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DETERMINING PATTERNS IN THE INFLUENCE OF THE NUMBER OF BLADES IN THE DUCTED AND UNDUCTED PROPFANS ON PROPFAN THRUST

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The efficiency of an aircraft engine is estimated by many parameters, one of which is the thrust force. Improving the efficiency of aircraft engines is an important task for engine building. However, questions remain regarding the effect of the number of blades on the change in the thrust of the ducted and unducted fans. In this work, the object of study is a propfan. 3 variants of the propfan with 8, 10, and 12 blades were investigated. The study was conducted by the method of numerical experiment. The aim of the work was to compile recommendations for choosing the number of blades in the ducted and unducted fans for motors with an ultra-high bypass ratio. That could make it possible to improve the efficiency of an aircraft engine with a propfan. Studies have shown that the number of blades in a propfan significantly affects the thrust force that it creates, as well as efficiency. With an increase in the blades of the ducted fan from 8 to 12, the thrust force increases to 38 %. With an increase in the blades of the propfan from 8 to 12, the thrust force increases to 36.9 %. An increase in the blades from 8 to 12 in the ducted fan leads to an increase in its performance, thereby improving efficiency by 2.4–5.7 %. When flowing around a propfan, it is possible to note the peculiarity that occurs when all three variants are streamlined – vortex traces of the blades in the peripheral parts. Visualization of current lines when flowing around an unducted fan with 8, 10, and 12 blades demonstrates a similar flow character. On the periphery, there are zones of higher speed but there are no zones with eddy formations. The resulting regularities of the influence of the number of blades on a change in the thrust of the ducted and unducted fans could improve the efficiency of the aviation power plant with an engine whose bypass ratio is ultra-high

Keywords: number of blades, ducted fan, propfan blade, propfan thrust, efficiency, propfan, flow modeling, aircraft engine

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1. Introduction

In the modern air transportation market, highly economical and highly efficient aircraft engines have a competitive advantage. Efficiency is estimated by specific fuel consumption. The efficiency of an aircraft engine is estimated by many parameters, one of which is the thrust force.

In order to ensure high efficiency and performance, world developers are constantly improving aircraft engines. The main trend of these improvements is to increase the bypass ratio in two-circuit turbojet engines, as well as optimize fan parameters. For regional transportation, turboprop or turboprop fan engines remain the most economical. One of the important and unresolved issues in these motors is the optimization of propellers or propeller fans. The tasks to reduce acoustic radiation, increase the efficiency and performance of turboprop or turboprop fan engines are still relevant.

2. Literature review and problem statement

Turboprop engines are highly economical, but the main issue related to turboprop engines is the high noise level [1]. The main source of noise is the propeller or propeller fan. A promising type of engine is a subclass of turboprop engines – the Open Rotor engine.

Paper [2] applied an interdisciplinary analysis to demonstrate that the concept of Open Rotor can have significant fuel saving potential. The Open Rotor engine is compared to a dual-circuit engine with a high bypass ratio at a given set of structural solutions and customer requirements. However, the authors note that with the existing fuel economy of 15 %, there are big risks associated with the launch of a new engine on the market.

With higher fuel efficiency than turboprop engines, the Open Rotor engine also has the problem of high acoustic radiation. The source of tonal and broadband noise is a coaxial propfan [3]. The issue of noise from coaxial propellers for Open Rotor motors was investigated by the authors of work [4]. The authors established the influence of airframe geometry on the tonal composition, directionality, and levels of broadband noise in a coaxial rotating propfan at radiation angles from 30 to 150 degrees. Depending on the angle of radiation (no more than 10 to 25 dB at the frequencies of the blades), both a significant increase and a decrease in noise was detected in relation to the basic configuration of the airframe in both the tonal and broadband levels. Although tonal level changes in general are greater than broadband level changes, broadband levels have been shown to be significant when considering the effect of airframe geometry on noise emission from a coaxial rotating propfan. However, the authors conclude that there is a problem when designing an airframe with the advantages of shielding for Open Rotor noise. The problem is related to the difference in directionality for different tones of discrete and broadband acoustic radiation.

Partially, noise reduction can be achieved through the use of a duct for propellers (propfans). The duct will make it possible to install sound-absorbing structures that are tuned to the required frequencies of acoustic radiation from the propeller (propfan).

