EFFECT OF THE PROPELLER INCIDENT ANGLE ON THE AERODYNAMIC CHARACTERISTICS OF THE AIRCRAFT

The article discusses the methodology for assessing the influence of the incident angle of the propeller on the aerodynamic characteristics of the aircraft, as well as on the characteristics of its stability and controllability. With the help of numerical simulation methods, the features of the influence of the air flow from the propeller on the lifting and control surfaces of the aircraft, its fuselage were revealed. A numerical experiment method for calculating the aerodynamic characteristics of an aircraft in the presence of a propeller was developed and formalized. The results of the study were implemented during the work on the training aircraft UTL-450.

Keywords: numerical simulation, Computational Fluid Dynamics (CFD), propeller, aircraft, aerodynamic characteristics, control and stability, propeller incident angle.

Introduction

Formulation of the problem. When the aircraft is remotorized, a situation may arise in which the thrust eccentricity changes significantly. This can cause significant changes in aircraft controllability, its trim characteristics, as well as changes in longitudinal stability. In addition, if the new engine with propeller has significantly more powerful thrust characteristics, then this can lead to serious uneven lift generation on the left and right wing sections.

Analysis of recent research and publications. Quite often, during remotorization, or even at the design stage, an aircraft detects thrust eccentricity.

This issue is solved by designers by turning the propeller in a vertical plane (incident angle). Papers on this subject are very rarely published in the public domain (with some exceptions [1]), because they are very "narrowly focused" in nature. Sometimes, the propeller incident angle is determined solely on the basis of flight experiments.

However, there are also works that present some fundamental results of research in wind tunnels [2–5], or mention this topic at the stage of preliminary design of aircraft [6; 7].

The purpose of the article is to develop a methodology for assessing the effect of the incident angle of the propeller on the aerodynamic characteristics, as well as on the characteristics of the stability and controllability of the aircraft using CFD methods.

Statement of the main material

The installation of the AI-450 engine on the UTL-450 aircraft results in an eccentricity of the propeller thrust relative to the center of gravity of the aircraft.

Changing the angle of the propeller in the vertical plane leads to a change in the eccentricity of the thrust, as a result of which the pitch moment from the propeller thrust changes (Fig. 1).

In addition, the rotation of the thrust vector changes the downwash of the flow on parts of the wing and tail, which are blown by the air flow. Also, due to the swirling of the flow by the propeller, the flow downwash on the left and right wing planes differ significantly. To study the effect of the propeller incident angle on the aerodynamic characteristics of the aircraft, a series of CFD calculations was carried out using the OpenFOAM software (actuatorDiskExplicitForceSimpleFoam solver). This solver is a modified version of the simpleFoam solver, which allows you to simulate the flow of a viscous incompressible fluid in a stationary formulation with averaging of turbulent fluctuations using a turbulence model. The solver modification consists in the possibility of adding one cell zone to the calculation, which simulates the propeller. This cell zone is determined by the location of the propeller in the calculation domain. Simulation of the propeller occurs by adding a source of impulse inside the given cell zone.

The radial distribution of normal and tangential forces that act on the blade is calculated in accordance with the optimal Goldstein distribution [8]. In circumferential direction the thrust force uniformly distributed.
over the entire propeller disk.

The thrust and torque of the propeller for each flight mode were determined from the diagrams obtained earlier and were explicitly specified in the solver settings [9]. The calculations were carried out on a grid that was generated using the cfMesh, and which consisted of 1.8 million cells. The grid was rebuilt only after the elevator deflect (δ). The change in the pitch angle of the aircraft and the flight regime were carried out by changing the boundary conditions.

The following flight regimes were simulated:
1) Takeoff (engine maximum takeoff power (MTOP), \( V = 64 \text{ kt}, \alpha = 12^\circ, \delta = -10^\circ \)).
2) Cruise flight I (engine maximum cruise power (MCP), \( V = 113 \text{ kt}, \alpha = 5^\circ, \delta = 0^\circ \)).
3) Cruise flight II (engine cruise power (CP), \( V = 113 \text{ kt}, \alpha = 5^\circ, \delta = 0^\circ \)).
4) “Run-through thrust” – extra flight regime for thrust influence study.

