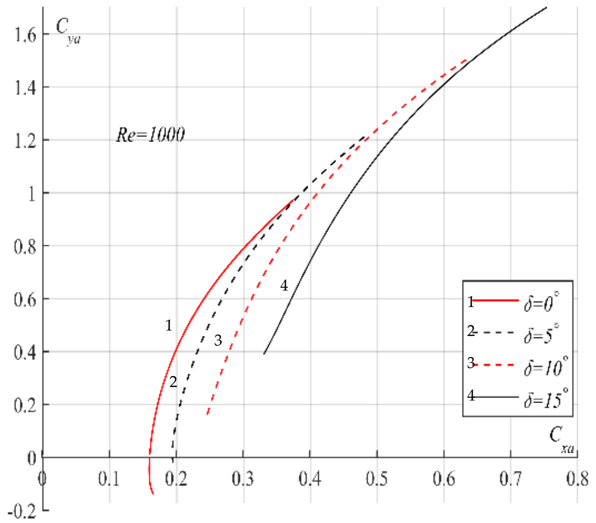


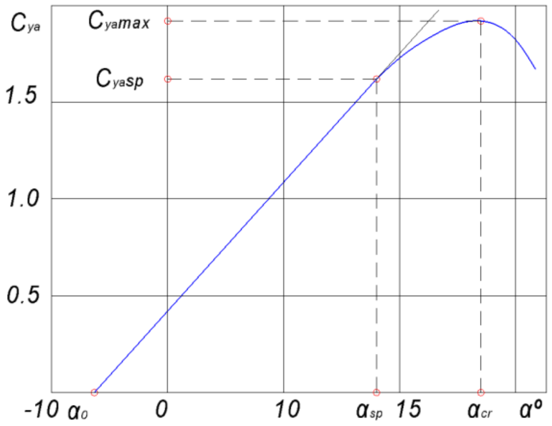
Figure 7. Polar curve of wing with flap at different flap deflection angles

3.3. Lift coefficient vs angle of attack and lift coefficient vs drag coefficient diagrams

For an aircraft, three design flight cases, of the design configuration of the aircraft, can be considered, as sufficient to take into account various flight conditions:

- takeoff at a safe speed with devices to increase lift in takeoff mode;
- cruising with retracted position of high-lift devices;
- landing with a device for increasing the lifting force in the appropriate landing position.

In each of these configurations, possible design cases must be taken into account during design wing. One of the important dependencies of aircraft aerodynamics is lift coefficient vs angle of attack. In Figure 8 lift coefficient vs angle of attack diagrams are shown for various flight conditions. This diagram can show the following characteristic points:

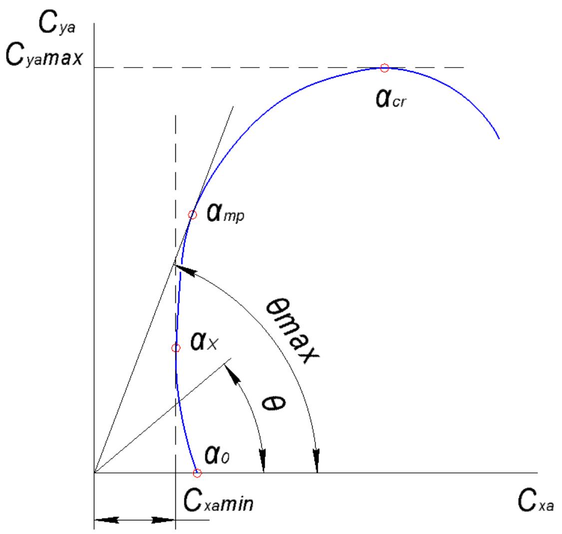


where α_0 – angle of attack of zero lift. This is the angle of attack at which the lift coefficient is zero;

α_{sp} – angle of attack corresponding to the beginning of the separation of flow around the airfoil. It is called the shaking angle, because. the pilot begins to feel the shaking of the controls when reaching this angle;

α_{cr} – critical angle of attack corresponding to the maximum value of the lift coefficient. It is called critical, because with an accidental increase in this angle, the boundary layer separates, the aircraft becomes poorly controlled, prone to stalling and going into a “spinning maneuver”.