In addition to the issue related to reducing noise for this type of engine, researchers are engaged in solving equally important problems such as flutter and optimization of aerodynamic characteristics. Work [5] reports an aeroelastic analysis of single-row and two-row propfans. The authors have devised a special procedure for modeling the flow in propfans. The study aims to evaluate the flutter during the design of propeller fans. However, the results for open rotors rotating in the opposite direction cannot be confirmed due to the lack of relevant data from the open literature.

The aerodynamic characteristics and thrust of the propeller and propfan are influenced by a lot of parameters, such as geometric dimensions, relative diameter of the bushing, an angle of installation of the blades, blade shape, the number of blades, angles of installation of airfoils, and much more. Also, in order to improve the acoustic and thrust characteristics, ducted propellers and propfans are used. In [6], the authors investigate the influence of such a parameter as the relative diameter of the ducted fan on the increase in specific power. It is concluded that the minimum value of the relative diameter of the fan is better at maintaining the balance of power and cooling. However, the paper does not compare the results of calculations of the specific power of the ducted fan with a propfan.

Work [7] considers the influence of the shape of the propfan blade on aerodynamic and acoustic characteristics. It is shown that optimizing the shape of the peripheral part of the blade makes it possible to reduce vortex flow, which reduces noise. It should be noted that the authors of work [7] did not consider the effect of the duct on the aerodynamic characteristics of the propfan.

Another important parameter is the angle of blade installation. In [8], the authors reported the results of the impact of the angle of installation of blades of the ducted propeller with active control over the boundary layer on the jet thrust and efficiency. In [9], a method of increasing the thrust force by actively controlling the boundary layer by blowing air is considered. The authors compare the characteristics of unducted and ducted propeller with the control over the boundary layer. It is shown that the use of boundary layer control makes it possible to increase the reactive thrust force.

The effectiveness of ducted fans and propfans is also confirmed by the fact that they have been widely used for aircraft vertical take-off and landing. In [10], a distributed propulsion system used in vertical take-off and landing of aircraft was investigated. A new distributed ducted fan system was proposed, eliminating the structural power gap and adjusting the narrowing and expansion of the trace through the deflecting wing. A multi-criteria method for designing a distributed ducted fan system is also proposed. The implementation of the design method by designing the inlet and outlet holes of the channel and the inductive wing was tested in the work. The design results show that the change in the performance of a distributed system of ducted fans is mainly due to a change in the inlet. By increasing the length and height of the inlet device, it was possible to reduce the separation of the flow and increase the thrust in the duct when flying on an air cushion, but the cruising drag increases. However, the increase in the size of the inlet device led to a shift in the working point of the blade crown during hovering and cruising flight, which complicated the multipurpose design.

In [11], the interference of the ducted fan with the wing was investigated in order to assess the possibility of increasing the efficiency of an aircraft with a distributed power plant in a hovering mode and cruising flight. A new approach to the conceptual design of the aircraft vertically take-off has been developed. An important step in the study is the calculation of the aerodynamic and thrust characteristics of the ducted fan on the vertical meridional plane and considering it as a lifting and propulsion element. That is, the process of conceptual design of an aircraft with a distributed power can be significantly simplified. In addition, the resulting design of the aircraft demonstrates high efficiency both under hovering and cruising modes of flight. In the process of optimizing the fan and duct in various flight conditions, the main focus is on optimizing the fan blades, to ensure efficiency during hovering. A multi-level workflow for optimizing the blade profile has been created, including Betz's theory of optimal circulation for initial blade design, band theory for rapid analysis of blade performance, and global and local optimization. The authors have achieved a significant improvement in sensitivity to the shape of the cross-section of the duct wall, which is necessary to create an integral structure of the ducted fan. A full-scale experiment with an optimized ducted fan demonstrates the effectiveness and accuracy of optimization results. It should be noted that the authors in the study did not investigate the effect of the number of blades on the change in thrust force.

Choosing a rational (optimal) number of blades for a propfan, propeller, fan, or compressor is an important factor that determines the efficiency of the blade machine, determines the thrust of the propeller/propfan or the aerodynamic load of the fan/compressor. Also, this parameter will affect the efficiency of the blade machine.

