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DESIGN OF THE PARAMETRIC APPEARANCE OF THE POWER PLANT FOR MODIFICATIONS OF THE REGIONAL PASSENGER AIRCRAFT AN-158

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The object of research is the process of remotorization of a regional passenger aircraft to increase its fuel efficiency. Based on the conceptual requirements for the remotorization of the An-158 aircraft with turbojet bypass engines, a parametric appearance of three modifications of this aircraft with turboprop engines for 80, 100, and 120 passenger seats was formed. The study was carried out on the basis of the well-known modular software systems «Integration 2.1» and «Air propeller 2.2» for typical flight profiles of the An-158 aircraft. Improved procedures of weight design and determination of the takeoff characteristics of aircraft with different types of power plant engines have made it possible to identify the most advantageous flight speeds of aircraft modifications with a turboprop engine corresponding to different flight masses. The results of the study of flight performance for optimal and «non-optimal» modifications of the aircraft are reported. The parametric appearance of the propeller was formed, the shape of the propeller blade for the cruising flight mode was determined for modifying the aircraft with a maximum number of passengers – 120 people. It is shown that the propeller for this modification of the aircraft cannot have less than 8 blades since with a smaller number of blades, the maximum chord of the propeller blade increases. The inductive power costs increase significantly due to the small elongation of the blades and, as a result, the flight efficiency of the propeller decreases. It is shown that the total fuel consumption for the entire typical flight of all modifications of the aircraft with turboprop engine at all studied flight speeds is less than the total fuel consumption of the An-158 base aircraft

Keywords: remotorization, turboprop engine, single-row propeller, takeoff and landing characteristics, kilometer fuel consumption

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1. Introduction

The improvement of the flight performance and economic characteristics of regional aircraft is achieved by improving their aerodynamic and weight characteristics, as well as the operational characteristics of the power plant (PP). The traditional method of improving the fuel efficiency of aircraft is to remotorize existing aircraft with engines of the same type as the base engines. Examples of such successful remotorization are the B-52 strategic bomber under the CERP (Commercial Engine Replacement Program), the A320neo narrow-body aircraft, the An-32 and An-132 light military transport aircraft, and many others. Aircraft remotorization also improves the cost efficiency, environmental performance, and overall performance of the aircraft. Replacing a bypass turbojet engine (BTJE) with a turboprop engine (TPE) is not always possible, as a change in the design of the aircraft and its systems is required to ensure the integration of the new engine. There are also changes in takeoff and landing characteristics, the weight and size of the aircraft, and its performance. Replacing BTJE with TPE, increasing the degree of electrification (hybridization) of an aircraft is a complex and expensive process. This process may require significant investment and time for implementation, which means that advanced research aimed at improving the fuel efficiency of aircraft during such remotorization is relevant. Therefore, studies on new technical solutions that improve the economic efficiency and environmental performance of the aircraft are relevant.

2. Literature review and problem statement

On the basis of earlier studies on the development of aviation technology, it has been established that the development of regional aircraft with TPE, with the number of passengers less than 20 people, is not advisable. It is shown in [1] that the development of «large» TPEs will have no future if the electrical component in the design and operation of engines is not developed.

In [2], an economic and energy analysis of a turboprop engine was carried out, which was performed using an integrated economic methodology to determine the sources of real costs. However, the authors note that quantifying these capabilities and drawbacks does not provide a deeper understanding for designers and developers. An option to overcome the corresponding difficulties may be a detailed study in the energy and economic field of turboprop engines.

In [3], the authors showed the need to study new aircraft design and layout schemes based on «non-classical» aerodynamic schemes (a flying wing with TPE, a tiltrotor). The authors established the need to develop a scientific and technical direction for hybrid power plants (HPP), which would include electric motors of various capacities. It is shown that it is necessary to investigate the advantages of integrating new and known schemes of aircraft and hybrid power plants based on the calculation of their performance characteristics of hybrid TPEs.

In [4], an advantageous way to improve the technical and economic characteristics of aircraft is to modify existing aircraft using advanced technologies. At the same time, issues related to the main reasons for the modification of transport category aircraft remained unresolved. The reason for this may be the objective difficulties of the need for a systematic increase in the productivity of the aircraft fleet in the period between the appearance of their basic versions.

Work [5] presents a significantly shorter creation time and lower cost of developing modifications, as well as ensuring the expansion of the scope of this aircraft. As a rule, developers modify famous aircraft using a power plant with a lower specific fuel consumption. At the same time, the goal is the same – to reduce costs at the operational stage.

It is shown in [6] that a characteristic feature of modification changes in aircraft of the transport category is the lengthening of the fuselage and the replacement of the power plant. Since modifications are more efficient in terms of cost effectiveness on each of the specific airlines, more modifications are operated by operating airlines than base aircraft.

It is this approach that was used in [7]; however, the creation of modifications of aircraft of the transport category has become widespread both in the world aircraft industry, while, however, the remotorization of BTJE with TPE, as well as the theory of non-optimal modification of passenger aircraft, is not fully substantiated. A variant of overcoming the corresponding difficulties is proposed, which consists in increasing the degree of electrification of passenger aircraft up to replacing the traditional power plant with electric one. This option requires the development of a specific scientific and methodological apparatus and new integrative circuits of the aircraft with the propellers of its power plant. All this gives grounds to assert that it is advisable to conduct a study on the creation and modification of passenger aircraft, especially promising aircraft with deep integration of propellers and airframe. In this case, it is necessary to take into account all the factors that affect the design of propellers in order to take into account the significant positive effect of propeller operation on the takeoff and landing characteristics of a remotorized aircraft.

Work [8] considered issues related to the methodology for the preliminary design of a hybrid regional aircraft with a fuel cell hybrid power plant. The main contribution of the proposed methodology is to provide a mathematical tool that takes into account the interaction between the choice of components in terms of installed capacity and energy management. In this way, it is possible to facilitate the assessment of the influence of various sizing criteria and technological features at the aircraft level on the on-board electrical system. The proposed combination of advanced sizing and energy management strategies has been able to meet the mass and volume constraints of current fuel cell and lithium ion battery performance. Such a solution corresponds to a high degree of hybridization between the fuel cell system and the battery pack. At the same time, the question of the parametric appearance of a hybrid regional aircraft with a fuel cell hybrid power plant remains unresolved.

In [9], the Blended-Wing-Body (BWB) configuration, as an innovative transport concept, has become the subject of research worldwide in the field of civil transport development. The study proves that the presented optimization sets have a dominant influence on optimized BWB designs in both aerodynamic shapes and weight distribution, which must be taken into account in the design process. At the same time, the authors conclude that the recommended stability margin of a practical commercial BWB aircraft can be half that of a conventional one.

Paper [10] reviews the introduction of liquid hydrogen fuel tanks into future commercial aircraft, focusing on fuel tank design dimensions and behavior under critical load conditions. The fuel tanks are sized according to mission requirements and the geometric constraints of a typical medium-range commercial aircraft. All this gives grounds to assert that the installation of two built-in fuel tanks, which the authors propose in the forward and aft parts of the fuselage of a conventional civil airliner, significantly reduces the available payload space.

In [11], a model of a multi-blade hybrid airship is presented, the aerodynamic characteristics of which are obtained using computational fluid dynamics tools, which are then used to estimate energy requirements by analyzing flight characteristics. A hybrid power plant is proposed, which is modified in accordance with the power needs of a hybrid airship. Finally, a detailed weight distribution between hybrid and conventional hybrid airship is presented, demonstrating a significant reduction in fuel weight of 350 kg due to the hybrid propulsion system.

In [12], major hydrogen storage technologies are explored and compared based on key performance parameters that are identified as critical for the aviation sector. For this work, a regional passenger aircraft ATR72-600 was selected. The potential reduction in aircraft overall weight is also being investigated, with future improvements in energy storage technologies and fuel cell systems. It has been shown that the use of hydrogen in combination with fuel cells is likely to be a suitable solution to power electric motors with near-zero emissions, but its technical feasibility remains to be explored.

Our literature review [1–12] gives reason to assert that it is advisable to conduct a study on the creation and modification of passenger aircraft, especially promising aircraft with deep integration of propellers and airframe.

3. The aim and objectives of the study

The aim of this study is to improve the scientific and methodological apparatus for the technical justification of the remotorization of a passenger aircraft with turbojet bypass engines. The use of an improved scientific and methodological apparatus will make it possible to improve the economic efficiency and, in the future, the environmental performance of a regional passenger aircraft.

To achieve the goal of the study, it is necessary:

– to devise procedures for weight design and determination of takeoff characteristics of aircraft of this category with various types of power plant engines;

– to improve the integrated methodology for determining the characteristics of the range and duration of a flight in a typical flight of a passenger aircraft;

– to improve the procedures of design, strength, and verification calculation of single-row propellers.

4. The study materials and methods

The object of our research is the process of remotorization of a passenger aircraft.

The main hypothesis of the study assumes the possibility of improving the economic efficiency of a regional passenger aircraft by replacing the basic power plant BTJE with TPE.

The accepted assumptions and simplifications are determined by the methods used in the work. Thus, the use of semi-empirical methods involves the simplification of complex local aerodynamics. The vortex method used in the design of propellers involves postulating the position of a vortex sheet behind the propeller. The main assumption adopted in the work is the assumption of a negligibly small effect of air compressibility on the field of inductive velocities behind the propeller.

During the study, methods of mathematical modeling of the process of flow around the surface of the airframe and its elements, general scientific methods of analysis and synthesis were used. A semi-empirical method was used to obtain the main aerodynamic characteristics of the aircraft and perform the engineering and navigational calculation of the aircraft flight.

The modular software package «Integration 2.1» [13–15] was developed to conduct parametric studies of the operational characteristics of an aircraft with BTJEs at the stages of its modernization or preliminary design.

As is known, when a power plant is placed on a wing, the lift force of the «power plant-wing» system changes and depends on the type of engine [16, 17].

Much research has been done on the effect of engine jets on aircraft aerodynamics. Semi-empirical schemes of the effect of jets from propellers on the wing aerodynamics were constructed in a wide range of values of the load factor on the area swept by the propeller [18, 19]. The study of the nature of the flow around the wing in the presence of airflow by experimental and theoretical methods is of great practical importance. When blowing a wing with deflected mechanization with jets of propellers in the presence of an oncoming flow, an additional lift occurs due to the effect of supercirculation and depends on the thrust of the propellers, the efficiency of mechanization, and the relative span of the blown part of the wing.

