Calculation of aerodynamic characteristics of light aircraft with distributed electric propulsion

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Abstract. This paper describes a numerical calculation method of the aerodynamic characteristic of an aircraft with distributed electric propulsion system (DEPS) taking into account influence of a blown wing. In addition, the studies of DEPS impact on aerodynamic characteristics of the light aircraft are represented.

1. Introduction

Nowadays application of the electric energy considering in the different industries including aviation. Light electric aircrafts are already used as training planes. Commuter, regional and short/medium range aircrafts with electric propulsion system (EPS) and hybrid propulsion system (HPS) are expected to appear in foreseeable future. The main reason for their development was the emergence of electric machines with high energy-to-weight ratio. Their applications in the aircraft propulsion systems resulted in creation a distributed electric propulsion systems (DEPS). The main advantage of DEPS over conventional propulsion systems is that it is used the energy transfer by wires to electric motors instead of using heavy mechanical transmission.

There are two approaches to calculate the aircraft aerodynamic performance. The first approach would be to apply special software that integrates Reynolds equations with aid of finite volume algorithm. The results of these calculations are quite accurate however they require very large computing resources and time to obtain them. The second approach would be to apply the empirical algorithms. The results of these calculations are less accurate, but giving the immediate result. The approach is therefore suitable for obtaining the preliminary results.

Methodologies of estimations those produce accurate result and need small number of arguments are excellent for approximately calculations of the lift/drag curve.

2. Mathematical model of calculation of the light aircraft lift/drag curve

The typical dependence of lift force coefficient on the attack angle $C_l(\alpha)$ of an aircraft with cruise flap position is shown in the figure 1 [1].
In the figure $\alpha_0$ is the attack angle at $C_l = 0$; $\alpha_0 = -90^\circ$, here $f$ is reference airfoil camber; $\alpha_1$ is the angle of the start of nonlinear part of the lift curve, $\alpha_1 = \alpha_0 + \frac{C_{l_1}}{C_f^\alpha} \cdot 57,3$; $C_{l_1} = 0,85C_{l_{max}}$; $\alpha_{max}$ is the angle of the max of lift coefficient $C_l = C_{l_{max}}$; $\alpha_{max} = \alpha_0 + \frac{C_{l_{max}}}{C_f^\alpha} \cdot 57,3 + \Delta\alpha$, $\Delta\alpha = 1,5^\circ$. $C_{l_{max}}$ is chosen according to figure 2 [1] depending on airfoil camber $f$ and it’s reference thickness $c$.

The angle of the linear part of the lift curve is calculated according to the following expression:

$$C_l^n = 2\pi \frac{\lambda \cos \chi}{2 + \lambda_e}$$

(1)

Effective wing aspect ratio can be defined by Brege expression:

$$\lambda_e = \frac{\lambda}{1 + 0,025\lambda}$$

(2)

To calculate influence of flaps we use the methodology from [2]. The additional part of a lift coefficient of airfoil associated with flaps deflection can be calculated according to the following expressions:

$$\Delta C_{l_{10wp}} = 2\pi \cdot 1,22 \sqrt{b_f \theta_{ef}}$$

(3)

$$\Delta C_{l_{max wp}} = \frac{1}{2} \sqrt{1-b_f} \Delta C_{l_{10 wp}}$$

(4)

Here $b_f$ is the flap reference chord, $\theta_{ef}$ is the effective flap deflection angle [2].

Drag coefficient is the sum of zero drag and drag-due-to-lift:
\[ C_d = C_{d0} + \frac{C_l^2}{\pi \alpha} \]  
(5)

\( C_{d0} \) is calculated as:

\[ C_{d0} = k \cdot C_f \cdot p_0 (G_0)^{\beta-1} \]  
(6)

Here \( p_0 \) is the wing loading, \( G_0 \) is the aircraft takeoff weight.

The empirical coefficient values for a light aircraft are following:

\( k=1.71; \beta = 0.515; C_f = 0.0065 \) [1].

This mathematical model describes rather good the linear part of the lift/drag curve of the aircraft.

3. Comparing the results obtained by test, experiment and using «Xfoil» software

There are panel methods of calculation of the aerodynamic performances. Those algorithms take intermediate place between empirical models and finite volume calculations. The most popular software that is used panel methods is «xfoil».

To verify the methodology we compared calculation of the lift coefficient \( C_l \) and the drag coefficient \( C_d \) of airfoils NACA-0012, NACA-2217, NACA-4412 and an airfoil of a light aircraft with results of the experiments [3], and «xfoil» calculations [4]. As it can be seen from figures 3-8 the calculated results are good consistent with experimental data. (Figures 3 - 8).

\[ \text{Figure 3. Lift coefficient of an airfoil NACA-0012} \]

\[ \text{Figure 4. Lift coefficient of an airfoil NACA-2217} \]

\[ \text{Figure 5. Drag coefficient of an airfoil NACA-0012} \]
As it can be seen «xfoil» calculations of lift coefficient is livable. But «xfoil» calculations of drag coefficient can’t be used. In addition, «xfoil» results are clearly worse than results of the mathematic model represented above.

4. Distributed propulsion system

One of the benefits of using electric or hybrid propulsion system is opportunity to create distributed one. Due to this fact the aircraft’s take-off and landing performances can be improved because of prop blown of the wing. It leads to using shorter airstrip because of takeoff airspeed reduction. Also smaller wing can be used to increase a lift/drag ratio. Decreasing the takeoff airspeed of aircraft is a topical problem for naval aviation because it’s directly influences on their seakeeping.

