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ESTIMATION OF THE AERODYNAMIC CHARACTERISTICS OF A STEPPED NACELLE FOR THE AIRCRAFT POWERPLANT

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Метою роботи є оцінка аеродинамічних характеристик ступінчастої мотогондоли газотурбінного двигуна з турбовентиляторною приставкою. Для проведення досліджень використовувався метод модельного фізичного експерименту. Аеродинамічна труба, в якій було проведено дослідження, забезпечена необхідним обладнанням, що включає в себе різні насадки статичного і динамічного тиску з координатними пристроями та ін. Для експериментальних досліджень було створено моделі мотогондол авіаційної силової установки з переднім розташуванням модуля вентилятора та з заднім розташуванням турбовентиляторної приставки. Проведено експериментальні дослідження аеродинамічних характеристик ступінчастої мотогондоли газотурбінного двигуна з турбовентиляторною приставкою.

Результати дослідження показали можливість зниження аеродинамічного опору ступінчастої мотогондоли двигуна з турбовентиляторною приставкою в порівнянні з мотогондолою турбореактивного двоконтурного двигуна з переднім розташуванням вентилятора. В діапазоні кутів атаки α***=0…20° значення аеродинамічного опору ступінчастої мотогондоли для газотурбінного двигуна з турбовентиляторною приставкою знижується на 49…55 %.***

Отримані результати показали, що коефіцієнт підйомної сили ступінчастої мотогондоли газотурбінного двигуна з турбовентиляторною приставкою збільшується на 24…64 %. Коефіцієнт аеродинамічного опору нижче на 18…28 % у порівнянні з коефіцієнтом аеродинамічного опору циліндричної мотогондоли двоконтурного турбореактивного двигуна в діапазоні кутів атаки α***=2…20°. Отримані результати свідчать про перспективність використання двигунів з турбовентиляторною приставкою. Конструкційна особливість ступінчастої мотогондоли дозволить зменшити втрати ефективної тяги двигуна за рахунок зниження аеродинамічного опору майже в два рази і підвищити паливну економічність двигуна***

Ключові слова: ступінчаста мотогондола, аеродинамічний опір, подйомна сила, газотурбінний двигун, турбовентиляторна приставка

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1. Introduction

Technical perfection of civilian aircrafts is determined by the aerodynamic layout of an aircraft, power unit, development of new materials, implementation of modern equipment and control systems.

The most important direction of improving the aerodynamics of mainline aircraft is minimizing the aerodynamic drag of an aircraft's elements. Among the essential issues related to this field is the optimization of the shape and location of nacelles, whose resistance is 1...5 % of the total aerodynamic drag of a plane. In addition, reducing the aerodynamic drag of nacelles would improve the effective force of engine thrust. Increase in effective thrust force could lead to the improved fuel efficiency of aircraft powerplant. Thus, it is a relevant task to decrease the aerodynamic drag of nacelles.

2. Literature review and problem statement

Measures aimed at reducing the aerodynamic drag of an engine's nacelle require reliable calculation procedures. For example, authors of papers [1–3] proposed and verified methodologies for determining the aerodynamic drag of an engine's nacelle. Study [1] suggested a procedure for calculating the drag coefficient of engine nacelles. The author assumes that the turboprop and turbojet engines are almost completely washed over by the turbulent boundary layer. Therefore, the main contribution to engine nacelles' drag is due to the resistances of friction and pressure. The cited study makes an assumption that an engine's nacelle has a well streamlined shape and its drag is slightly different from the resistance of a flat plate, which has the same area of the wetted surface. This procedure is suitable for first approximate estimates of the aerodynamic drag of differently shaped nacelles. The methodology for determining a nacelle's general resistance, consisting of external, internal, and wave resistance, was proposed in paper [2]. The authors gave test problems for 2D models, which demonstrated high accuracy of the proposed method. However, the techniques for determining the aerodynamic drag of a nacelle, proposed in [1, 2], do not take into consideration the 3D effects of flowing around a nacelle, as well as the impact of the pylon, wing, and fuselage. Study [3] reports a devised procedure for predicting the aerodynamic drag of a running engine's nacelle, which takes into consideration the impact of the pylon, wing, and fuselage. Based on the results from a physical experiment, the authors verified the proposed calculation procedure, which showed the high convergence of results.