Thus, when improving the methodology for determining the characteristics of the range and duration of a flight in a typical flight of a passenger aircraft with TPE, the following features are taken into account:

– the available thrust of the power plant is mainly created by the propeller, the ratio of the propeller thrust and the reaction of the engine jet varies according to the flight modes;

– the effect of propeller jets on the wing is manifested in the change and redistribution of the aerodynamic load along the chord and span of the wing. An increase in the velocity head in the jet leads to an increase in the bearing properties and a decrease in the aerodynamic quality. A change in the distribution of circulation along the span of the wing, the appearance in some cases of sharp changes in circulation along the lines of intersection of jets with the wing surface is accompanied by a change in inductive resistance, a change in the flow bevel behind the wing and in the area of the horizontal tail, a shift in focus along the angle of attack, as well as a change in the parameters of longitudinal stability;

– there is an improvement in the take-off and landing characteristics of aircraft due to blowing from a propeller, the take-off speed of a modification of an aircraft with TPE is reduced by 15...20 %, and the takeoff run – by 25...30 %;

– the aerodynamic characteristics of a propeller operating as part of the layout differ from the characteristics of an isolated propeller to the extent that the elements of the airframe change the flow field in the vicinity of the propeller.

Thus, in order to take into account the differences between TPE and BTJE during remotorization of the aircraft, it was necessary to obtain the exact geometry of the propeller, for which a specialized modular software package was developed and tested.

Modular software package «Air propeller 2.2» is based on sufficiently proven procedures of design, strength, and verification calculation of single-row propellers. It is intended to design and test a propeller that requires quite a certain power for its rotation and has a sufficiently high efficiency. In the developed package, the value of circulation is automatically found, which determines the power of the propeller, the law of its distribution along the blade, which affects the efficiency of the propeller. This is how the blade sections are selected so that the parameters and angle of attack of the profile would provide the necessary circulation at a given radius. The problem of finding the most advantageous circulation distribution law is considered to be solved – the distribution of circulation along the working part of the blade according to the semi-ellipse law is considered to be the best, it is possible to choose another circulation distribution law.

The improvement of known procedures of design and verification calculation of propellers consists in the introduction of a semi-empirical universal model of the airfoil along with the use of reference data. The introduction of a universal model of the airfoil allowed the designer to take into account the local Mach and Reynolds numbers when choosing the value of the blade chord. They also take into account the thickness and curvature of the profile used, the elongation of the blade, design features of the blade, affecting the position of the laminar-turbulent transition.

In order to develop a parametric design of the power plant for a regional passenger turboprop aircraft, an analysis was made of the ways to form a rational aerodynamic scheme of a propeller as part of a regional passenger turboprop aircraft. Based on the passenger aircraft of the An-158 type (Fig. 1), two basic design and layout schemes of an aircraft with TPE as part of PP are promising for research:

– PP includes two TPEs, which are placed in front of the wing (pulling propeller) symmetrically from the fuselage axis (Fig. 2);

– PP includes two TPEs and two electric motors with multidirectional rotation of propeller, which are located at the ends of the wing symmetrically from the fuselage axis (Fig. 3).

Fig. 1. Base aircraft An-158

Fig. 2. Modification of aircraft No. 1

Fig. 3. Modification of aircraft No. 2

It is known that propeller that rotate in one direction create an asymmetric distribution of circulation over the aircraft wing, cause the aircraft to unbalance in three channels when the engine operation mode changes. In aircraft modification No. 2, propeller rotate in different directions, so that the local angles of attack in the blown sections will increase, and the lift in these sections will increase, which is critical for improving the takeoff and landing characteristics of the aircraft. In this case, the asymmetry of the flow and the roll moment, the parrying of which causes an increase in resistance, will disappear, and the inductive drag will decrease due to a decrease in the intensity of the tip vortices. A decrease in inductive drag makes it possible to increase the cruising lift-to-drag ratio of the aircraft by about 2 units, which is confirmed in the wind tunnel experiment [20].

An increase in the number of propeller blades, provided that a constant thrust is maintained in the takeoff mode of the engine, will lead to a decrease in the aerodynamic load acting on the blade. Accordingly, to a decrease in the harmonic noise component from the aerodynamic load, to a shift in the frequencies of the harmonic components in the high-frequency region [21–23]. It is expedient to design the structural scheme of TPE propeller blade of a passenger aircraft based on the considerations of a multi-bladed propeller with thin saber-shaped blades. When designing saber blades, unlike conventional design, much attention must be paid to issues of strength and propeller pitch control. Accounting for the influence of saber on inductive bevels and torsional deformations when calculating the blade twist, as well as questions about the orientation of the blade sections.

The main characteristics for evaluating modifications of the base aircraft (modification No. 1) are:

- fuel efficiency of an aircraft with TPE;
- estimated range and duration of the aircraft flight;
- range of change of the diagram «cargo – range»;
- the maximum speed of the aircraft;
- takeoff and landing characteristics of the aircraft;
- mass and overall characteristics of the aircraft.

5. Technical justification for the remotorization of the passenger aircraft AN-158 with turbojet bypass engines

5. 1. Devising procedures for the weight design of aircraft with various types of power plant engines

As you know [23], the take-off weight of the aircraft is the sum of:

$$m_0 = m_{des} + m_{prop} + m_{con.eq} + m_f + m_{t.l} + m_w, \qquad (1)$$

where $m_{des}=f_1(m_0$, wing parameters) is the mass of the structure; $m_{prop}=f_2$ (m_0 parameters of the power plant) is the mass of the power plant; $m_{con.eq}=f_3$ (m_0, parameters of the control equipment and the entire aircraft) – equipment and control mass; $m_f=f_4(m_0, V, L, H, c_p, K=c_y/c_x$, flight mode) – fuel mass; $m_{t.l}$=const – given target load m_w=const – known payload and equipment.

The dependence of m_{des}, m_{prop}, $m_{con.eq}$, on m_0 is very strong and complex; the dependence of m_0 on m_t is almost linear. The result is a complex transcendental equation that cannot be solved explicitly (finitely) for m_0. To get out of this difficulty when calculating the takeoff weight, in order to reduce the influence of m_0 on m_{des}, m_{prop}, $m_{con.eq}$, m_f are divided into both parts by m_0 [14]:

$$1 = \bar{m}_{des} + \bar{m}_{prop} + \bar{m}_{con.eq} + \bar{m}_f + \frac{m_{t.l} + m_w}{m_0}. \qquad (2)$$

The relative values $\bar{m}_{des}$, $\bar{m}_{prop}$, $\bar{m}_{con.eq}$ depend less on m_0 than their absolute values; m_f does not depend on m_0.

If we accept ($\bar{m}_{des}$, $\bar{m}_{prop}$, $\bar{m}_{con.eq}$, $\bar{m}_f$)=const according to statistics (Table 1), then the takeoff weight of the aircraft in the first approximation [24]:

$$\left(m_0\right)_I = \frac{m_{t.l} + m_w}{1 - \bar{m}_{des} + \bar{m}_{prop} + \bar{m}_{con.eq} + \bar{m}_f}. \qquad (3)$$

Table 1

Relative masses of the structure, power plant, equipment and control, as well as aircraft fuel

Purpose of the aircraft		$\bar{m}_{des}$	$\bar{m}_{prop}$	$\bar{m}_{con.eq}$	$\bar{m}_f$
passenger	dedium	0.28...0.30	0.10...0.12	0.10...0.12	0.26...0.30

The procedure for calculating the aircraft mass in the second approximation $(m_0)_{II}$ is as follows. To solve equation (1), we accept some value m_0 and calculate the sum on the right at fixed values of the parameters of the units and flight characteristics. The calculation is repeated until changing the value of m_0 until m_0 on the left and the sum on the right are equal (with some allowable error). Thus, the main difference between the calculation $(m_0)_{II}$ and the calculation $(m_0)_I$ is that, in the second approximation, the dependence of the masses of the structure, power plant, equipment, and control on the takeoff mass is taken into account. As a result, it is not possible to find $(m_0)_{II}$ in an explicit (final) form (as well as in the first approximation) and it is necessary to apply the iteration method.

The dependence of the number of passengers *n* on the takeoff weight of the optimal modification obtained for parametric studies to find the minimum fuel consumption per passenger per kilometer is shown in Fig. 4.

Fig. 5–7 show the obtained dependences of kilometer fuel consumption per passenger on the flight weight of aircraft modifications with TPE for different speeds and flight altitudes. Solid lines show dependences for a flight altitude of 10970 m, dashed lines for a flight altitude of 9000 m, dash-dotted lines for a flight altitude of 8000 m.

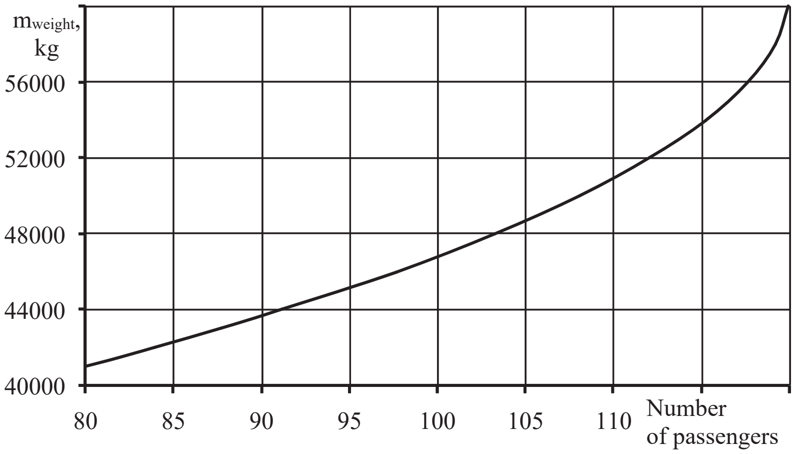


Fig. 4. Dependence of the take-off weight of modifications on the number of passengers carried