Work [12] reports a study into the optimal ratio of the number of blades and the length of the chord (lattice step) and the curvature of the profile of the compressor grille in order to improve aerodynamic characteristics.

In [13], the influence of changes in various factors, including the number of blades, on changes in the aerodynamic characteristics of the fan was studied. Studies have shown that the number of blades has an effect on the aerodynamic characteristics of the fan.

To increase the thrust of the propeller, it is necessary to increase the diameter of the propeller, increase the number of blades, and increase the chord of the blade. However, increasing the diameter of the propeller has a greater impact on increasing the required power to drive the propeller. For propellers, there are restrictions on the number of blades; for metal blades – up to 5, for composite ones – up to 8 blades [14].

The results of the study into the effect of the number of blades for a birotational unducted rotor are given in [15]. The studies were carried out using a numerical experiment; the Navier-Stokes equations were closed by the SST turbulent viscosity model. It is shown that the number of blades of the first and second row and the length of the chord affect the aerodynamic load of the propeller. However, the working process and flow characteristics of the two-row birotative propfans are significantly different from a single-row propfan.

In [16], the authors investigate the influence of the number of blades (the relative pitch of the lattice of the blades) on the characteristics of the ducted propeller with active control over the boundary layer. The peripheral radius of the studied ducted propeller is 301.625 mm. However, it should be noted that the use of active control over the boundary layer in the ducted propeller significantly complicates the design of the propeller blades (propfan).

Our literary review [1–16] showed that the problem of improving the characteristics and parameters of unducted and ducted propellers and propfans (fans) requires further research. In addition, the presence of a propeller duct or propfan makes it possible to partially solve the problem of noise reduction and improve thrust characteristics. Available research shows that the shape and number of blades affect the thrust of the ducted propeller. The propfan, unlike the propeller, has a larger number of blades. The propeller usually has 2–5 blades, the propfan has 6–19. The research results reported in works [12–16] showed that the number of blades affects the aerodynamic characteristics and aerodynamic load (thrust) of blade machines (propeller, propfan, fan, compressor). However, questions remain regarding the identification of patterns of influence of the number of blades on the change in the thrust of the ducted and unducted propeller fan.

3. The aim and objectives of the study

The purpose of this work is to determine the patterns of influence of the number of blades of the ducted and unducted propeller fan on the thrust force of the propeller fan for engines with an ultra-high bypass ratio. This will make it possible to improve the efficiency of an aircraft engine with a propfan.

To achieve the set aim, the following tasks have been solved:

– to estimate the effect of the number of blades from 8 to 12 in the ducted and unducted propeller fan on the thrust force of the propfan. To assess the effect of the number of blades from 8 to 12 in the ducted fan on the efficiency of the propeller fan;

– to assess the nature of the flow of the ducted and unducted propeller fan, with a propfan diameter of 2,924 m and the number of blades of 8, 10, 12.

4. The study materials and methods

The object of research is a propfan. Three variants of the propfan with 8, 10, and 12 blades were investigated. The geometrical parameters of the blades did not change. The diameter of the sleeve was 0.6 m; the end diameter of the propfan, 2.924 m.

Studies were conducted for the following modes of operation. The rotational speed of the propfan was 1650 rpm. Flight altitude, 11 km. The range of Mach numbers at the input ranged from 0.54 to 0.8. For the study, the height corresponding to the cruising mode of operation was chosen; under this mode, the engine runs more than 40 % of the time. The range of Mach numbers chosen for the study also corresponds to the characteristic Mach numbers for turboprop fan (turboprop) engines.

The following hypothesis is put forward in the work – an increase in the number of blades in the propfan will increase the thrust force of the propfan and improve the efficiency of the motor by increasing the efficiency of the propeller fan.

The work uses the methods of the theory of blade machines, the theory of heat engines, and the theory of propellers.

Fig. 1 shows three-dimensional models of the investigated blade crown of the propeller.