Numerous theoretical and experimental studies addressed the estimation of effect exerted by various factors on the aerodynamic drag of a nacelle [4, 5]. For example, paper [4] assessed the drag of a nacelle for four different variants. The study involved a numerical experiment. It was shown that a reactive jet has a significant impact on the overall drag of a nacelle. However, the cited study does not take into consideration the interaction between a nacelle and the pylon, wing, and fuselage. Work [5] reports results from modeling a flow around nacelle in the near and far fields. In contrast to paper [4], modeling accounted for the impact of the pylon, wing, and fuselage of an aircraft. The research involved several variants of nacelles with long and short channels. The result of modeling a flow around was the calculation of wave and induction resistance, resistance of friction and additional resistance. However, calculation was performed for a two-dimensional statement of the problem; the authors note that a given calculation procedure should be tested for a three-dimensional flow-around modeling.

An important direction in solving the task on reducing the drag of a nacelle is the research tackling the optimization of nacelle location with respect to the fuselage, wing, and pylon [6, 7]. Results from optimizing the shape and location of a nacelle are reported in paper [6]. The objective function of optimization was to reduce drag. Work [7] emphasized decreasing an acoustic radiation. However, the studies described in [6, 7] were performed using a numerical experiment method.

It is necessary to separately note those studies that dealt with the development of nacelles with a minimum aerodynamic drag for the next generation engines with a high bypass ratio [8–10]. Paper [8] proposes a design of the engine's nacelle with a large bypass ratio, which makes it possible to reduce the aerodynamic drag of a nacelle by reducing the input part of the nacelle. The authors designed a special structure of the nacelle's internal part to ensure lower input turbulence at the input. Article [9] addresses the optimization of nacelles' shape for engines with ultra bypass ratio. The result of optimization could lead to a decrease in the aerodynamic resistance of a nacelle. Paper [10] tackles the task of designing and optimizing a nacelle for a turbojet double-pass engine (TJDE) with a high bypass ratio. The design methodology is based on the numerical solution to the system of Reynolds equations. The objective function of an engine's nacelle optimization is the loss of effective thrust. As a result of the optimization, the effective thrust increased by 1.5 %. The authors showed that a powerplant changes the pressure distribution at the surface of an aircraft. This leads to a substantial reduction of the aerodynamic drag coefficient.

It is worth noting that engines with a large bypass ratio are highly efficient. However, the design of such engines is characterized by the presence of a fan with a large diameter, which entails a significant increase in nacelle diameter. This, in turn, leads to the growth of aerodynamic drag of the nacelle and the airplane.

A new solution is to use, in a powerplant, a gas turbine engine (GTE) with a turbofan unit (TFU) and a stepped nacelle. Structurally, this type of engine consists of a gas generator (single-circuit or double-pass with a low bypass ratio) and a TFU located behind a gas generator [11]. The effectiveness of GTE with TFU is comparable to the effectiveness of TJDE with an ultra bypass ratio. The presence of a gas generator module and the module of TFU led to the construction of a stepped nacelle: a gas generator module is placed in the nacelle of the gas generator, and the TFU module – in the turbofan's nacelle. Arranging a TFU in a separate nacelle behind a gas generator module makes it possible to reduce the total area of wetted surface of the nacelle, which enables a decrease in aerodynamic drag in comparison to engines with an ultra bypass ratio.

A new approach to resolving the task on improving the thrust and economic characteristics of a GTE is the concept of integrating a multi-pass engine with a turbofan unit and a stepped nacelle. However, up to now, the issue of estimating the aerodynamic drag of nacelles for GTE with TFU has remained insufficiently studied. Thus, it is a promising task to estimate the aerodynamic characteristics of a stepped nacelle for GTE with TFU.

3. The aim and objectives of the study

The aim of this study is to estimate the aerodynamic characteristics of a stepped nacelle for GTE with TFU. That would make it possible to perform a comparative assessment of the aerodynamic drag and lift force coefficients of the cylindrical nacelle for TJDE and a stepped nacelle for GTE with TFU.