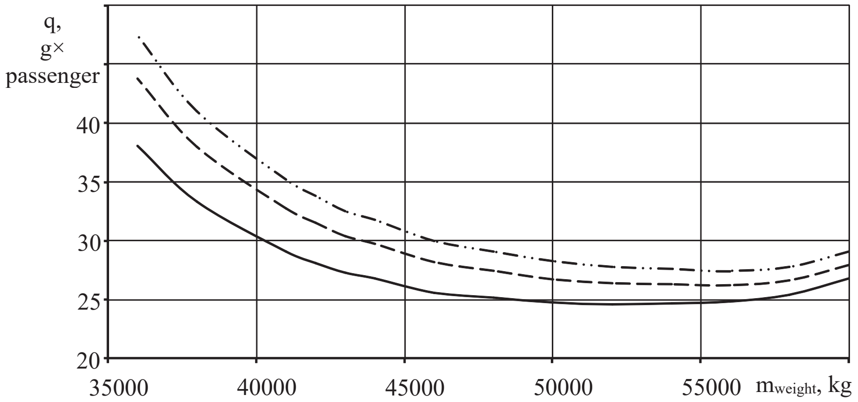


Fig. 5. Dependence of kilometer fuel consumption per passenger on the flight weight of aircraft modifications with turboprop engines for a flight speed of 780 km/h and different flight altitudes

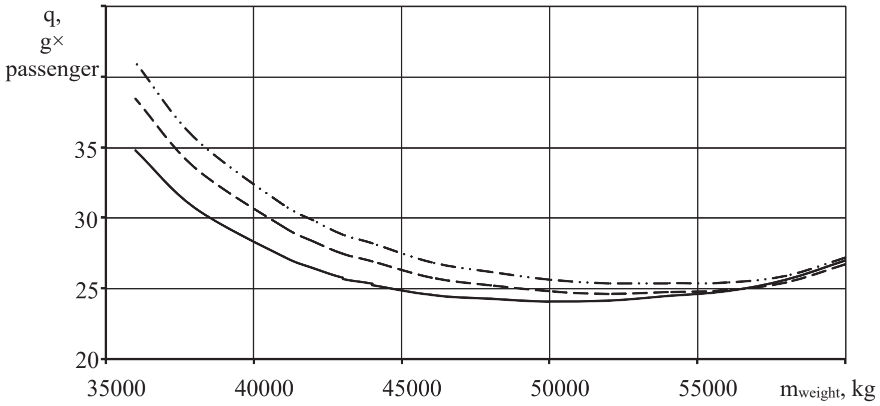


Fig. 6. Dependence of kilometer fuel consumption per passenger on the flight weight of aircraft modifications with turboprop engines for a flight speed of 700 km/h and different flight altitudes

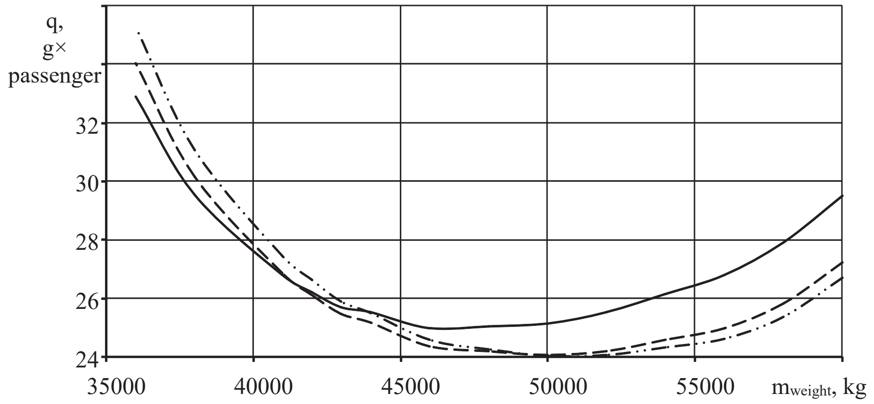


Fig. 7. Dependence of kilometer fuel consumption per passenger on the flight weight of aircraft modifications with turboprop engines for a flight speed of 600 km/h and different flight altitudes

Analysis of the above dependences allows us to conclude that there is a flat minimum of kilometer fuel consumption per passenger for flight masses of 50,000...52,000 kg.

Fig. 8–10 show similar dependences of kilometer fuel consumption per passenger on the number of passengers carried in modifications for different flight speeds and altitudes.

Solid lines show dependences for a flight altitude of 10970 m, dashed lines for a flight altitude of 9000 m, dash-dotted lines for a flight altitude of 8000 m.

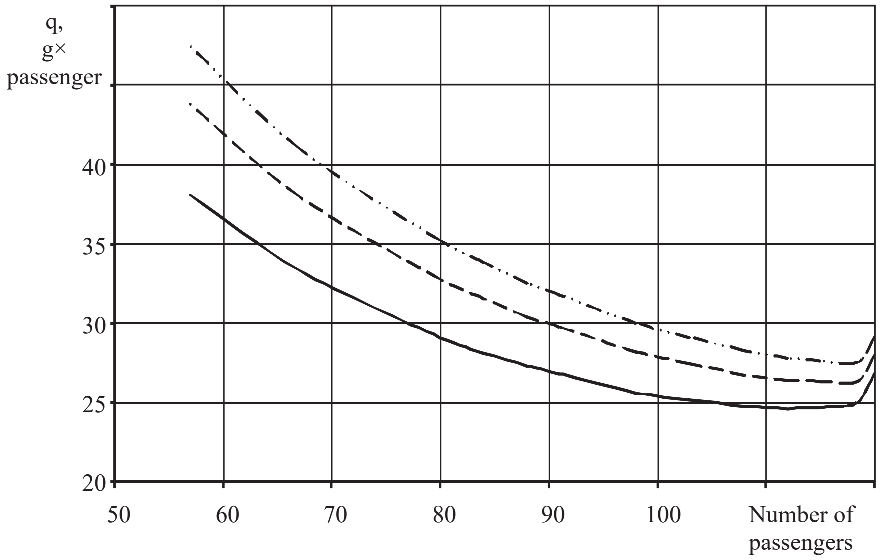


Fig. 8. Dependence of kilometer fuel consumption per passenger on the number of passengers of aircraft modifications with turboprop engines for a flight speed of 780 km/h and different flight altitudes

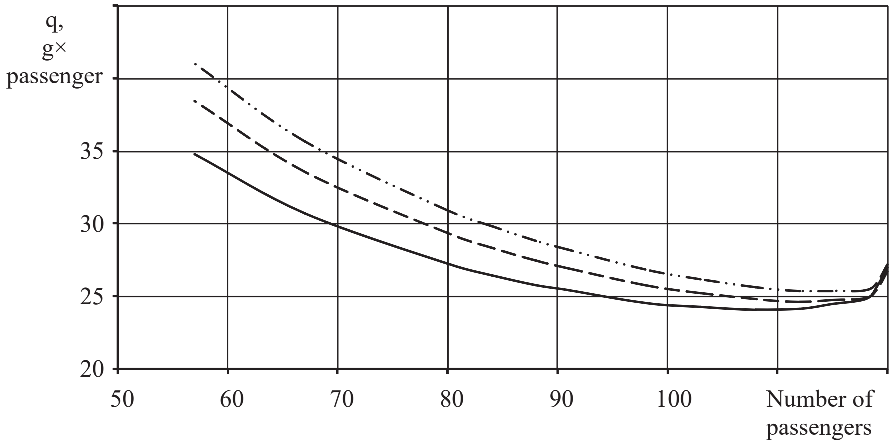


Fig. 9. Dependence of kilometer fuel consumption per passenger on the number of passengers of aircraft modifications with turboprop engines for a flight speed of 700 km/h and different flight altitudes

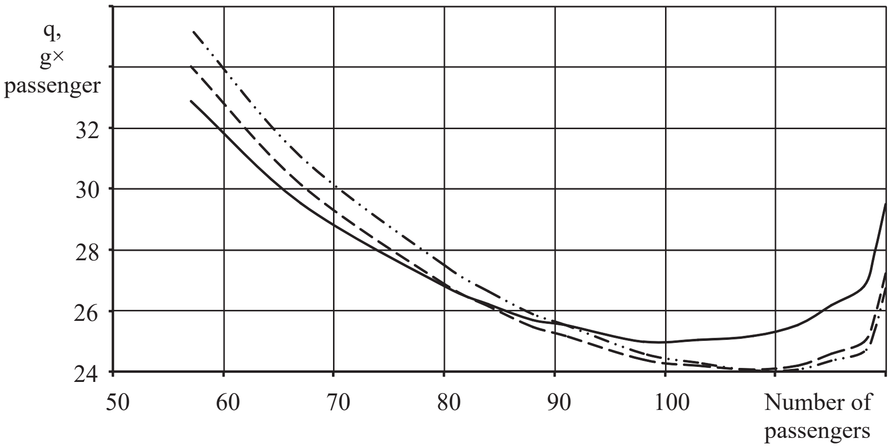


Fig. 10. Dependence of kilometer fuel consumption per passenger on the number of passengers of aircraft modifications with turboprop engines for a flight speed of 600 km/h and different flight altitudes

Analysis of the above dependences allows us to conclude that there is a flat minimum of kilometer fuel consumption per passenger for aircraft modifications with turboprop engines for 100...110 passengers.

Fig. 11–13 show our dependences of the product of the lift-to-drag ratio on the flight Mach number. The maximum of this product characterizes the greatest flight range without taking into account the efficiency of fuel consumption by the engine and the power required for the flight of aircraft modifications for a flight speed of 780 km/h and different flight altitudes.

Analysis of the above dependences makes it possible to identify the most advantageous flight speeds of aircraft with TPE, corresponding to different flight masses, and the modification of the aircraft for 100 passengers is accepted as the basic optimal modification of the An-158 aircraft with TPE.