Based on the results of each calculation case, the values of the coefficients of lift, drag force and pitching moment from the aerodynamic forces that acting on the aircraft were obtained. The additional torque coefficient from the propeller thrust is determined by the formula:

\[
m_{z_{\text{prop}}} = -\frac{M_{z_{\text{prop}}}}{q \cdot S_{W} \cdot b_{\text{MAC}}},
\]

where \( q \) – dynamic pressure, [Pa];
\( S_{W} \) – wing area, [m²];
\( b_{\text{MAC}} \) – mean aerodynamic chord of the wing, [m];
\( M_{z_{\text{prop}}} \) – the moment from the thrust of the propeller relative to the center of gravity of the aircraft, which is determined by the formula:

\[
M_{z_{\text{prop}}} = -T \cdot \cos \beta \cdot \cos \chi \cdot (y_{\text{prop}} - y_{\text{CoG}}) + \\
+ T \cdot \cos \beta \cdot \sin \chi \cdot (x_{\text{prop}} - x_{\text{CoG}}),
\]

where \( T \) – propeller thrust, [N];
\( \beta \) – turning angle of the propeller in the horizontal plane;
\( \chi \) – turning angle of the propeller in the vertical plane;
\( y_{\text{prop}}, x_{\text{prop}} \) – propeller plane coordinates;
\( x_{\text{CoG}}, y_{\text{CoG}} \) – center of gravity coordinates.

To analyze the trimming characteristics of the aircraft (taking into account the thrust of the propeller), the value of the total pitching moment coefficient was determined:

\[
m_{z_{\text{z}}} = m_{z_{\text{prop}}} + m_{z_{\text{z}}}.
\]

To evaluate the efficiency of the elevator, the derivative of the pitching moment with respect to the elevator deflection angle was calculated.

\[
m_{z_{\text{elevator}}} = \frac{\Delta m_{z}}{\Delta \delta_{\text{elevator}}}.
\]

To evaluate the forces on the aircraft control stick, the values of hinge moments on the elevator were determined:

\[
M_{\text{elevator}} = \frac{q \cdot S_{W} \cdot b_{\text{MAC}}}{m_{z_{\text{elevator}}}}.
\]

The moment on the aircraft control stick was determined through the gear ratio coefficient:

\[
k_{\text{elevator}} = \frac{\Delta \delta_{\text{control stick}}}{\Delta \delta_{\text{elevator}}}.
\]

The hinge moment on the aircraft control stick is determined by the formula:

\[
M_{\text{control stick}} = \frac{M_{\text{elevator}}}{k_{\text{elevator}}},
\]

The forces on the aircraft control stick were determined by the formula:

\[
P_{\text{control stick}} = \frac{M_{\text{control stick}}}{l_{\text{control stick}} \cdot \beta},
\]

where \( l_{\text{control stick}} \) – arm of the hinge of the aircraft control stick to the handle, [m].

Based on the calculation results, the aircraft drag curves were built for the previously determined flight regimes. Fig. 2 shows drag curves, which are plotted based on the results of numerical simulation and also on the results of calculations by the classical method.

![Fig. 2. Coefficients of lift and drag versus angle of attack](image)

Source: developed by the authors.

According to Fig. 2 and Fig. 3, it is possible to assess the degree of influence of the propeller on the lifting capabilities of the wing and the aircraft. It can also be seen (see Fig. 2) that over a limited range of angles of attack, the classical calculation method is suitable for the initial assessment of aircraft performance character-
istics (if we neglect the effect of the propeller) with an acceptable error.

![Fig. 3. Drag curves of the aircraft](image)

Source: developed by the authors.