To accomplish the aim, the following tasks have been set:

– to conduct a modeling experiment in order to determine the aerodynamic drag and lift force of the stepped nacelle and TJDE nacelle with the front arrangement of the fan;

– to perform a comparative assessment of the aerodynamic resistance and lift force coefficients of the stepped nacelle and TJDE nacelle with the frontal arrangement of the fan.

4. Method for studying the characteristics of a stepped nacelle

We used a method of model physical experiment in the course of research.

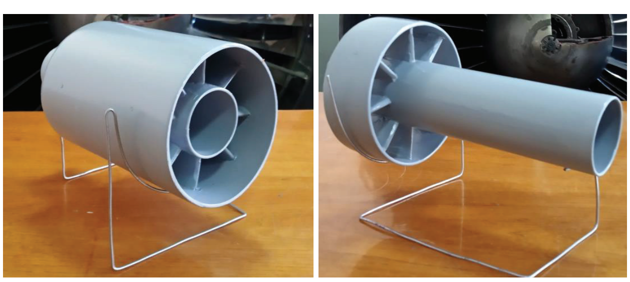
Methods of experimental research in wind tunnels are based on measuring forces, pressures at different flow rates. In terms of the principal diagram, wind tunnels are the channels in which an artificial air flow is created with a fan. At present, model experimental research has become widespread, and wind tunnels have become the basic set-up for such studies.

The wind tunnel used in our study was provided with the necessary equipment, which includes various nozzles of static and dynamic pressure with coordinate devices, etc. The installation makes it possible to determine the distributed and total aerodynamic characteristics of the models of aircrafts and their elements. The aerodynamic installation consists of a lemniscate input confuser, a honeycomb, a working part, a fan, an electric motor, a diffuser, aerodynamic scales, a measurement and registration system.

The lemniscate confuser section of a narrowing pipe in front of the working part is required to form a flow in the working part. The wind tunnel's fan is driven into motion by a DC motor. The honeycomb and nets are installed in the wind tunnel chambers in front of the manifold to align the flow and split large vortices into small ones. Diffuser, a section of the pipe behind an expanding working part, is designed to reduce speed and increase pressure in front of the fan. The length of the working part is 1.2 m. Aerodynamic scales are two-component.

The wind tunnel and measuring system are certified and ensure the accuracy of measured parameters of 0.5...1 %.

For our experimental study we fabricated models of nacelles for an aircraft powerplant with the front arrangement of a fan module and the rear location of TFU. The material of the models is polystyrene. Mounting components of the model on the holder of the aerodynamic scales are installed in the lower part of the nacelle in the region of possible position of the center of mass. Fig. 1 shows nacelle models for conducting an experimental study.



a *b*

Fig. 1. Nacelle models for conducting experimental study: *a* – model of TJDE nacelle; *b* – model of stepped nacelle for GTE with TFU

Diagrams and basic geometric parameters of the examined models of nacelles for aircraft powerplants are shown in Fig. 2.

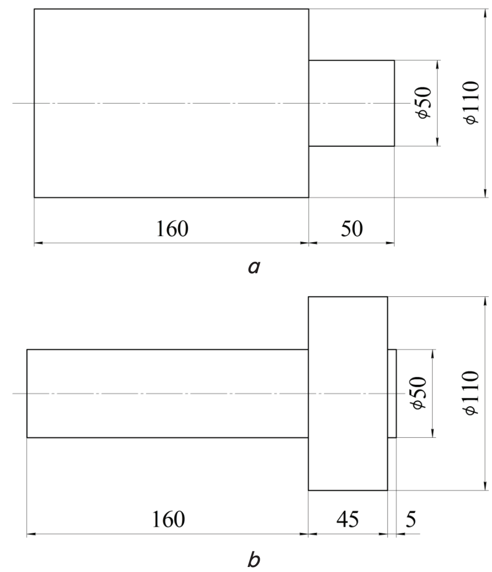


Fig. 2. Diagrams and basic geometrical parameters of nacelles for powerplants: *a* – TJDE nacelle; *b* – stepped nacelle for GTE with TFU

When conducting a study, the characteristics of the stepped nacelle were compared to the nacelle for a turbojet double-pass engine with the front arrangement of the fan.