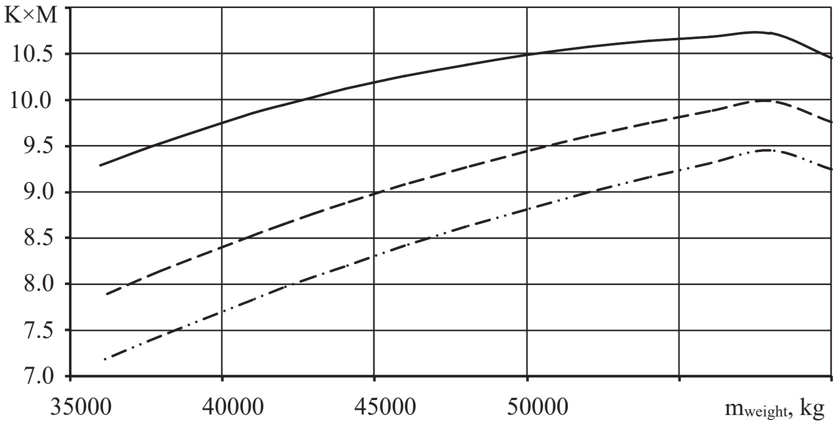


Fig. 11. Dependence of the product of aerodynamic quality on the flight Mach number of aircraft modifications with turboprop engines for a flight speed of 780 km/h and different flight altitudes

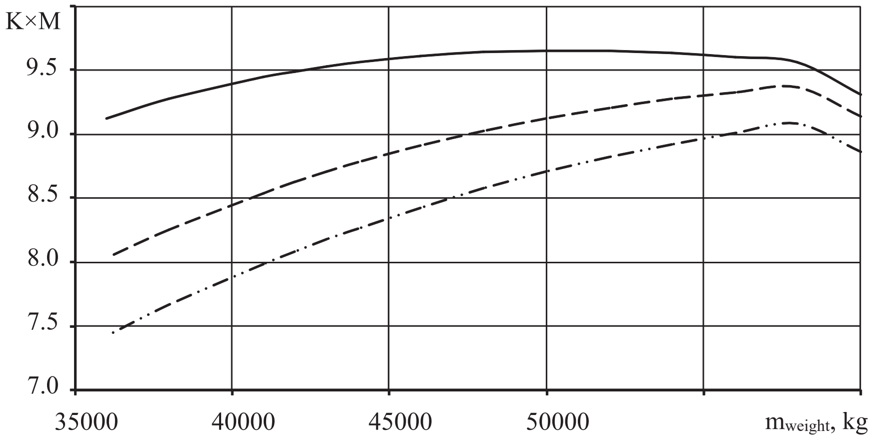


Fig. 12. Dependence of the product of aerodynamic quality on the flight Mach number of aircraft modifications with turboprop engines for a flight speed of 700 km/h and different flight altitudes

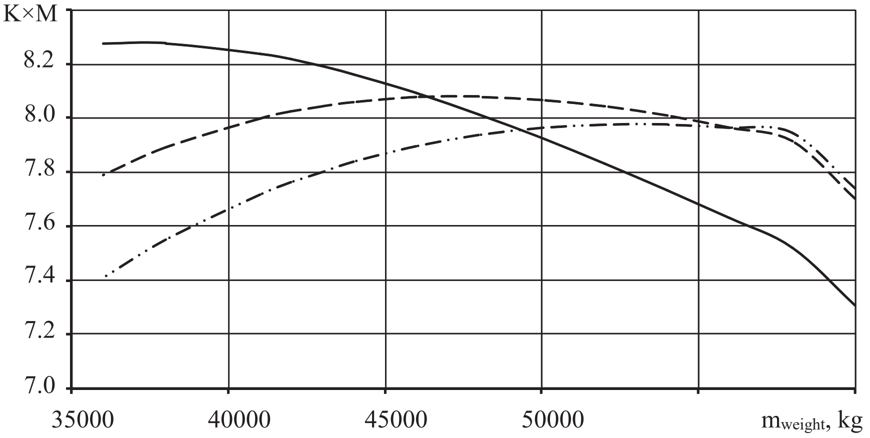


Fig. 13. Dependence of the product of aerodynamic quality on the flight Mach number of aircraft modifications with turboprop engines for a flight speed of 600 km/h and different flight altitudes

Based on the analysis of the requirements for modifications of aircraft of the passenger category and the preliminary studies on takeoff and landing characteristics, weight calculations, a preliminary formation of structural layout diagrams of the aircraft for three «non-optimal» modifications was carried out. Aircraft schemes are shown in Fig. 14.

Since the design of optimal modifications is not always economically feasible, then in the future, «non-optimal design» is performed, that is, the design of non-optimal modifications of aircraft with a carrier system and a power plant. This corresponds to the basic modification of the aircraft with TPE (100 passengers), but with a different number of passengers carried (80 and 120 passengers).

5. 2. Improvement of the methodology for determining the characteristics of the range and duration of the flight in a typical flight of an aircraft

For the calculations, the main initial data were set: the engine power under a takeoff mode (H_f=0 m) is N_e= =6100 kW, the engine output shaft speed is n_{eng}=1000 rpm.

At cruising flight altitude H_f=9000 m, the engine power is N_e=2600 kW, engine output shaft speed n_{eng}= =850 rpm.

The mass distribution of the aircraft is given in Table 2.

Flight performance was studied for two aircraft flight speeds: V_f=600 km/h and V_f=700 km/h. The main results are shown in Fig. 15–23.

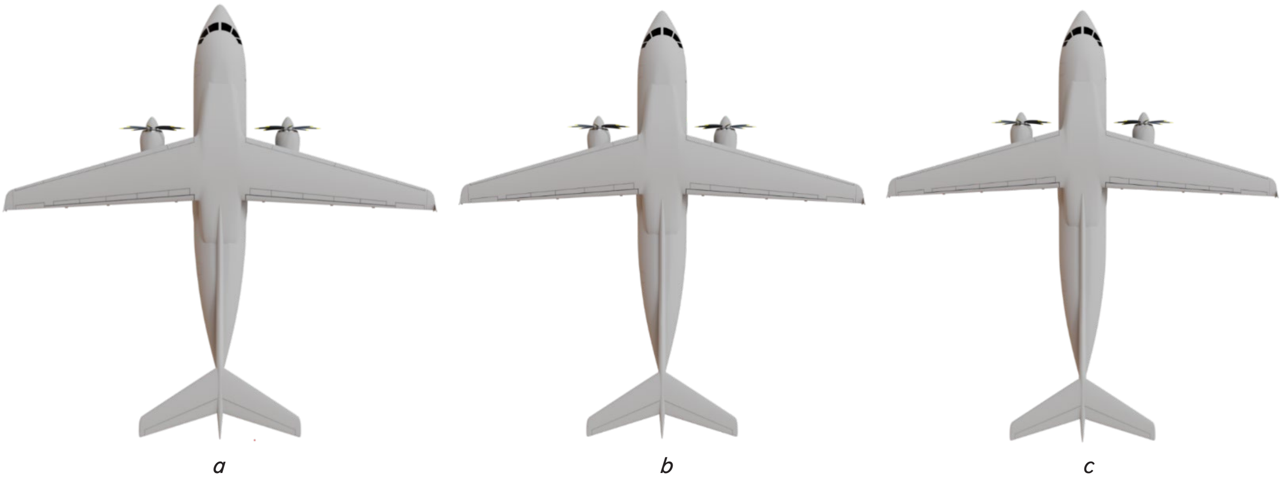


Fig. 14. Type of modifications of the An-158 aircraft with turboprop engines with a capacity of 80 passengers: *a* – with a capacity of 100 passengers; *b* – with a capacity of 120 passengers; *c* – with a capacity of 180 passengers

Table 2

Mass distribution of aircraft elements

Take-off weight, kg	Weight of the airframe and control systems, kg	Weight of the power plant, kg	Weight of crew and equipment, kg	Fuel weight, kg	Weight of commercial load, kg	Weight of empty equipped AC, kg	Payload weight, kg
40136 (80 passengers)	13459	5030	5598	8050	8000	24086	16050
44386 (100 passengers)	14026	5538	6372	8450	10000	25936	18450
48285 (120 passengers)	14626	5945	7164	8550	12000	27735	20550