One more important aerodynamic characteristic that determine the force interaction of the aircraft or its parts with the air flow is the “Polar” (lift coefficient vs drag coefficient diagrams, see Figure 9).



The following characteristic angles of attack can be determined from the wing polar:

- the point of intersection of the polar with the abscissa axis corresponds to the angle of attack of zero lift (α_0);
- the point of contact of the polar with a straight line parallel to the coordinate axis corresponds to the angle of attack of least drag coefficient (α_x);
- the most profitable angle of attack is at the point of contact of the polar with a straight line drawn from the origin (α_{mp}). This is the angle at which the aerodynamic efficiency of the wing is maximum.

For illustration purposes of difference airfoil flow during difference flight cases like a cruise, takeoff, and landing, velocity near airfoil are shown in Figure 10. In Figure 11, pressure distribution near airfoil for different cases are shown. The angle of attack 12 degrees was chosen. At this angle of attack, at cruise mode (Figure 10, a) we can see area of beginning of the separation of flow. At the same angle of attack, there is no separation of flow on the upper surface of wing at takeoff and landing mode (Figure 10, b and c).

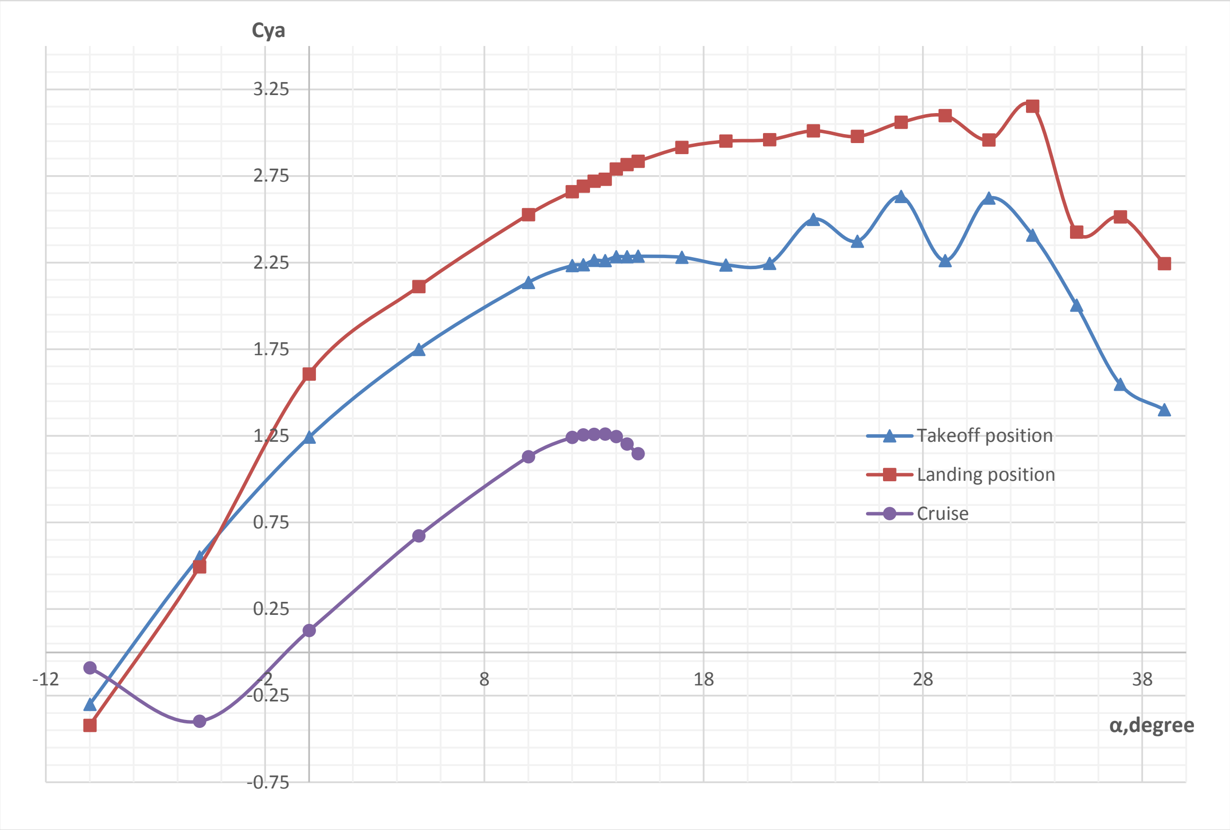


Figure 8. Lift coefficient vs angle of attack for cruise, takeoff, and landing flight cases (numerical analysis)