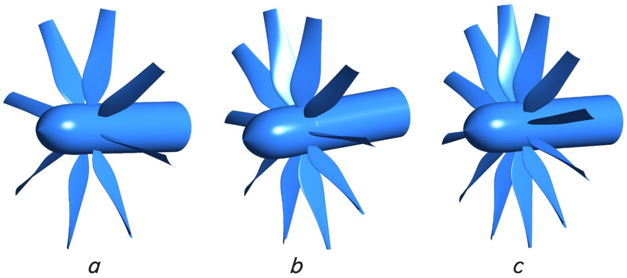

Fig. 1. Three-dimensional models of the investigated blade crown of the propeller fan: *a* — the blade crown of a propfan with 8 blades; *b* — the blade crown of a propfan with 10 blades; *c* — the blade crown of a propfan with 12 blades

According to the tasks set, the work first investigated the parameters of an unducted fan with a different number of blades, and then a ducted propeller fan with a different number of blades. To assess the impact of the duct, the thrust force for the ducted and unducted fans is compared under the same operating conditions.

The research was carried out using the method of numerical experiment in the software environment ANSYS CFX. The reliability of the results obtained using a numerical experiment was ensured by preliminary test studies to adjust the numerical experiment. The results of the test problem are reported in [17]. Flow modeling in a propfan was carried out by solving an average system of Navier-Stokes equations, which was closed by a model of turbulent viscosity. To calculate the flow in blade machines, many models of turbulent viscosity have been built, each of them has drawbacks and advantages. In practice, both linear and nonlinear turbulent viscosity models are used. The SST family of turbulent viscosity models has advantages over k-ω and k-ε turbulent viscosity models. The SST Gamma Theta Transitional model has additional equations that more correctly simulate the transition from the flow nucleus to the boundary layer. The choice of a turbulent viscosity model was carried out in [17] by comparing the results of a numerical experiment and experimental data obtained during flight tests. The discrepancy between the flight test data and the selected SST Gamma Theta Transitional turbulent viscosity model is 0.57 % for thrust calculations and 0.22 % for the coefficient of restoration of the full pressure of the input device.

To simulate the flow in a propeller fan, the Ansys Workbench software environment was used. The flow was calculated in the CFX module. All boundary conditions for flow modeling (pressure, temperature, axial velocity at the inlet, rotational speed) were set in the CFX Pre submodule. In the CFX Post submodule, with the help of built-in tools, the necessary calculated data were obtained: thrust force, total pressure, full temperature at the inlet and at the outlet of the propeller fan.

To simulate the flow, a calculated grid of an unstructured type was built in order to describe the geometric parameters of the propfan as best as possible. During the study, the influence of the boundary layer was taken into account through the use of adaptation of the calculation grid in the places of formation of the boundary layer (the surface of the blades, bushings, duct).

When calculating, the level of non-bindings was set at RMS$<10^{-5}$. Depending on the Mach number at the input, the calculation demonstrated a convergence of results upon reaching 70–200 iterations.

The following assumptions and limitations are used in the work:

– when modeling the flow, the Businesque hypothesis is used;

– in order to speed up the modeling time, the periodicity condition was used. The model under study consisted of a blade and an interblade channel. That is, the nature of the flow and the flow parameters in all interblade channels are the same;

– all blades in the blade crown are the same, although in real engines each blade has permissible deviations in geometric dimensions;

– all walls in the model are accepted adiabatic (blades, duct, sleeve);

– the air flow at the inlet was considered uniform without perturbations (at the inlet, the degree of turbulence was set, 5 %);

– calculations were carried out for the conditions of a standard atmosphere.

5. Results of determining the patterns of influence of the number of blades in the ducted and unducted propeller fan

5. 1. Effect of the number of blades in the propfan on the thrust force and propeller fan efficiency

The thrust force of the propeller blade depends on many factors. Among them are the angle of installation of the blade element, the shape of the aerodynamic airfoil, the shape of the blade, the number of blades, the diameter of the propeller, the number of blades, the speed of rotation of the propfan shaft, and others. When assessing the impact of each parameter, all other parameters must remain unchanged. The influence of the number of propfan blades on the thrust force of the ducted and unducted fans is investigated. As well as the effect of the number of blades on the efficiency of the ducted propeller fan. So, to assess one of the important factors influencing the efficiency of the propfan – the number of blades, all other parameters of the blade are unchanged.

For the study, models of an unducted and ducted propeller fan with 8 blades, 10 blades, and 12 blades were constructed.