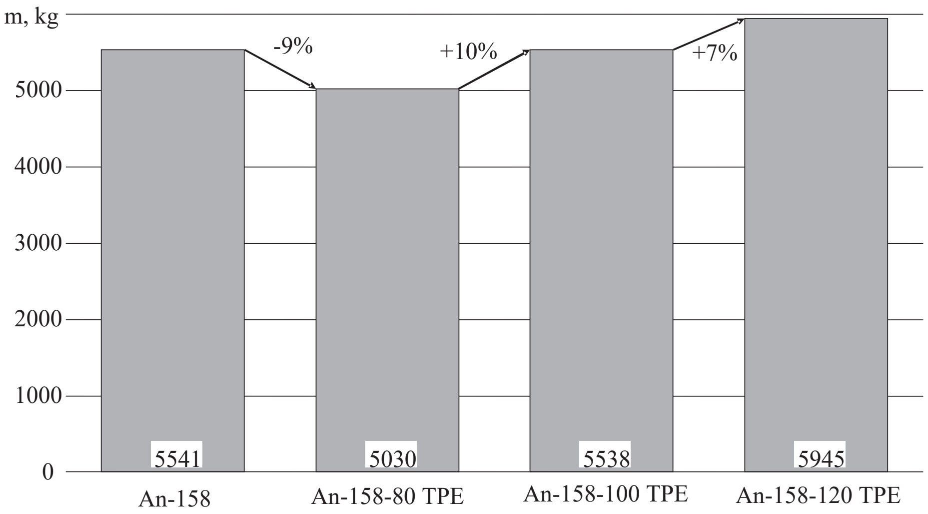


Fig. 15. Comparison of the mass of the power plant

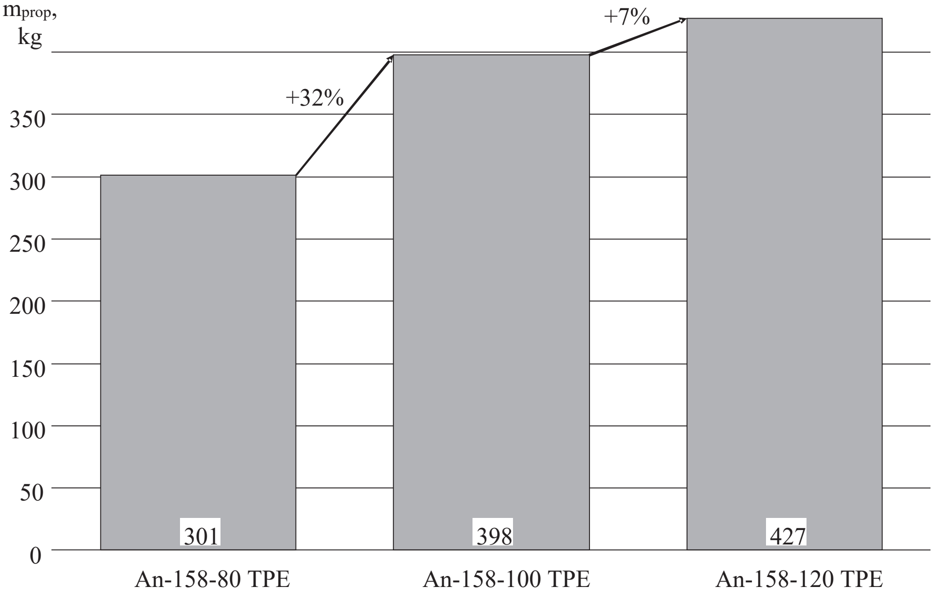


Fig. 16. Comparison of the mass of the propeller

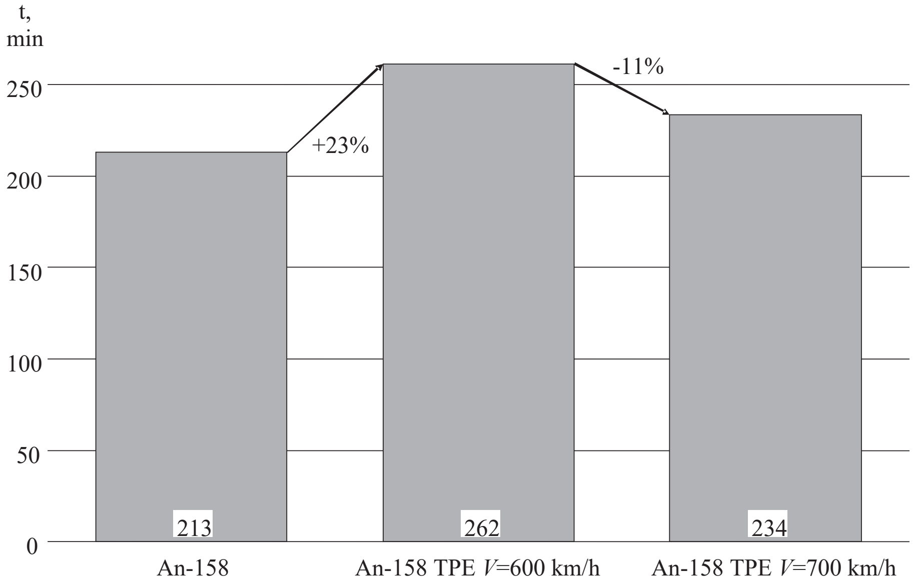


Fig. 17. Comparison of the flight time of the aircraft

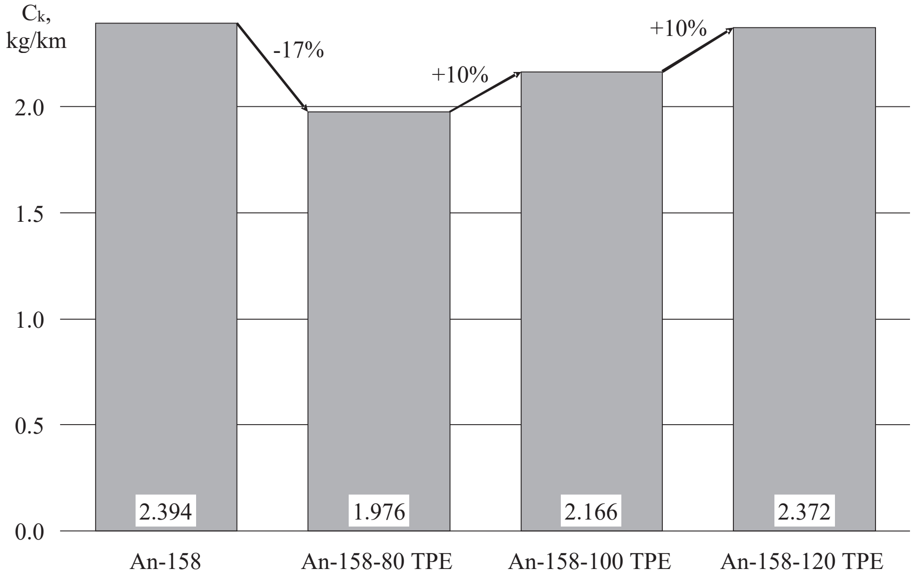


Fig. 18. Comparison of kilometer fuel consumption in cruising mode (*H*=9000 m, *V*=600 km/h)

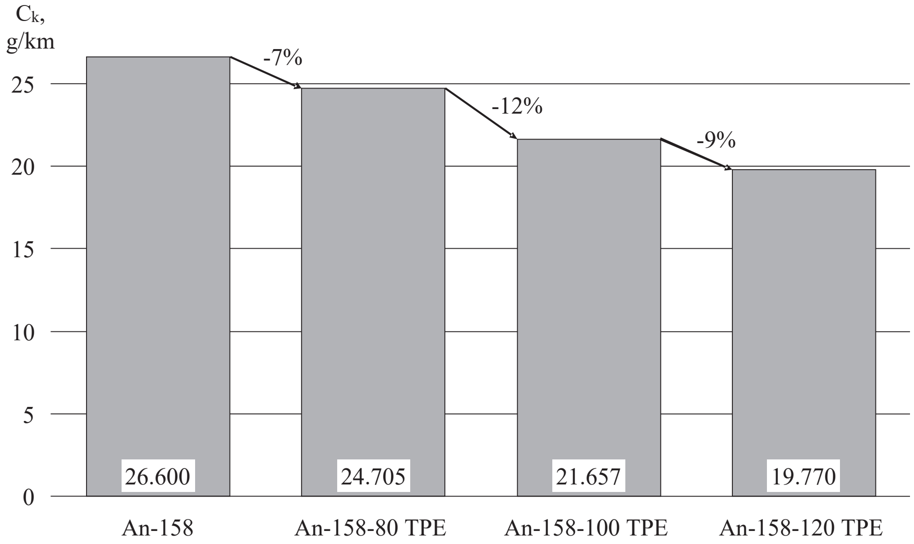


Fig. 19. Comparison of kilometer fuel consumption in cruising mode per passenger (*H*=9000 m, *V*=600 km/h)

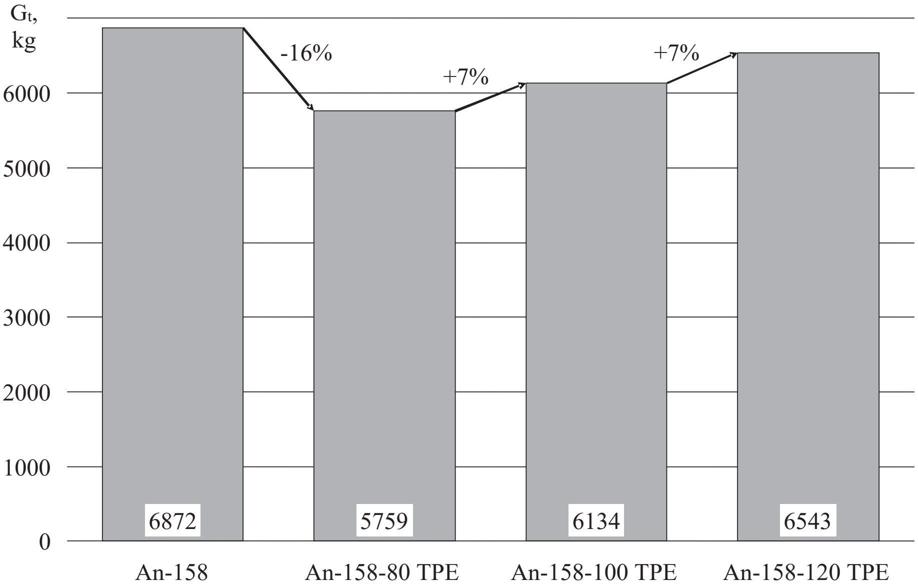


Fig. 20. Comparison of total fuel consumption per flight (*H*=9000 m, *V*=600 km/h)

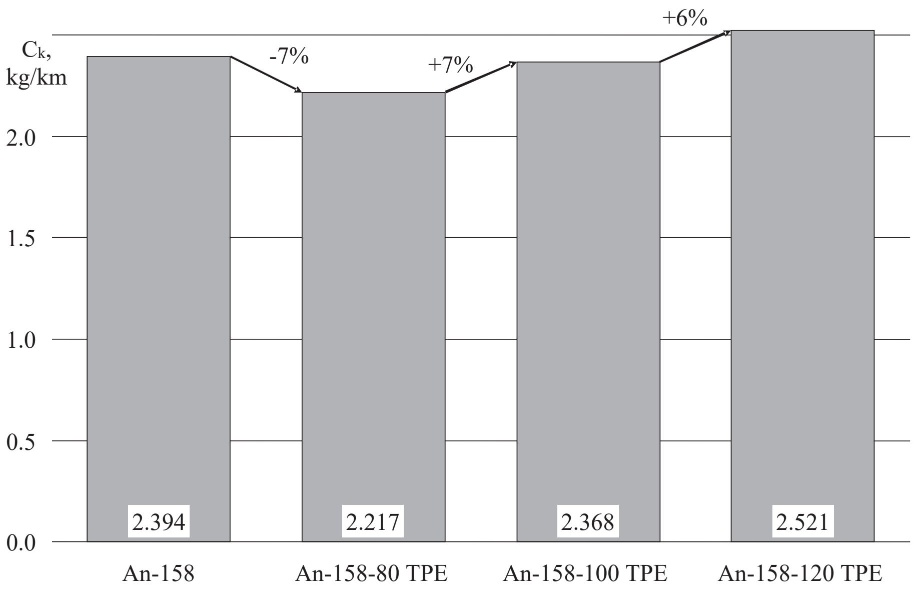


Fig. 21. Comparison of kilometer fuel consumption in cruising mode (*H*=9000 m, *V*=700 km/h)

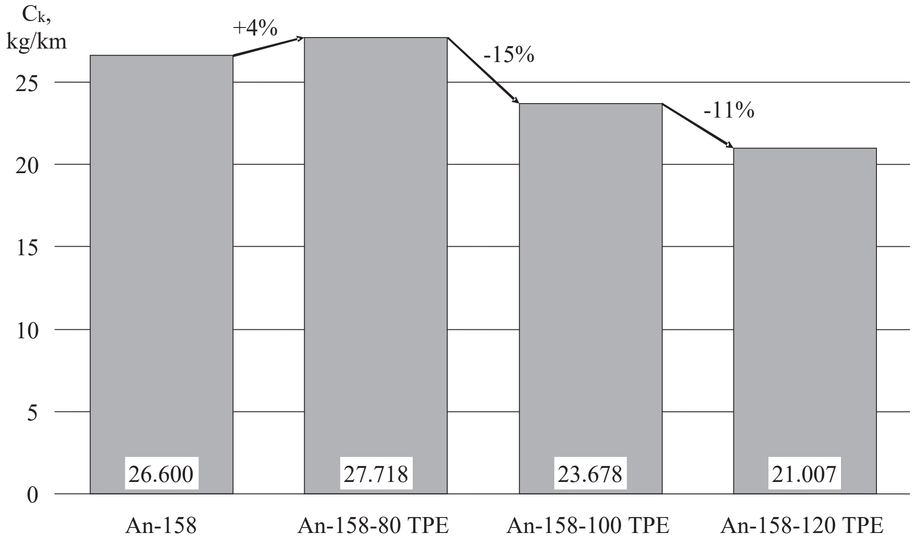


Fig. 22. Comparison of kilometer fuel consumption in cruising mode per passenger (*H*=9000 m, *V*=700 km/h)