The program of the experiment implied determining, for nacelle models, the thrust force, the force of aerodynamic drag, and dimensionless coefficients of the thrust force and drag force. The obtained results were reduced to the field conditions, which made it possible to derive the dependences of aerodynamic drag coefficient on the angle of attack $C_x=f(\alpha)$, and a lift force factor on the angle of attack $C_y=f(\alpha)$.

During the experiment, the angle of attack α varied in the range from 0° to 20°. The experiment was repeated six times, readings from the aerodynamic scales were processed on a computer thereby yielding the estimated aerodynamic parameters.

The study was carried out in the wind tunnel at the flow rate in the working part of $V=20$ m/s. This speed is matched with the Re number of $2.77\cdot10^5$, calculated based on the characteristic size – lengthening the nacelle model $l_0=205$ mm.

After each series of experiments, we accounted for adjustments and errors in measurements with the test results being reduced to the field flight conditions.

In determining the model's drag coefficient C_x, we calculated the adjustments to take into consideration the part of the wind tunnel occupied by the model (ε_m) and the accompanying jet (ε_{jet}). The specified corrections to the model within the closed round working part of the tunnel were determined from formulae:

$$\varepsilon_m = 1.356\lambda\left(\frac{c}{d}\right)^2, \quad (1)$$

$$\varepsilon_{jet} = 0.321\frac{l_0}{d}C_x, \quad (2)$$

where λ is a coefficient that depends on the geometry of a nacelle; d is the diameter of the tunnel's working part; c is the model's wall thickness; l_0 is the nacelle length; C_x is the model's drag coefficient.

5. Results of studying the characteristics of a stepped nacelle

5. 1. Aerodynamic drag and lift force of the stepped nacelle and the TJDE nacelle with the frontal arrangement of the fan

In accordance with the set goal of the study, we carried out tests in the wind tunnel for two types of nacelles: a cylindrical nacelle for TJDE and a stepped nacelle for the engine with TFU. The result of the experiments performed is the acquired data that made it possible to build the dependence of lift force *Y* on the angle of attack α and aerodynamic drag force *X* on the angle of attack α. Fig. 3, 4 show the resulting dependences.

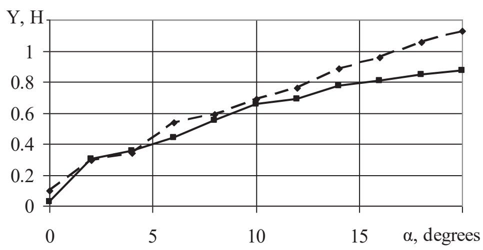


Fig. 3. Dependence of lift force *Y* on angle of attack α: – – – – – – TJDE nacelle; ———— – stepped nacelle for engine with TFU

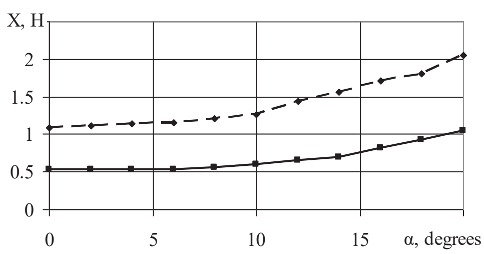


Fig. 4. Dependence of aerodynamic drag force *X* on angle of attack α: – – – – – – TJDE nacelle; ———— – stepped nacelle for engine with TFU

Analysis of results from the model physical experiment allows us to assert that the aerodynamic drag of a stepped nacelle is less than that of a cylindrical nacelle.

5. 2. Calculation of aerodynamic drag coefficients and lift force coefficients for a stepped nacelle and a cylindrical nacelle

The data obtained have made it possible to determine the dimensionless coefficient of lift force C_y and aerodynamic drag coefficient C_x. To this end, we used the following formulae [12]:

$$Y = C_y \frac{\rho V^2}{2} S, \quad (3)$$

$$X = C_x \frac{\rho V^2}{2} S, \quad (4)$$

where ρ is the air density; *V* is the speed of air flow; *S* is the wetted area of a nacelle.