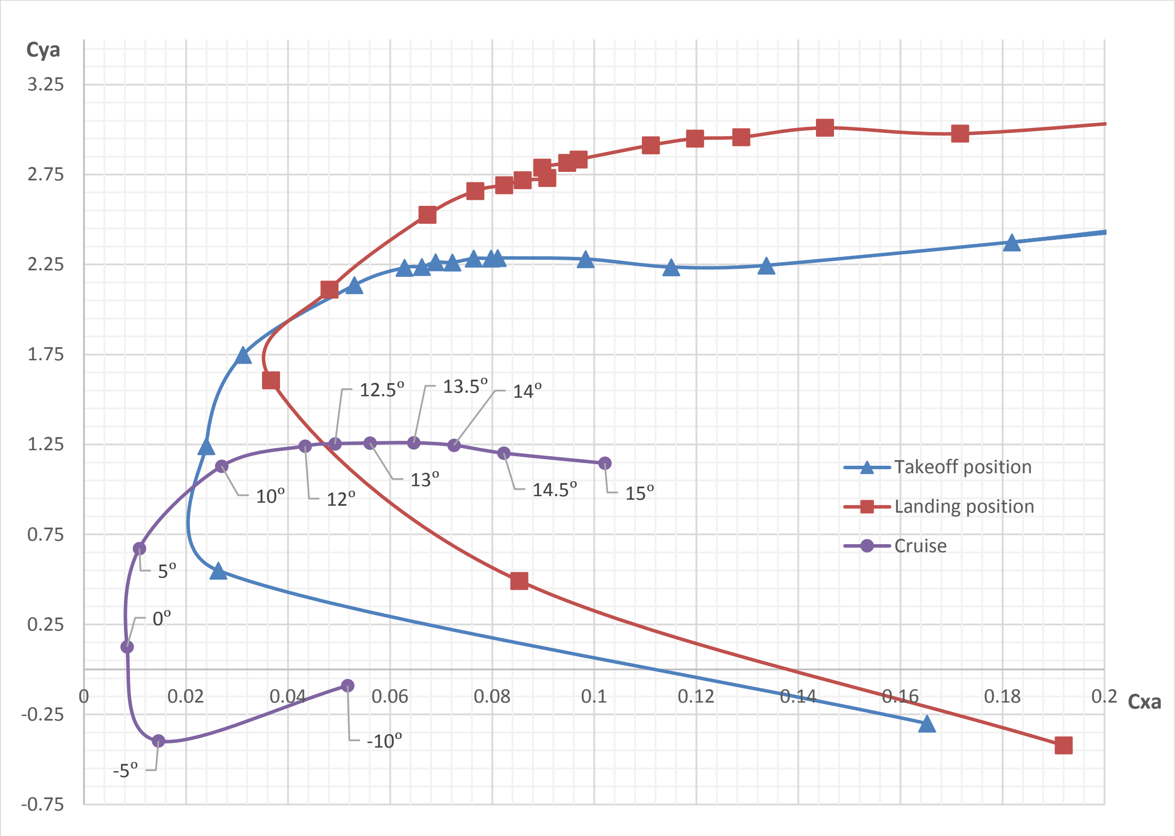


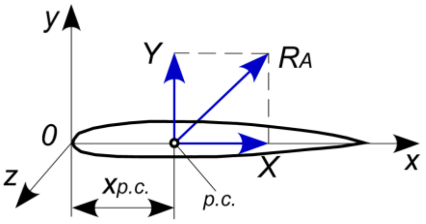
Figure 9. Lift coefficient vs drag coefficient for cruise, takeoff, and landing flight cases (numerical analysis)

In addition, Figure 11 shows us how is large the area of low pressure on the upper surface of airfoil during takeoff and landing mode compared to cruise case. This can be explained by an increase in the curvature of the airfoil during the extend of high-lift devices.