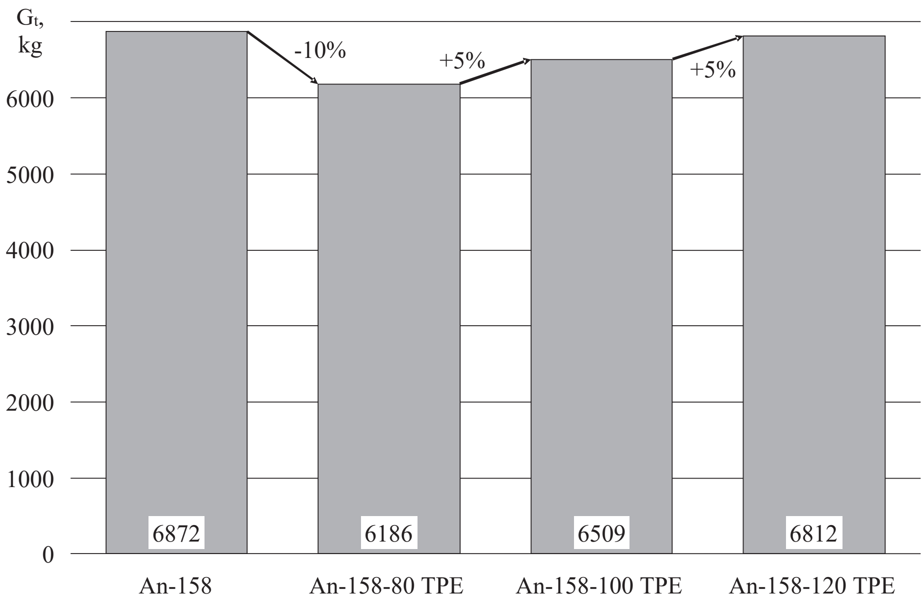


Fig. 23. Comparison of total fuel consumption per flight (*H*=9000 m, *V*=700 km/h)

Thus, the total fuel consumption for the entire typical flight of all modifications of the aircraft with TPE at all flight speeds is less than the total fuel consumption of the An-158 base aircraft. The base aircraft An-158 thus gains in flight time.

Parametric studies were carried out and the choice of one control system for all modifications of the aircraft was made. The research results are given in Table 3. A graphical representation of the research results is shown in Fig. 24–28.

The geometric data of the variants of aircraft modifications are given in Tables 4–6.

Our data of non-optimal modifications are not contradictory. With an increase in the number of passengers carried, the average kilometer fuel consumption will increase from 2.3069 to 2.5164 kg/km, hourly fuel consumption from 1975 to 2086 kg/hour. At the same time, the maximum value of the product of the aerodynamic quality and the Mach number of the cruising flight is from 8.786 to 9.123.

Table 3

Results of parametric studies of modifications

Parameter name	Modification name of aircraft				
	An-158 original	An-158-80	An-158-100	An-158-120	An-158-120; $M=0.655$
Kilometer fuel consumption in cruising mode, kg/km	2.394	2.565	2.406	2.349	2.513
Kilometer fuel consumption in cruising mode per passenger, g/km	26.5995	32.061	24.057	19.578	20.943
Magnitude (K×M) in cruising mode (max)	8.66	8.957	8.965	9.256	8.802
Average required engine power in cruising mode, h.p.	–	3962	4057	4326	4110
Average required engine thrust in cruising mode, kg	1430	1538	1575	1679	1645

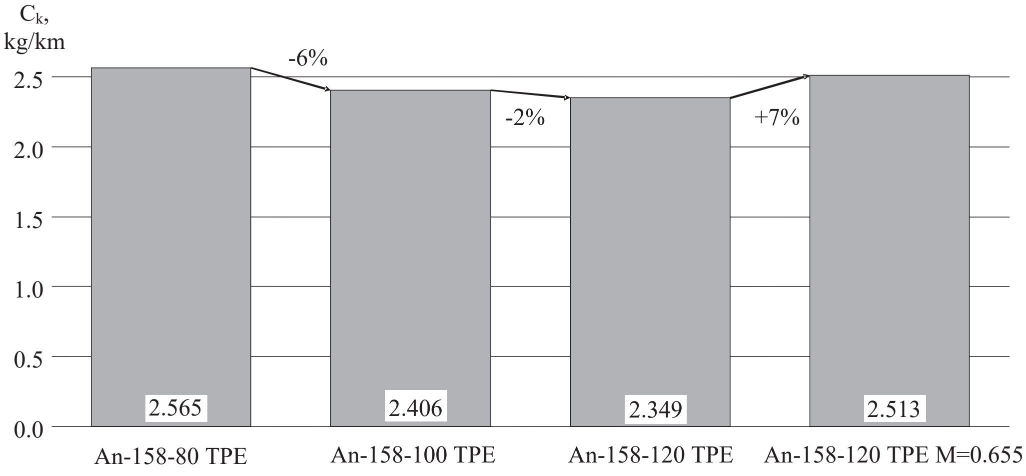


Fig. 24. Comparison of kilometer fuel consumption in cruising mode ($H_f=9000$ m, $M_f=0.68$)

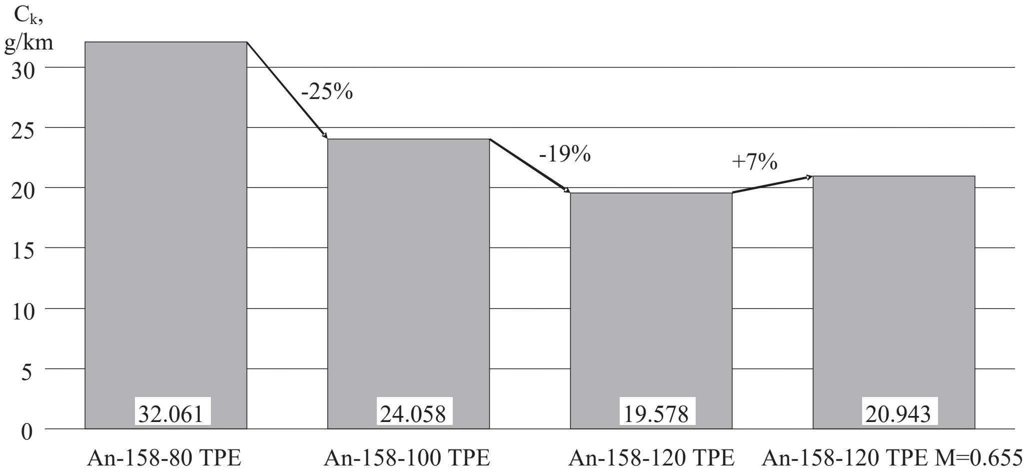


Fig. 25. Comparison of kilometer fuel consumption in cruising mode per passenger ($H_f=9000$ m, $M_f=0.68$)

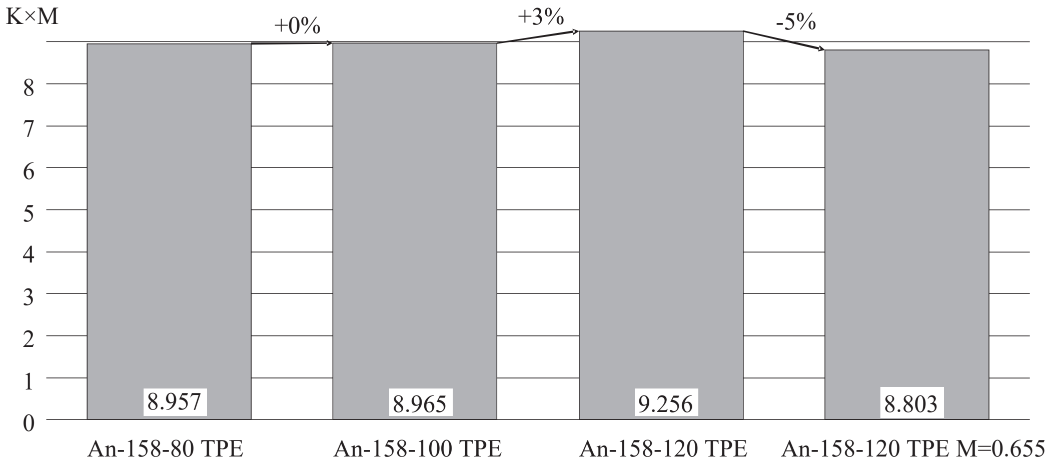


Fig. 26. Comparison of the product of aerodynamic quality and Mach number of flight in cruising mode (H_f=9000 m, M_f=0.68)

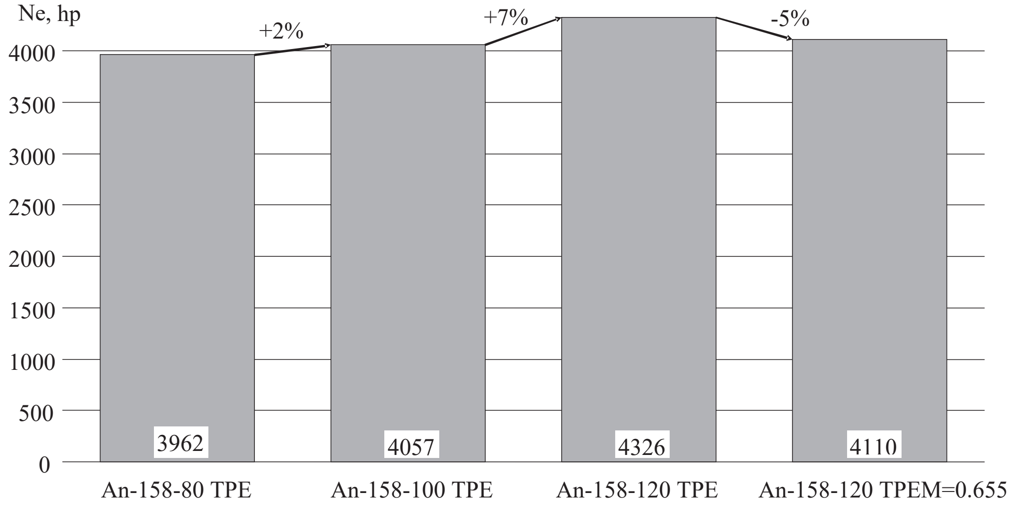


Fig. 27. Comparison of the average required engine power in cruising mode (H_f=9000 m, M_f=0.68)