The calculation of the flow was carried out using the Ansys Workbench software environment, the CFX module. When modeling the flow in the fan at the inlet, the parameters of the atmosphere at an altitude of 11 km were set: temperature, 56.35 °C; ambient pressure, 22699 Pa. The axial velocity was regulated by setting the value of the axial air velocity at the inlet to the propeller fan, respectively, 160, 180, 200, and 236 m/s for each variant of the fan under study. After performing the calculation using the built-in tools in the CFX Post submodule, using the «Force» function, the thrust force of the propfan was calculated. The topology of the calculatation grid and the turbulence model of the object under study did not change. Therefore, for each variant of the propfan, the calculation of flow modeling was carried out once for each value of the axial velocity at the input.

Our results of calculating the thrust force of unducted and ducted fans are shown in the plot in Fig. 2.

The resulting dependences of thrust force on the axial speed at the inlet for the unducted and ducted propfans show that an increase in the blades from 8 to 12 leads to an increase in the thrust force in both ducted and unducted propfans.

In order to assess the effectiveness of the ducted propeller fan, the dependences of efficiency on the axial speed at the inlet were also constructed (Fig. 3).

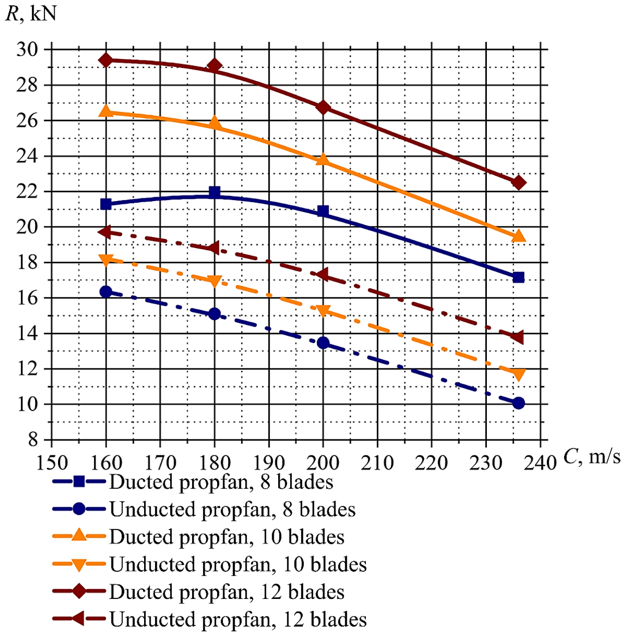

Fig. 2. Dependence of thrust force on the axial speed at the inlet for unducted and ducted propfans

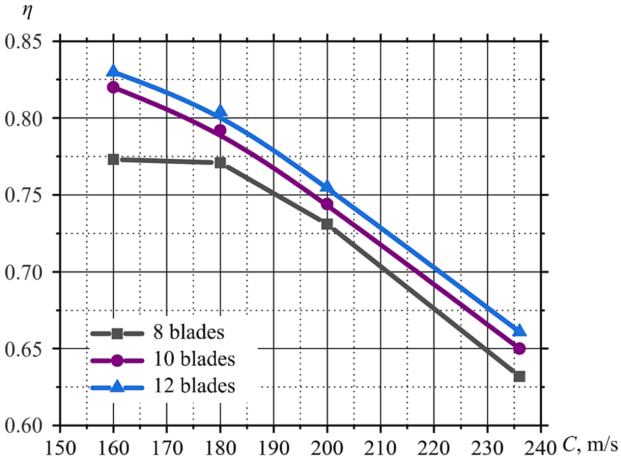

Fig. 3. The dependence of efficiency on the axial speed at the inlet for the ducted propeller fan

The efficiency of the ducted propeller fan was calculated on the basis of the data obtained in the CFX Post submodule. The tools of the CFX Post submodule were applied to calculate the total pressure and temperature at the inlet and outlet of the propeller fan. The efficiency of the propfan is calculated by the following formula [18]:

$$\eta=\frac{L_{ef}}{L_{ad}}=\frac{\frac{k}{k-1}\cdot R\cdot\left(T_{out}-T_{in}\right)}{\frac{k}{k-1}\cdot R\cdot T_{in}\cdot\left(\pi^{\frac{k-1}{k}}-1\right)}=\frac{T_{out}-T_{in}}{T_{in}\cdot\left(\pi^{\frac{k-1}{k}}-1\right)},$$

where L_{ef} – efficient operation of the propfan, L_{ad} – adiabatic operation of the propfan, k – adiabatic coefficient (for air, k=1.41), R – universal gas constant, T_{out} – inhibited temperature at the outlet of the propfan, T_{in} – ambient temperature at the inlet, π – the degree of pressure increase (the ratio of the total pressure at the outlet to the full pressure at the inlet to the propfan).