3.4. Location of pressure point relative to the length of the airfoil chord

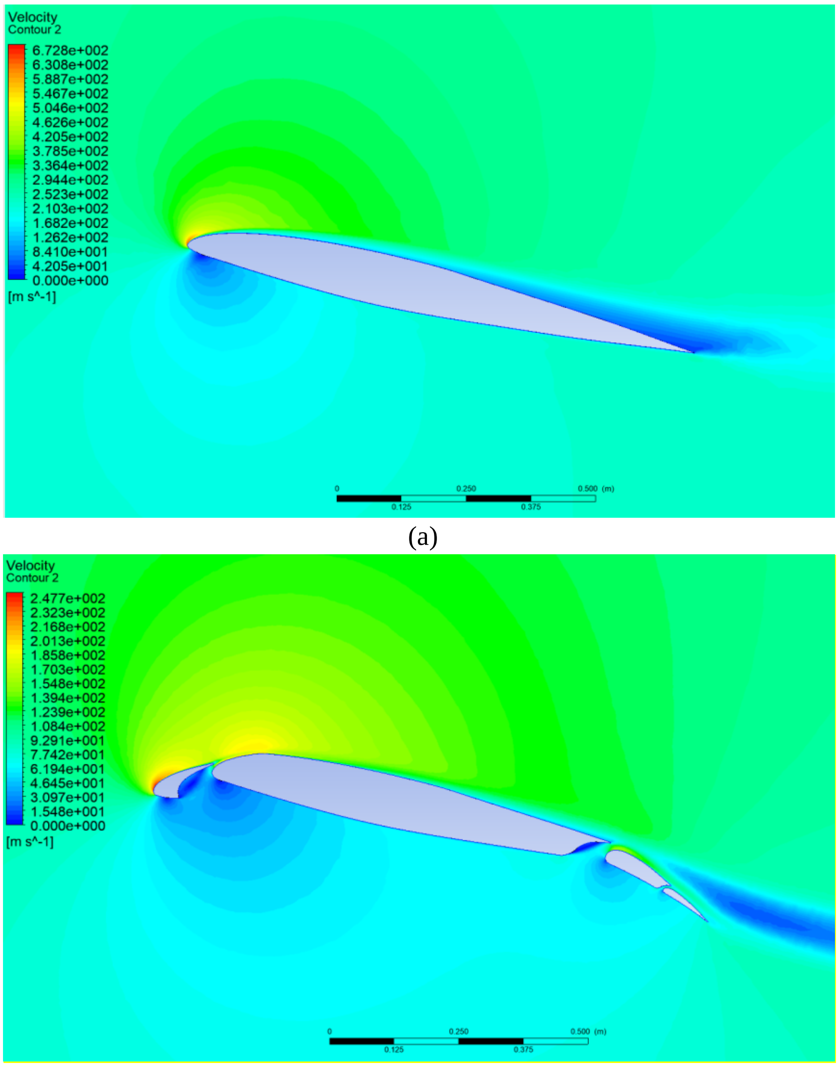
When designing a wing, it is important to know the position of the center of pressure on the airfoil. Since the mismatch between the pressure point (point of lift force) and the center of shear center leads to an undesirable effect of twisting the wing.

The position of the center of pressure can be determined from the condition of equilibrium relative to the leading edge of the airfoil according to the formula (2):