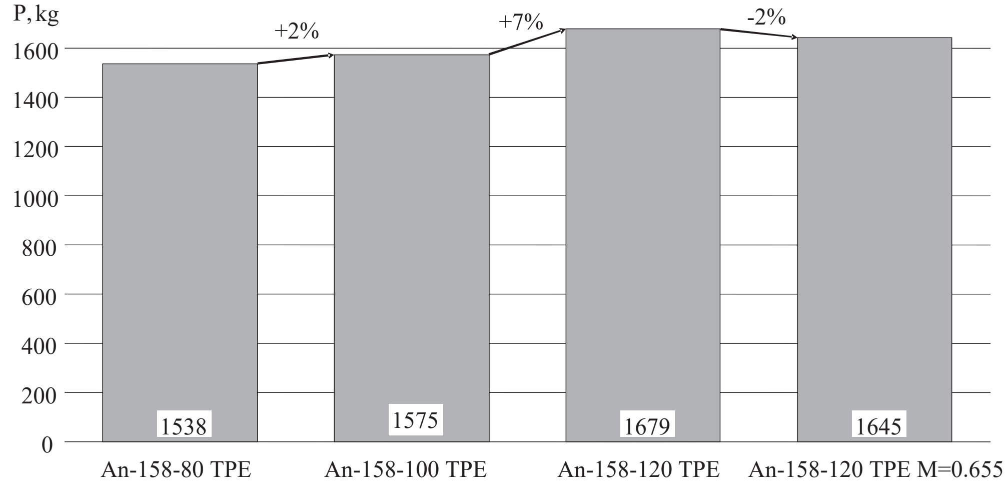


Fig. 28. Comparison of the average required engine thrust in cruising mode (H_f=9000 m, M_f=0.68)

Table 4

Geometrical data of variants of aircraft modifications

Modification option	Flight conditions, cruising mode	S_{wing}, m^2	$L_{fuselage}$, m	M_f, kg	M_{pn}, kg	M_{pp}, kg
N_{pess}=80 persons	H_f=9000 m; V_f=743.6 km/h (M_f=0.68)	70	24.81	41103.4	17000	5475.5
N_{pess}=100 persons	H_f=9000 m; V_f=743.6 km/h (M_f=0.68)	70	27.81	43732.5	19150	5475.5
N_{pess}=100 persons	H_f=9000 m; V_f=743.6 km/h (M_f=0.68)	70	30.81	46556.3	21450	5475.5

Table 5

Geometrical data of variants of aircraft modifications

Modification option	Flight conditions, cruising mode	M_{wing}, kg	G_{tf}, kg	G_t, kg/h	$q_{cp\ cruise}$, kg/km	$(K\times M)_{\text{cruise}}$, max
N_{pess}=80 persons	H_f=9000 m; V_f=743.6 km/h (M_f=0.68)	3862.3	7453	1975	2.3069	8.786
N_{pess}=100 persons	H_f=9000 m; V_f=743.6 km/h (M_f=0.68)	3862.3	7653	2028	2.4058	8.965
N_{pess}=100 persons	H_f=9000 m; V_f=743.6 km/h (M_f=0.68)	3862.3	7907	2086	2.5164	9.123

Table 6

Data of aircraft modifications

Modification option	Flight conditions, cruising mode	L_f, km	t_f, min	L_{dis}, m	$N_{eng.weiht}$, hp	The coefficient of power ВВ при $(K\times M)_{cruise}$, max
N_{pess}=80 persons	H_f=9000 m; V_f=743.6 km/h (M_f=0.68)	2508	226.46	1100	8400	1.6239
N_{pess}=100 persons	H_f=9000 m; V_f=743.6 km/h (M_f=0.68)	2508	226.5	1372	8400	1.6956
N_{pess}=100 persons	H_f=9000 m; V_f=743.6 km/h (M_f=0.68)	2520	227.48	1529	8400	1.7764

5. 3. Improving the methodology for design, strength, and verification calculation of single-row propellers

The initial data for the design calculation of propeller are the maximum power of one engine required for horizontal flight, the altitude and speed of the horizontal flight of the aircraft, the number of revolutions of the engine output shaft, and design limitations on the diameter of the propeller.

For the design of a propeller with a different number of blades, quantitative initial data are established:

– flight altitude H_f=9000 m;
– flight speed – V_f=745 km/h;
– the number of revolutions of the output shaft of the engine n_{eng}=850 rpm;
– engine power N_{eng}=4300 hp;
– propeller diameter D_{prop}=4.5 m;
– blade material – composite;
– aerodynamic profile of the blade – Clark-Y;
– effective nacelle diameter $D_{ef\ mg}$=0.7 m.

Refined non-optimal modifications of the An-158 aircraft with TPE have been obtained. That is, the wing, power plant, empennage and landing gear are the same, but the fuselages are different.

The characteristics of a propeller with a different number of blades (k=4, 6, 8, 10) were studied for flight conditions: N=4300 hp, H=9000 m, V=745.2 km/h. As a result of the research, it was found that it is not advisable to choose less than 8 blades in the composition of the propeller. Reason: insufficient blade elongation, low efficiency, etc.

The number of blades k at this stage is selected from the condition of ensuring the maximum value of the relative chord of the blade $\overline{b}_{\text{max}}$ within the recommended range $\overline{b}_{\text{max}} = 0.1...0.2$. At $\overline{b}_{\text{max}} > 0.2$, the inductive power costs increase significantly due to the small elongation of the blades and, as a result, the flight efficiency of the propeller decreases. Data on the parameters of the propeller blade are given in Table 7; graphical results are shown in Fig. 29–32.

As a result of preliminary studies, an 8-bladed propeller was designed for given flight conditions. A 3D model of an 8-blade propeller is shown in Fig. 33, *a*, a 3D model of the designed 10-bladed propeller for given flight conditions, but at n_{eng}=930 rpm, is shown in Fig. 33, *b*.

Table 7

Propeller blade parameters

Parameter name	D_{prop}=450 cm			
k blades, pcs.	4	6	8	10
b_{max}, cm	130	85	63	50
b_{max}/D, %	0.289	0.189	0.140	0.111
h_{max}	0.740	0.764	0.778	0.787
l_{blades}	1.73	2.65	3.57	4.50

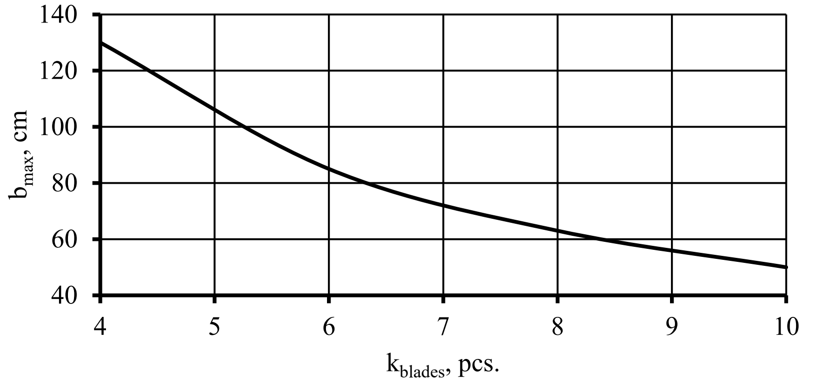


Fig. 29. Comparison of magnitude b_{max}

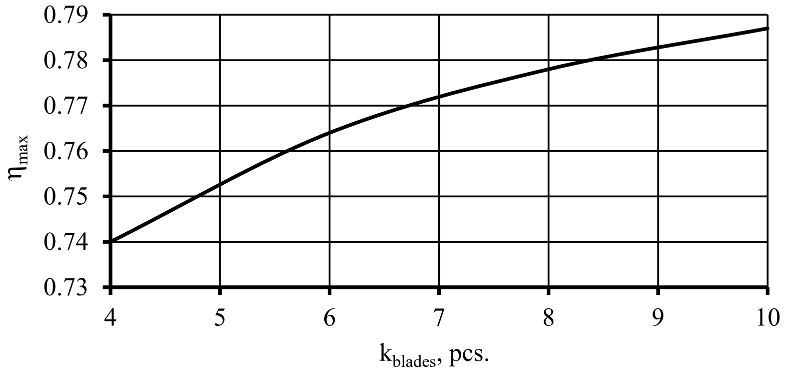


Fig. 30. Comparison of magnitude $\eta_{\max}$

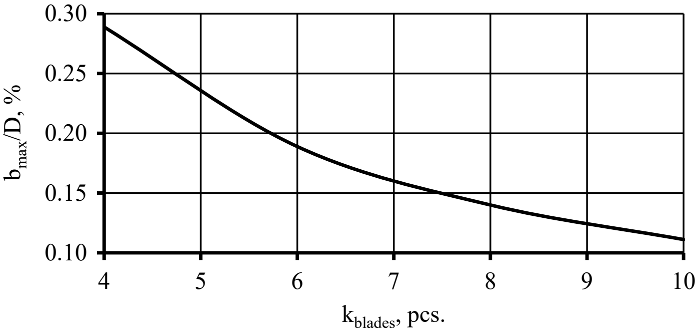


Fig. 31. Comparison of magnitude $b_{\max}/D$

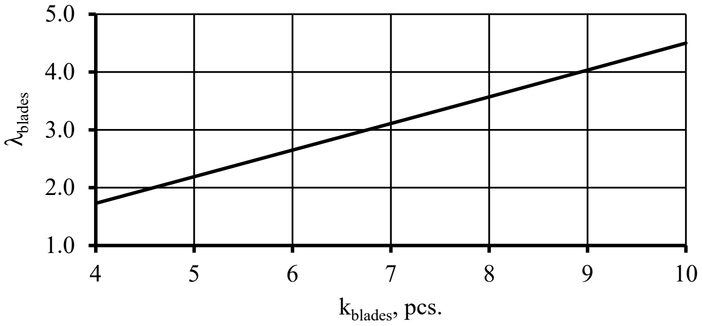
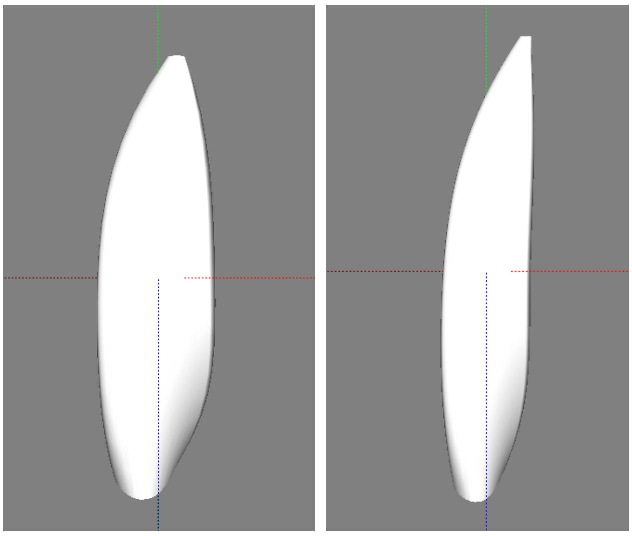