Unfortunately, there are not enough experimental data about prop blown wing influence on takeoff and landing characteristics. Mathematical modeling of those processes is not developed too. Method from [5] can be used for approximately calculation of prop blown effect. This numerical scheme doesn’t allow to get accurate result, but can help to estimate order of value of an additional lift force.

Additional lift coefficient due to prop blown is the sum of two coefficients: additional lift coefficient due to vertical part of the stream reaction \( \Delta C_{ip} \) and additional lift coefficient due to supercirculation \( \Delta C_{il} \):

\[
\Delta C_i = \Delta C_{ip} + \Delta C_{il}
\] (7)

\[
\Delta C_{ip} = i k B \frac{S_0}{S} \sin \theta_{ef}
\] (8)
Here $i$ is the number of props; $k$ is coefficient of the thrust recovery [5]; $B$ is prop loading coefficient; $S_0$ is prop blown wing area; $S$ is wing area.

Additional lift coefficient due to blown for infinity wing aspect ratio (according to the Spence’s theory of a jet flap) is represented below:

$$
\Delta C_{l_{\mu}} = \Delta C_{l_{i}}^\theta \sin \theta_{ef} + \Delta C_{l_{i}}^\alpha \alpha
$$

(9)

Here $\Delta C_{l_{i}}^\theta$, $\Delta C_{l_{i}}^\alpha$ are increment of a flap deflection and attack angle derivative of the lift coefficient;

$$
\Delta C_{l_{i}}^\theta (C_{\mu}) = C_{l_{i}}^\theta (C_{\mu}) - C_{l_{i}}^\theta (0)
$$

is chosen according figure 9 [5] depending on a flap reference chord $b_f$.

![Figure 9](image)

**Figure 9.** Functional dependence of the $C_{l_{i}}^\theta$ on $C_{\mu}$

$$
\Delta C_{l_{i}}^\alpha = 1,152 \sqrt{C_{\mu}} + 1,106 C_{\mu} + 0,051C_{\mu} \sqrt{C_{\mu}}
$$

(10)

Here $C_{\mu} = k B \frac{F}{S_0}$; $F$ is an area covered by the prop.

Taking into account the airfoil thickness and limited wing aspect ratio we can get final expression:

$$
\Delta C_{l_{i}} = \left( \Delta C_{l_{i}}^\theta \sin \theta_{ef} + \Delta C_{l_{i}}^\alpha \alpha - i k B \frac{F}{S_0} \sin \theta_{ef} \right) \frac{S_0}{S} \frac{1}{2 \pi} \frac{C_{l_{i}}^\alpha}{S} + i k B \frac{F}{S} \sin \theta_{ef}
$$

(11)

This mathematical model was verified and tested. Comparing result of calculations of 23.5 tons aircraft with result of experiments are represented in the figure 10. As it can be seen this calculation methodology yields good result.
5. Calculation of aerodynamic performances of the DEPS light aircraft

Distributed propulsion system strongly raises characteristics of aircrafts with large flap deflection angles and well-developed high-lift system. Thus, a light aircraft with double-slotted flaps and 20° takeoff flap deflection angle has been chosen. In addition, the airfoil of this aircraft has high value of a lift coefficient.

According mathematical methodologies that are described higher, calculations of the aerodynamic characteristics of the light aircraft without prop blown, with two props blown and with eight props DEPS have been done. Condition of a choosing power of one engine is equality total thrust to 1500 N.

Plots of aerodynamic characteristics for cruise (flaps 0°, velocity 47 m/s) and takeoff (flaps 20°, velocity 23 m/s) flight mods are presented below.

![Figure 10](image1.png)

**Figure 10.** Lift coefficient of an aircraft with weight 23.5 t.

![Figure 11](image2.png)

**Figure 11.** Lift coefficient of a light aircraft, flap 0°

![Figure 12](image3.png)

**Figure 12.** Drag coefficient of a light aircraft, flap 0°
As it can be seen, the blown effect is low in case of cruise flight, because of zero flap deflection angle and high speed of cruise flight. The blown effect is much higher in case of takeoff mode.

As seen from the charts, DEPS lets to raise $C_L$ by about 30%, but $C_d$ also increase by 35%. Worth note that this numerical scheme is approximately and calculations are provisional. This method does not consider useful interference effect that reduces drag. So drag can be lower with more accurate methods of calculating, for example finite volume algorithms. Number of props is linked with prop blown wing area and this parameter is one of the most primary.

Intermediary calculations of takeoff mode have been done to analyze distributed propulsion effect on aerodynamic characteristics. Figures 17-18 show functional dependence of the lift and drag coefficients increase due to blown effect on the prop number of light aircraft. Increase of blown wing area leads to lift force rise. So research in area of a distributed electric propulsion is reasonable.
6. Conclusion

- The methodology of estimation of aerodynamic performances not including blown effect allows getting accurate result fast. It's used the minimum number of arguments. This method allows to make preliminary design of advanced aircrafts.
- Preliminary calculation of takeoff and cruise lift and drag coefficients of a light the aircraft with DEPS is done. Various schemes of DEPS with different number of props have been estimated. Functional dependence of adding lift and drag coefficients on number of props is plotted.
- $C_l$ of a DEPS aircraft with 8 props 29% higher than of a aircraft with 2 props. Due to this fact takeoff airspeed of a DEPS 8 props aircraft decrease.
- The impact of DEPS on aircraft aerodynamic performances during cruise flight is not significant.
- It is reasonable to use DEPS with blown all wing surface.
- In order to design a concept of the advanced aircraft with DEPS, experimental tests and more accurate calculations are needed. It would therefore be useful to use software based on the finite volume algorithm to that calculations.

References

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