$$M_z = Y \cdot x_{p.c.} \rightarrow x_{p.c.} = \frac{M_z}{Y}. \tag{2}$$

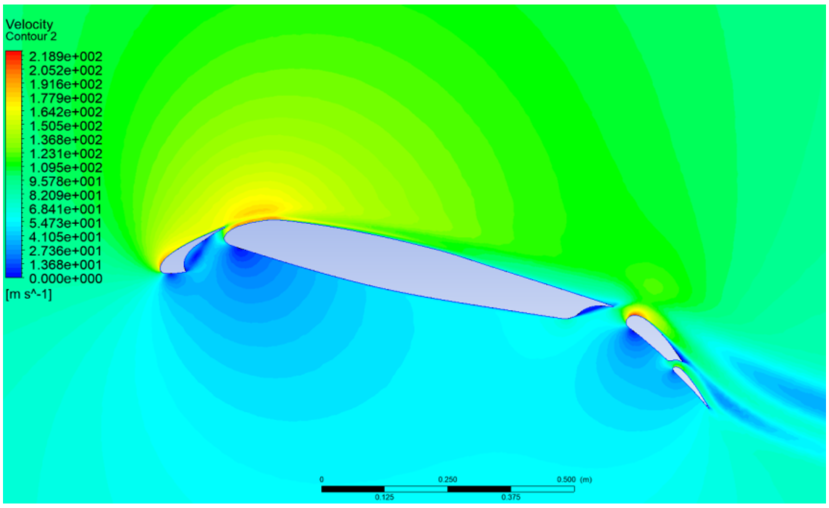
The position of pressure point for a clean profile is approximately 25 % of the chord width. From the obtained results, it can be seen that the pressure center (p.c.) at the airfoil with the extended high-lift devices is shifting to the trailing edge (Figure 12), which can be explained by the fact that the pressure redistributes closer to the trailing edge when the high-lift devices is released.



(a)

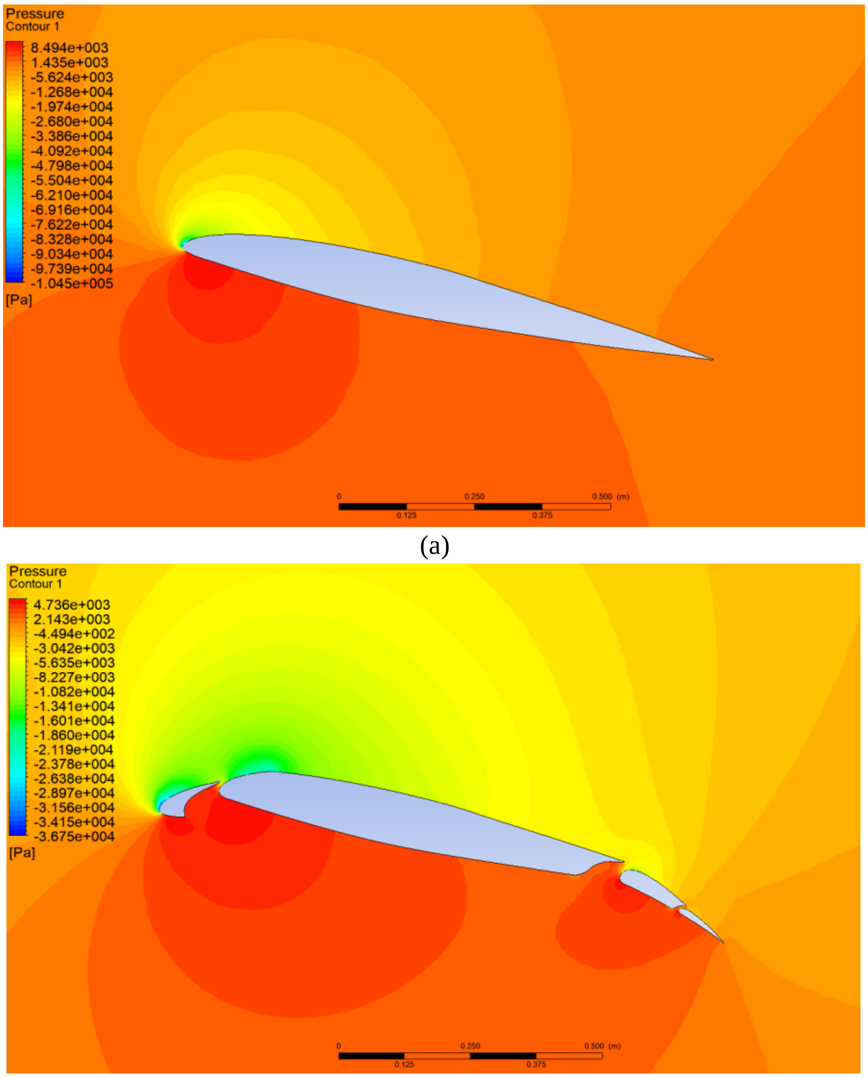
(b)