Fig. 32. Comparison of magnitude λ_{blades}



a *b*

Fig. 33. 3D model of a blade: *a* – 3D model of an 8-blade propeller; *b* – 3D model of a 10-blade propeller

Based on the results of the design calculations of propeller, the following conclusions can be drawn:

– the use of saber-shaped propeller blades for high-power TPEs mmakes it possible, at a given flight speed, to slightly increase the number of revolutions of the output shaft, thereby reducing the mass of the gearbox, increasing the power per unit area swept by the propeller;

– the devised procedures for design and verification calculations of propeller blades are based on the airfoil model, taking into account the influence of local Mach and Reynolds numbers. The thickness and curvature of airfoils have been developed, which allows for parametric studies to optimize the characteristics of the propeller;

– since the number of blades is selected from the condition of ensuring the maximum value of the relative chord of the blade $\bar{b}_{\max}$ within the recommended range, the propeller for these modifications of the aircraft cannot have less than 8 blades. Since with a smaller number of blades, the maximum chord of the propeller blade $\bar{b}_{\max} > 0.2$, increases, the inductive power costs increase significantly due to the small elongation of the blades and, as a result, the flight efficiency of the propeller decreases.

6. Discussion of results of studying the parametric appearance of three modifications of the passenger aircraft of the An-158 type

The devised procedures of weight design and determination of the takeoff characteristics of aircraft with different types of power plant engines were necessary for parametric studies to find the minimum kilometer fuel consumption per passenger from the takeoff weight of the optimal modification. The conceptual requirement of equality of the takeoff distance of the base aircraft and its modifications determined the appearance of the optimal modifications of the An-158 type aircraft with TPE for 80, 100, and 120 passengers (Fig. 13). The current study made it possible to establish the presence of a flat minimum of kilometer fuel consumption per passenger for aircraft modifications with TPE for 100...110 passengers. Thus, the modification of the aircraft for 100 passengers is reasonably accepted as the basic modification of the An-158 aircraft with TPE.

The lower total fuel consumption for a typical flight of all modifications of an aircraft with TPE is explained by the greater fuel efficiency of TPE. At the same time, the parametric appearance of three modifications of the An-158 passenger aircraft with TPE is determined by the conceptual requirement to reduce costs at the operational stage. Fig. 15–28 show the results of a study of the flight performance of an An-158 passenger aircraft with TPE for optimal and «non-optimal» aircraft modifications for 80, 100, and 120 passengers. An analytical description of the relationship between the flight performance of a passenger aircraft and its parametric appearance was not obtained in this study due to the complexity of this relationship. Such a formalized relationship obtained for one type of aircraft can hardly be correctly extended to another type of aircraft.

Compared to known procedures [19–21], the methodology for determining the characteristics of flight range and duration in a typical flight of a passenger aircraft [25–27] is integrated with the procedure for design calculation of a propeller [28–31]. The improvement of these procedures was intended to take into account the effect of propeller operation on the aerodynamic performance of an aircraft that previously had a different type of engine. This is especially important for taking into account the significant positive effect of propeller operation on the takeoff and landing characteristics of a remotorized aircraft. The combination of procedures will make it possible in the future to take into account the features of advanced aircraft with deep integration of propellers and airframe [7, 8]. Alternative methods of this study, methods for determining the aerodynamic characteristics of an aircraft are experimental and numerical methods of aerodynamics. At the same time, experimental methods of aerodynamics, in comparison with the methods of this study, have the highest level of reliability. Experimental methods of aerodynamics are a verifier of alternative methods, but their application is associated with high calendar and material costs.

Also, experimental methods of aerodynamics are inapplicable for broad parametric studies of aerodynamic configurations of aircraft that have not yet been designed. Numerical methods of aerodynamics are developing rapidly and are a real alternative to semi-empirical and experimental methods. At the same time, numerical methods of aerodynamics, in comparison with the methods of this study, at the same level of reliability, allow us to study local aerodynamic effects. However, the internal problems of computational aerodynamics, high calendar costs, comparable to experimental methods, hinder the use of numerical aerodynamics. The advantage of our method for determining the aerodynamic characteristics of an aircraft is the possibility of integration with such numerical methods of aerodynamics as the modified method of discrete vortices, the panel method of perturbed potentials.

The main feature of our study is the use of reliable and well-tested methods. The limitation of this study is the impossibility of designing supersonic and coaxial multi-blade propellers. The proposed procedures are not intended to study aircraft modifications with engines built according to the open rotor concept.

The preliminary studies of the parametric design of the power plant with TPE made it possible to establish the required power of one engine to ensure a cruising flight speed of 700 km/h of the basic modification of an aircraft with TPE. The required power was approximately 4100 kW (Table 3). The magnitude of the engine power determines the preliminary appearance of the propeller.

Since it is reliably known that the design of optimal modifications is not economically feasible, the so-called «non-optimal design» is performed in this work. The design of non-optimal aircraft modifications assumes a carrier system and a power plant corresponding to the basic modification of an aircraft with TPE (100 passengers), but a different number of passengers carried (80 and 120 passengers).

Our data on non-optimal modifications do not contradict the known data on optimal modifications [5–7]. Thus, with an increase in the number of passengers carried, the kilometer fuel consumption per passenger decreases (from 26.6 grams/km for the An-158 aircraft to 21.0 grams/km for the modification with a TPE for 120 passengers). At the same time, the power of one engine required for horizontal flight (H_f=9000 m; V_f=743.6 km/h) is less for an aircraft with a smaller number of passengers 3962 hp in modification for 80 passengers. For a modification for 120 passengers, the power required for level flight is 4110 hp (Table 3). The combination of the method for determining the aerodynamic characteristics of an aircraft with the procedure of design calculation of a propeller made it possible to establish the mutual influence of the paremetric shape of the power plant with TPE and the parametric shape of the aircraft itself.

All modifications of aircraft with PTE surpass the original An-158 aircraft with BTJE in terms of efficiency (total fuel consumption in a given flight cycle and kilometer fuel consumption in level flight). Modifications of the aircraft with TPE lose somewhat in the speed of horizontal flight.

Improvement in the procedures of design, strength, and verification calculation of single-row air propellers (AP) was necessary for parametric studies to optimize the characteristics of the propeller for aircraft modifications of different takeoff weights. The shape of the propeller blade was designed for cruising flight with a maximum number of passengers – 120 people. Design calculations of propellers for «non-optimal» modifications of the aircraft with a high-power TPE have been carried out. It has been established that the use of saber-shaped propeller blades for such TPE makes it possible to slightly increase the number of revolutions of the output shaft. In this case, it is possible to increase the power per unit area swept by the propeller. It is substantiated that the propeller for these modifications of the aircraft cannot have less than 8 blades. With a smaller number of blades, the maximum chord of the propeller blade increases, and the inductive power costs increase significantly due to the small elongation of the blades. As a consequence of the above, the flight efficiency of the propeller decreases. A similar number of blades can also be seen in a promising TPE project with Dowty Propellers.

The resulting value of fuel consumption per passenger per kilometer is 24 grams of fuel per passenger per kilometer, with a desired level of 20 grams per passenger per kilometer. This forces a further search for ways to reduce kilometer fuel consumption. This can be achieved by increasing the efficiency of the propellers by increasing the diameter of the propeller. In addition, it is possible to increase the elongation of the blades, reduce the load on the swept surface, rational design of saber-shaped blades, and reduce the midsection of the engine nacelle. A separate area for further research is the use of layout solutions with deep integration of the power plant and the airframe, namely, the use of useful interference of the aircraft wing and a swirling jet of propellers. Conducting such studies is facilitated by the already indicated advantage of the methodology for determining the characteristics of the range and duration of an aircraft flight – the possibility of integration with numerical and experimental methods of aerodynamics.

The development of this study may involve a quantitative assessment of the reduction in the level of noise pollution of aircraft modifications with conventional and hybrid power plants. A theoretical and experimental study of improving the aerodynamic quality of an aircraft using propellers of different directions of rotation, located at the ends of the wing and specially designed for climb modes, is planned. The difficulty of future research will be the absence of semi-empirical aerodynamic dependences for «non-traditional» layouts with a significant influence of local aerodynamic effects. The resolution of this difficulty is possible by using modern numerical and experimental methods of aerodynamics.

7. Conclusions

1. Improved procedures of weight design and determination of the take-off characteristics of aircraft of this category with various types of power plant engines made it possible to identify the most advantageous flight speeds of aircraft modifications with TPE. These speeds correspond to different flight masses, and as the basic optimal modification of the An-158 aircraft with TPE, a modification of the aircraft for 100 passengers should be taken.

2. An integrated procedure for determining the characteristics of the range and duration of a flight in a typical flight of a passenger aircraft and a methodology for design and verification calculation of single-row propellers have been improved. This made it possible to prove that the total fuel consumption for a typical flight of all modifications of the aircraft with TPE at all studied flight speeds is less than the total fuel consumption of the An-158 base aircraft. The preliminary studies of the parametric design of the power plant with TPE made it possible to establish the required power of one engine to ensure a cruising flight speed of 700 km/h of the basic modification of an aircraft with TPE (approximately 4100 kW).

3. The improved procedures of design and verification calculation of single-row propellers have made it possible to form a preliminary image of the propeller. Thus, the shape of the propeller blade for the cruising flight mode of the aircraft modification with a maximum number of passengers of 120 people has been determined.

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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