The resulting dependences of efficiency on the axial speed at the inlet for the ducted propfan show that an increase in the blades from 8 to 12 leads to an increase in the efficiency of the ducted propfan. That is, the ducted propfan with 12 blades will be more effective than the ducted propfan with 8 blades.

5. 2. Assessing the nature of the flow of the unducted and ducted propeller fan

The qualitative nature of a flow change when the number of blades changes is demonstrated by the visualization of current lines when flowing around an unducted propfan (Fig. 4) with the Mach number at the input of M=0.7.

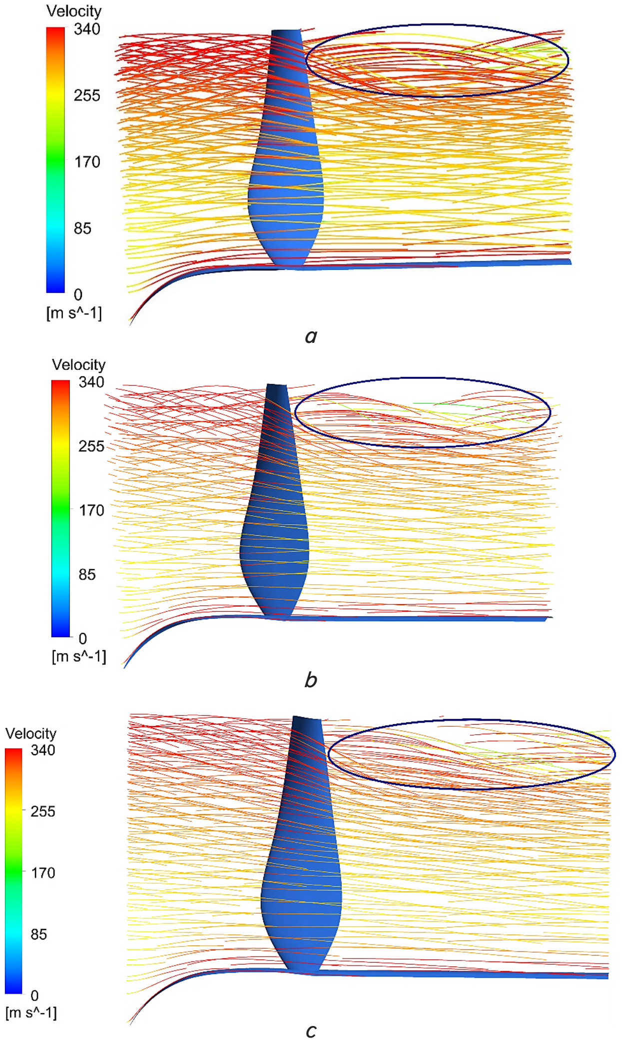

Fig. 4. Visualization of current lines in the meridional cross-section when flowing around an unducted propfan: *a* – unducted propfan with 8 blades; *b* – unducted propfan with 10 blades; *c* – unducted propfan with 12 blades

Fig. 5 shows a visualization of the flow when changing the number of blades of the ducted propeller fan with the Mach number at the inlet of M=0.7.