Figure 10. Velocity near airfoil: (a) cruise, angle of attack 12 degrees, V= 243.5 m/s, H=11000 m; (b) takeoff, angle of attack 12 degrees, V=95.2 m/s, H=0 m



(c)

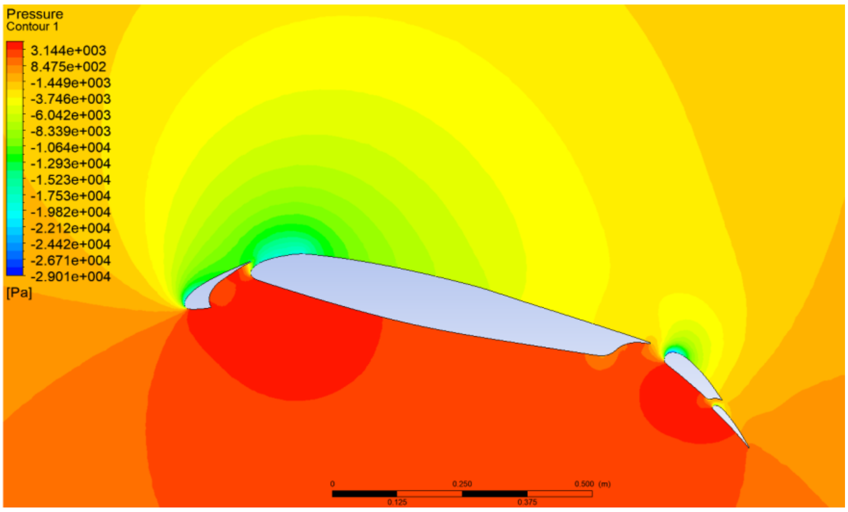
Figure 10. Velocity near airfoil: (c) landing, angle of attack 12 degrees, V= 83.34 m/s, H=0 m



(a)

(b)

Figure 11. Pressure near airfoil: (a) cruise, angle of attack 12 degrees, V= 243.5 m/s, H=11000 m; (b) takeoff, angle of attack 12 degrees, V=95.2 m/s, H=0 m



(c)

Figure 11. Pressure near airfoil: (c) landing, angle of attack 12 degrees, V= 83.34 m/s, H=0 m