Upon transformations, we obtain formulae to determine the dimensionless coefficients:

$$C_y = 2\frac{Y}{\rho V^2 S}, \quad (5)$$

$$C_x = 2\frac{X}{\rho V^2 S}. \quad (6)$$

Fig. 5, 6 shows the obtained dependences of lift force coefficient C_y and aerodynamic drag coefficient C_x on angle of attack α.

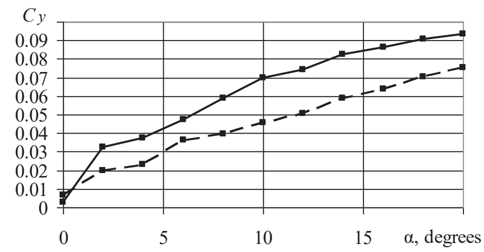


Fig. 5. Dependence of lift force coefficient C_y on angle of attack α: – – – – – – TJDE nacelle; ———— – stepped nacelle for engine with TFU

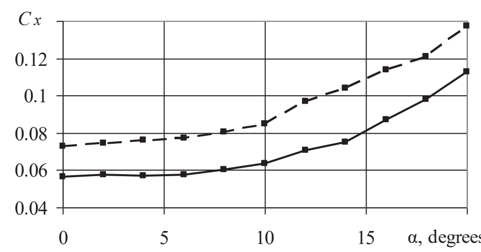


Fig. 6. Dependence of aerodynamic drag coefficient C_x on angle of attack α: – – – – – – TJDE nacelle; ———— – stepped nacelle for engine with TFU

Thus, our physical experiment has made it possible to derive the aerodynamic characteristics for the examined nacelles. Analysis of the data obtained would allow us to estimate the aerodynamic characteristics of a stepped nacelle.

6. Discussion of results from studying the aerodynamic characteristics of a stepped nacelle

The results of our studies have shown that using a stepped nacelle reduces aerodynamic drag and improves the nacelle's lift force coefficient. This is because the location of the fan module behind a gas generator decreases the total wetted area of a nacelle.

No influence of the aircraft's pylon, fuselage, and wing was considered within the framework of a given study.

Let us conduct a detailed comparison of the aerodynamic characteristics of the examined nacelles. In the range of angles of attack α=0...20° the value of aerodynamic drag force *X* of the stepped nacelle for GTE with TFU is 49...55 % lower than that of the nacelle for TJDE (Fig. 4). However, in this case, the value of the lift force of the stepped nacelle decreases by 3...22.6 % at the angles of attack α=0...20° (Fig. 3). To generalize, that would not significantly affect the total lift force generated by an aircraft, given that the main element that creates lifting force is the wing. In addition, it is important that the lift force coefficient of the stepped nacelle grows by 24...64 %, an exception being a zero angle of attack (Fig. 5). It should also be noted that the increase in nacelle lift force depends on the ratio of surface areas of the module of a gas generator and a turbofan unit – this should be addressed in the further research.

The obtained results indicate the prospects of using engines with a turbofan unit. The structural feature of a stepped nacelle would reduce the loss of efficient engine thrust by lowering the aerodynamic drag by almost two times and could improve engine fuel efficiency.

7. Conclusions

1. We have conducted an experimental study into the aerodynamic characteristics of the stepped nacelle for a turbine engine with a turbofan unit. The results of our study showed the possibility of decreasing the aerodynamic drag of a stepped nacelle for an engine with a turbofan unit compared to the nacelle for a turbojet double-pass engine with the frontal fan arrangement. In the range of angles of attack α=0...20° the value of aerodynamic drag of the stepped nacelle for a gas turbine engine with a turbofan unit decreases by 49...55 %.

2. The obtained results have demonstrated that the lift force coefficient of the stepped nacelle for a gas turbine engine with a turbofan unit increases by 24...64 %. Coefficient of aerodynamic drag is lower by 18...28 % compared with the aerodynamic drag coefficient of the cylindrical nacelle for a double-pass turbojet engine in the range of angles of attack α=2...20°.

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