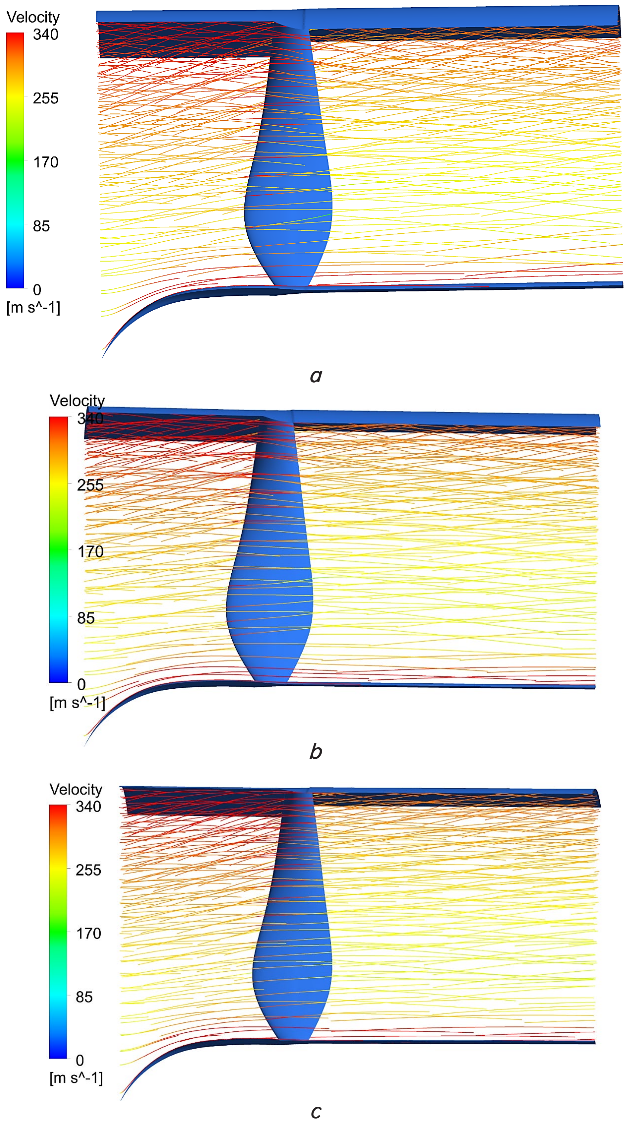

Fig. 5. Visualization of current lines in the meridional cross-section when flowing around the ducted propeller fan: *a* – a ducted propeller fan with 8 blades; *b* – a ducted propeller fan with 10 blades; *c* – a ducted propeller fan with 12 blades

Analysis of our results of flow modeling in the ducted and unducted propeller fans shows that the nature of the flow changes. In Fig. 4, ellipses highlight areas where the nature of the flow undergoes changes. The presence of a duct helps reduce vortex flow in the peripheral zone of the blade.

6. Discussion of results of determining the patterns of influence of the number of blades of the ducted and unducted propeller fan

The results of our studies into the influence of the number of blades of the ducted and unducted propeller fans on the thrust of the propfan showed that the change in the number of blades of the propfan from 8 to 12 significantly affects the thrust force that it creates: the thrust force increases by 20–38 % (Fig. 2).

Increasing the number of blades in the ducted fan from 8 to 10 makes it possible to increase the thrust force of the propfan by 13–24 % (Fig. 2). With an increase in the blades from 8 to 12, the thrust force increases by 28–38 %. The maximum increase occurs under the mode of operation at an axial speed at inlet of 160 m/s.

Increasing the number of blades in the unducted propeller fan from 8 to 10 makes it possible to increase the thrust force of the propeller fan by 11–16.7 % (Fig. 2). With an increase in the blades from 8 to 12, the thrust force increases by 20–36.9 %. In this case, the maximum increase occurs under the operating mode at an axial speed at inlet of 236 m/s, in contrast to the ducted fan.

One should also consider how the duct of the propeller fan affects the thrust. In general, Fig. 2 demonstrates a general trend towards increasing the thrust force of the propfan in the presence of a duct. For example, an unducted propfan with 12 blades creates less thrust than a ducted propeller fan with 8 blades. That is, the number of blades in the ducted fan is 30 % less than that in an unducted propfan.

A ducted propeller fan with 8 blades has a 30–70 % increase in thrust force compared to an unducted propfan with 8 blades. A ducted fan with 10 blades creates a thrust force of 45–65 % compared to an unducted propfan with 10 blades. The presence of a duct in a propfan with 12 blades provides an increase in thrust force by 49–63 % compared to an unducted propfan (Fig. 2).

It should also be noted that the greatest increase in the thrust force of the ducted propeller fan occurs at an axial speed at an inlet of 236 m/s (Fig. 2). The axial velocity at the inlet of 236 m/s for an altitude of 11 km corresponds to the Mach number of $M=0.7$.