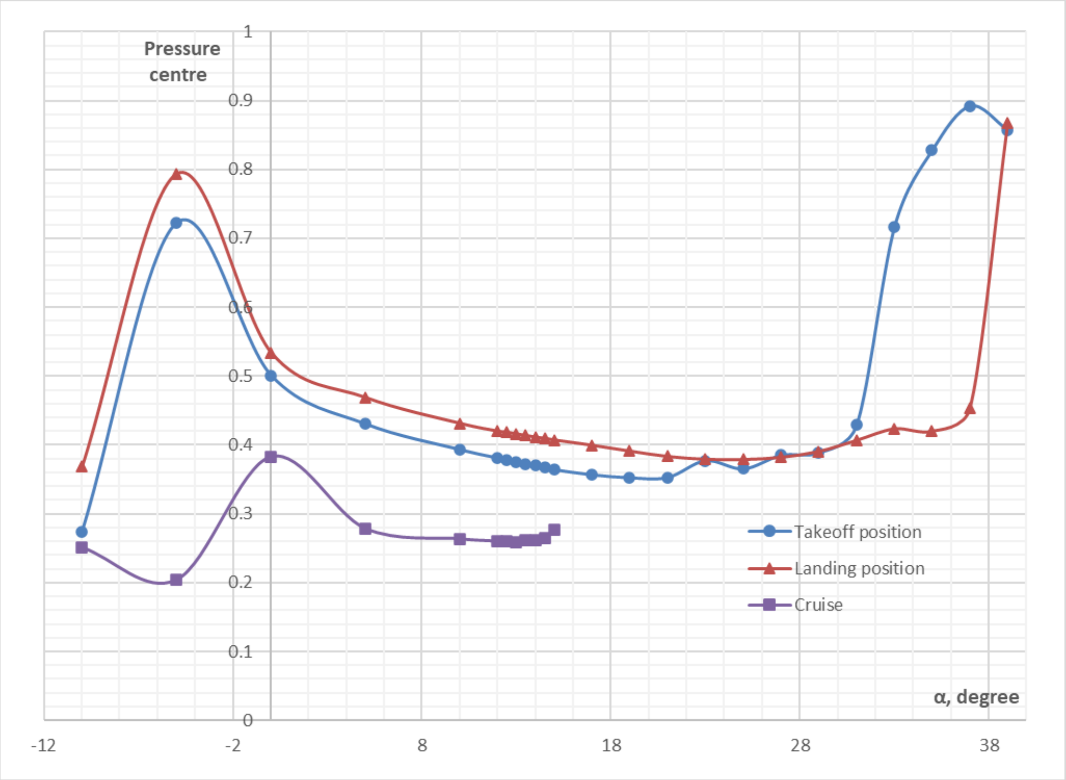


Figure 12. Position of the pressure point along the chord for cruise, takeoff, and landing flight cases

3.5. Influence of the interface on the aerodynamic characteristics of a wing with high-lift divaces

When an aircraft is flying near the ground (during takeoff or landing), the physical conditions of the flow around the wing change, since the influence of the earth's surface significantly changes the flow around the profile. As a result of an increase in pressure under the wing, the speed sharply increases on the leading edge of the wing, which leads to a redistribution of pressure along the profile (Figure 13) [15].

Therefore, when studying the loads on the wing, it is also necessary to take into account the design case near the ground (boundary).

Some results of the influence of the fixed boundary on aerodynamic characteristics can be found in the study [13]. Figure 14 shows the dependence of the lift coefficient vs the angle of attack at various distances to the interface.

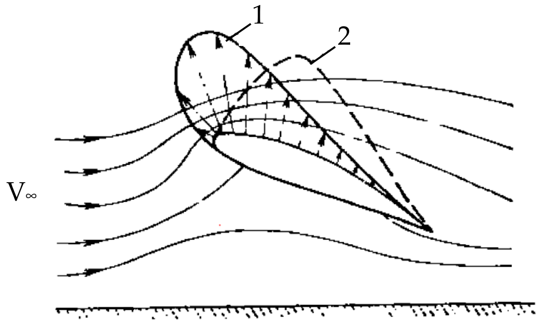


Figure 13. Effect of ground proximity on pressure distribution:1 – near the ground; 2 – away from the ground

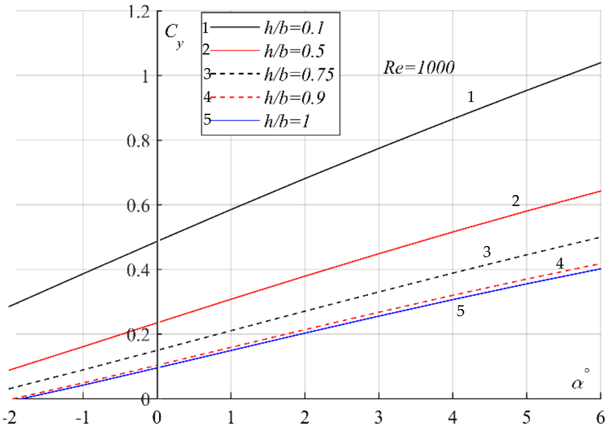


Figure 14. Dependence of the lift coefficient vs the angle of attack at different distances to the interface

As you can see from the Figure 14, as the profile approaches the section difference, the lift coefficient increases and can reach a difference of 2.5 times (h/b =1 and h/b=0.1), that is confirmed by full-scale test [6].

4. Discussion

The results of a numerical study of the aerodynamic characteristics of the Boeing 737 Midspan b737c-il airfoil in cruise, takeoff and landing modes are presented. The calculation model was verified with publicly available aerodynamic data for clear airfoil. The obtained data shows the effect of flap and slat extension on the airfoil flow.

From the obtained graphs, it can be seen how the lift coefficient changes during takeoff and landing in comparison with the cruising flight mode. It should be noted that the ground effect was not taken into account in the numerical calculations (effects of distance to surface). But, some investigation about influence of the earth on aerodynamics parameters was performed by Y. A. Krashanytsya [13] and can be used for analysis. According to the pictures of distribution of the velocities along the profile, it can be seen that a clean profile at an angle of attack of 12 degrees has signs of flow separation, while an airfoil with high-lift devices separation is not present. Released two slotted flap leads to delaying of flow separation.