Fig. 3. Drag curves of the aircraft

Fig. 4 shows the dependence of the lift-to-drag ratio on the aircraft's angle of attack for cruise flight. It is noted that turning the propeller down by $4^\circ$ increases the aircraft's lift-to-drag ratio by $0.55\%$ over the entire range of angles of attack. Turning the propeller up by $4^\circ$, on the contrary, reduces the lift-to-drag ratio of the aircraft by an average of $0.24\%$.

![Fig. 4. Lift-to-drag ratio of the aircraft versus angle of attack](image)

Source: developed by the authors.

Fig. 4. Lift-to-drag ratio of the aircraft versus angle of attack

Fig. 5 and Fig. 6 shows the dependence of the pitching moment coefficient versus the angle of attack of the aircraft – for the extreme rearward and extreme forward CG positions. Dependencies are given for three incident angles of the propeller ($\alpha = 0^\circ; -4^\circ; +4^\circ$) and cruise flight mode. It is noted that the propeller has a sufficient effect on the stability characteristics of the aircraft. Fig. 7 shows the dependence of the forces on the aircraft control stick versus the thrust developed by the propeller.

![Fig. 5. The functions of the pitching moment coefficient versus the angle of attack of the aircraft (cruise flight, extreme rearward CG position)](image)

Source: developed by the authors.

Fig. 5. The functions of the pitching moment coefficient versus the angle of attack of the aircraft

![Fig. 6. The functions of the pitching moment coefficient versus the angle of attack of the aircraft (cruise flight, extreme forward CG position)](image)

Source: developed by the authors.

Fig. 6. The functions of the pitching moment coefficient versus the angle of attack of the aircraft

![Fig. 7. Dependence of load on the control stick versus the thrust developed by the propeller](image)

Source: developed by the authors.

Fig. 7. Dependence of load on the control stick versus the thrust developed by the propeller

$V = 64 \text{ kt, } \alpha = 12^\circ, \delta = -10^\circ$
The nature of the dependences is close to linear with almost uniform monotonic growth. However, for the case of the incidence angle of the propeller, there is some deviation from the linear law towards a lower growth rate, which is a positive feature.

On Fig. 8. the trimming angles of the elevator of the UTL-450 aircraft are given, which are calculated according to the results of numerical simulation (for the MTOP regime), as well as those calculated by the method [10; 11] and experimental data for the Yak-52 aircraft, which are obtained as a result of flight tests [12]. According to the results of calculations, the UTL-450 aircraft has a sufficient control margin over the entire range of propeller incident angles.

Fig. 8. Dependence of the trim angle of the elevator on the aircraft flight speed
Source: developed by the authors.

Fig. 9. shows the distribution of the pressure coefficient over the surface of the aircraft and the airflow streamlines in its vicinity. The lift asymmetry on the wing and engine exhaust pipes is clearly visible, which is a side effect of the interference of the airflow thrown by the propeller.

Conclusions

As a result of the study, a method for conducting a numerical experiment to determine the influence of the propeller incidence angle on the aerodynamic and trimming characteristics of the training aircraft was developed. With the help of modern numerical methods, the operation of the propeller and its influence on the aerodynamics of the aircraft were simulated, which made it possible to significantly reduce the number of flight tests, as well as improve flight safety and prepare the pilot for the possible difficult-to-predict behavior of the aircraft.

Based on the results of numerical simulation, the following conclusions can be drawn.

1. Turning the propeller down by 4° increases the lift-to-drag ratio of the aircraft in cruise flight by 0.55% (compared to a horizontal propeller setting by default). In takeoff mode, when the propeller is turned down, the increase in lift-to-drag ratio reaches 2%. With the extreme forward CG position and the propeller incidence angle of 4° down, in takeoff regime, at maximum propeller thrust and minimum flight speed (worst combination of conditions), the required trim angle of the elevator is −9.3° (the design range of the elevator angle is: −25°...+25°). With extreme forward CG position, an engine failure during takeoff will cause the aircraft pitch
down slightly, which is a completely understandable aircraft behavior for the pilot. With an extreme rearward CG position, an engine failure on takeoff will lead aircraft to a slight pitch up, which is an incomprehensible behavior of the pilot for the correct reaction of the pilot to the behavior of the aircraft can lead to a stall if the pilot does not timely deviate the aircraft control stick “forward” by 1°.  