Thus, an increase in the number of propeller blades from 8 to 12 will lead to an increase in the thrust force of the aviation power plant by more than 20 % (Fig. 2). The presence of a duct has a positive effect on increasing the thrust force of the propfan – the thrust force increases by at least 30 % (Fig. 2).

The resulting data on changes in the efficiency of the ducted propeller fan show that the number of blades affects the efficiency. Thus, with an increase in the blades from 8 to 10, the efficiency increases by 1.3–4.7 % for the considered range of Mach numbers. However, with an increase in the number of blades from 10 to 12, the increase in efficiency is no longer so significant and amounts to 1.0–1.2 %. So, with an increase in the number of blades from 8 to 12, the increase in efficiency is 2.4–5.7 %. Also, it should be noted that the greatest increase in the efficiency of the propeller fan is observed under the operating mode at an axial speed at an inlet of 160 m/s (Fig. 3).

Consequently, an increase in the blades from 8 to 12 in a ducted propeller fan with an end diameter of 2,924 m leads to an increase in the efficiency of the propeller fan (Fig. 3).

The flow of the blades of the unducted and ducted propeller fans has a complex flow character. At the same time, the cross-sections of the blades are flown around with angles of attack variable in radius of the blades and relative Mach numbers.

When flowing around an unducted propfan, one can note the peculiarity that occurs when all three variants are flown around – vortex traces behind the blades in the peripheral part (Fig. 4). This causes an uneven flow behind the propfan in the radial and circular direction (in Fig. 4, the characteristic zones are highlighted by an ellipse). If the engine is placed behind such a propeller fan, then the distance between the propfan and the engine should be significant enough to be able to equalize the flow of air that will be supplied to the inlet to the engine as much as possible. Increasing the distance between the propfan and the engine will lead to an increase in the size of the aircraft and an increase in weight, which will negatively affect its efficiency.

Visualization of current lines when flowing around a ducted propeller fan for all the studied variants with 8, 10, and 12 blades has a similar flow pattern (Fig. 4). On the periphery, there are zones of high speed, but there are no zones with eddy formation. It should also be noted that the uneven flow behind the ducted propeller fan is much lower, so the distance between the propeller fan and the inlet device of the power plant can be reduced, unlike the power plant with an unducted propeller fan. Reducing the distance will have a positive impact on the weight and efficiency of the engine.

In contrast to the results reported in [16], our paper shows that an increase in the number of blades significantly affects the increase in thrust force, even without the use of active control over the boundary layer.

The following limitations were adopted in the study: the range of change in the number of propeller blades varied from 8 to 12, and we did not assess the efficiency of the propeller fan and the drag of the duct.

The area of further research is the quantitative assessment of the effect of the duct on the acoustic characteristics of the propfan in the near field. Also, it is planned to investigate the qualitative nature of the flow in the ducted propeller fan when modeling the flow using RSM turbulent viscosity models.

7. Conclusions

1. Our studies have shown that for a propeller fan with a propfan diameter of 2,924 m and a blade number of 8, 10, 12 blades, the number of propfan blades significantly affects the thrust force it creates, as well as efficiency. In particular, an increase in the number of blades in a ducted propeller fan from 8 to 10 makes it possible to increase the thrust force of the propfan by 13–24 %. With an increase in the blades from 8 to 12, the thrust force increases by 28–38 %.

Increasing the number of blades in the unducted propfan from 8 to 10 makes it possible to increase the thrust force of the propfan by 11–16.7 %. With an increase in the blades from 8 to 12, the thrust force increases by 20–36.9 %.

The increase in the efficiency of the ducted propeller fan with an increase in the number of blades from 8 to 12 is 2.4–5.7 %.

Increasing the blades from 8 to 12 in a ducted propeller fan with a final diameter of 2,924 m leads to an increase in the efficiency of the propeller fan.

2. The qualitative nature of a flow change when the number of blades changes is demonstrated by the visualization of current lines when the unducted and ducted propeller fan is flown around. When flowing around an unducted propfan, it is possible to note the peculiarity that occurs when all three variants are flown around – vortex

traces behind the blades in the peripheral parts. Visualization of current lines when flowing around a ducted propeller fan for all the studied options with 8, 10, and 12 blades has a similar flow character. On the periphery, there are zones of higher speed but there are no zones with eddy formations.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

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