The center of pressure (pressure point) is not a constant point, however, rather it moves depending on the angle of attack. For convenience, it's customary to consider the lift and drag forces as being centered at a point that is on the chord line 25% back from the leading edge [16]. Obtained results, related to the location of pressure point for clear airfoil, show that this point is located approximately at 25 % (Figure 12) that corresponded open data results. In addition, the position of the center of pressure was obtained for the takeoff and landing flight cases, which contributes to the calculation of wing loads for these design cases.

The results of current article were used to determine the load on the wing of a transport category aircraft at the high-lift section of the wing [17] for later study loading of wing during takeoff/landing flight cases.

Contributions of authors: conceptualization – **Yuri Krashanitsa, Dmytro Zhyriakov**; methodology – **Yuri Krashanitsa, Dmytro Zhyriakov**; formulation of tasks – **Yuri Krashanitsa, Dmytro Zhyriakov**; analysis – **Yuri Krashanitsa, Dmytro Zhyriakov**; development of model – **Yuri Krashanitsa, Dmytro Zhyriakov**; software – **Dmytro Zhyriakov**; verification – **Yuri Krashanitsa, Dmytro Zhyriakov**; analysis of results – **Yuri Krashanitsa, Dmytro Zhyriakov**; visualization – **Yuri Krashanitsa, Dmytro Zhyriakov**; writing – original draft preparation – **Yuri Krashanitsa, Dmytro Zhyriakov**; writing – review and editing – **Yuri Krashanitsa, Dmytro Zhyriakov**.

All the authors have read and agreed to the published version of the manuscript.

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ЧИСЕЛЬНЕ ДОСЛІДЖЕННЯ АЕРОДИНАМІЧНИХ ХАРАКТЕРИСТИК МЕХАНІЗОВАНОГО ПРОФІЛЯ

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Предметом вивчення в статті – механізований аеродинамічний профіль крила літака транспортної категорії. При використанні механізації крила аеродинамічний потік крила істотно змінюється, що призводить до зміни напружено-деформованого стану крила. Це пов'язано не тільки зі збільшенням підйомної сили за рахунок зміни кривизни крила і збільшенням площі крила, але і зі зміною положення центру тиску щодо хорди крила. **Метою** роботи є вивчення впливу механізації крила на аеродинамічні характеристики профілю при зальотному, крейсерському і посадочному розрахункових випадках чисельними методами. Отримані дані будуть використовуватися для визначення навантажень на крило при різних розрахункових випадках. **Завдання** полягає у визначенні аеродинамічних коефіцієнтів підйомної сили і опору, зміні положення центру тиску під час: зльоту, крейсерському і посадочному режимі. При аналізі був використаний аеродинамічний профіль b737c-il. В аналітичній моделі були використані однощілинний передкрилок і двухщілинний закрилок. При вивченні, були використані чисельні **методи** за допомогою системі CAE ANSYS Fluent. Для порівняння використовувалися розрахункові моделі k-epsilon і transition SST. Застосування чисельних методів в процесі проектування конструкцій літака широко застосовується для точного визначення аеродинамічних параметрів крила в різних розрахункових випадках. Були отримані наступні **результати**: залежність коефіцієнта підйомної сили від кута атаки, коефіцієнта підйомної сили від коефіцієнта лобового опору а також положення центру тиску по хорді профілю при зальотному, крейсерському і посадочному розрахункових випадках. **Висновки.** Наукова новизна отриманих результатів полягає в наступному: використання чисельних методів для визначення аеродинамічних характеристик крила із механізацією зокрема, визначення залежності положення центру тиску щодо хорди при різних кутах атаки. Отримані результати будуть використані для визначення навантаження на крило, зокрема розподіленого навантаження на передкрилки і закрилки, для уточнення крутного моменту в поперечному перерізі крила, де установлена механізація.

Ключові слова: механізація крила; аеродинамічний профіль; численні методи; положенні центру тиску; аеродинамічні характеристики; число Рейнольдса.

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