2. Turning the propeller up by 4° decreases the lift-to-drag ratio of the aircraft in cruise flight by 0,24% (compared to a horizontal propeller setting by default). With extreme forward CG position, engine failure during takeoff will cause a significant additional pitch-down moment, to compensate for which, it is necessary to deflect the aircraft control stick “backward” by 7,5°. With extreme rearward CG position, an engine failure during takeoff will cause the aircraft pitch down slightly, which is understandable behavior of the aircraft for the pilot.

3. Horizontal installation of the propeller (default). With extreme forward CG position, an engine failure on takeoff will cause an additional pitch-down moment, to compensate for which it is necessary to deflect the aircraft control stick “backward” by 5,25°. With extreme rearward CG position, an engine failure on takeoff will result in a slight tendency to pitch-down. The required deflection of the aircraft control stick “backward” to maintain the pitch angle is 0,5°.

References


Список літератури


Надійшла до редакції 13.03.2023
Схвалена до друку 10.05.2023

Відомості про авторів:
Кибальний Михайло Юрійович
начальник конструкторського бюро
AT “Мотор Січ”,
Запоріжжя, Україна
https://orcid.org/0000-0003-2322-6988

Притула Олексій Володимирович
повідний інженер
AT “Мотор Січ”,
Запоріжжя, Україна
https://orcid.org/0000-0001-8422-0577

Ізвекова Катерина Сергіївна
начальник відділу
AT “Мотор Січ”,
Запоріжжя, Україна
https://orcid.org/0000-0003-0480-1668

Дьомін Андрій Навдович
заместник Головного конструктора
AT “Мотор Січ”,
Запоріжжя, Україна
https://orcid.org/0000-0003-0343-0957

Information about the authors:
Mykhaylo Kybalny
Chief of the Design Bureau
of JSC “Motor Sich”,
Zaporizhzia, Ukraine
https://orcid.org/0000-0003-2322-6988

Oleksi Prytula
Leading Engineer
of JSC “Motor Sich”,
Zaporizhzia, Ukraine
https://orcid.org/0000-0001-8422-0577

Katerina Izvekova
Head of Department
of JSC “Motor Sich”,
Zaporizhzia, Ukraine
https://orcid.org/0000-0003-0480-1668

Andriy Dyomin
Deputy Chief Designer
of JSC “Motor Sich”,
Zaporizhzia, Ukraine
https://orcid.org/0000-0003-0343-0957

ВПЛИВ КУТА ВСТАНОВЛЕННЯ ПОВІТРЯНОГО ГВИНТА НА АЕРОДИНАМІЧНІ ХАРАКТЕРИСТИКИ ЛІТАКА

У статті досліджується вплив кута установки повітряного гвинта на аеродинамічні характеристики літака. При розробці моделювання літака можливо виникнення ситуації, коли з'являється екскентриситет тяги. Одним із шляхів усунення негативних наслідків від його появи є зміна кута установки повітряного гвинта. У рамках роботи проводиться аналіз впливу екскентриситету тяги на аеродинамічні характеристики літака.

Знайдено, що правильне обрання кута установки повітряного гвинта може не тільки зменшити екскентриситет тяги, а й підвищити аеродинамічну якість літака. Визначено, що правильна установка повітряного гвинта може призвести до неоцінених змін авіаційної пригоди або передумови до неї.

Ключові слова: численне моделювання, обчислювальна гідродинамика (CFD), повітряний гвинт, літак, аеродинамічні характеристики літака.