CALCULATION OF THE MAIN PARAMETERS OF AN AIRCRAFT WITH A CHANNEL PROPULSION SYSTEM

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Abstract. A set of basic aerodynamic parameters of an electric aircraft propulsor is proposed. An analytical method is given for determining the optimal values of design parameters, at which the maximum efficiency of the propulsor on channel fans is achieved, as well as a method for calculating parameters other than aerodynamically optimal ones, which expands the designer's possibilities for optimizing the dimensions and mass of the propulsor. The key aerodynamic parameters for the design of aircraft propulsors are emphasized. The peculiarities of considering the flight altitude at the stage of thruster design are shown. *The purpose.* Show the relationship between the aerodynamic parameters of an aircraft propulsion system. Explain the meaning of basic aerodynamic parameters. Show the physical meaning of the optimal values of aerodynamic parameters. To present a method of determining the limiting values of parameters at the design point, based on experimental studies, which allows you to establish the boundary of the region of existence of parameters of such thrusters. This method, together with the determination of optimal parameters by the value of the coefficient of efficiency and the same coefficient at suboptimal parameters, completes the problem of selecting the design parameters of the aircraft propulsor. The method makes it possible to solve such important problems as creating a propulsor that develops maximum pressure at a given circular velocity, or a propulsor with minimum diameter, maximum static efficiency, etc. *Methodology.* The methodology is based on the method of determining optimal and limiting design parameters using the Bernoulli equation. Definitions of the main aerodynamic characteristics are given.

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The method of calculation by the method is shown on the example of the simplest case of the propulsor with one fan, when the diameters of the inlet and outlet channels are the same and the pressure outside the outlet channel is atmospheric. The result of the calculations is illustrated graphically. The method of comparing calculated and experimental data of thrusters having different aerodynamic schemes with equal and different design parameters allows for the revelation of the peculiarities of their characteristics, and to apply one or another scheme of the thruster fan in each specific case. *Results.* The proposed method allows for developing an electric propulsor for an aircraft based on its requirements and selecting a ready-made propulsor from the existing catalogs for a specific task. *Practical implications.* The presented aerodynamic calculation of axial fans has been tested at the State Key Laboratory for Strength and Vibration of Mechanical Structures. *Value/originality.* The peculiarities of calculating propulsors in the form of tubular axial fans with propellers in a ring are considered. These fans are more efficient, which allows for a gain in the dimensions of the aircraft. Besides, they are safer and more reliable in operation than the propeller fan.

1. Introduction

Unmanned aerial, ground, and marine uncrewed vehicles are widely used worldwide [1]. The uncrewed aerial vehicles (UAVs) class has been most widely developed. The continuous development of uncrewed aerial vehicles of various types and methods of takeoff and landing is directly related to the need to create simple, highly maneuverable, and easily upgradable aircraft designs that perform various tasks, such as solving the tasks of mining and forestry prospecting, mapping, fire control, and others. Aerodynamic calculation of its propulsion system plays a significant role in the design of the aircraft structure. For UAVs, axial fans in the form of free propellers or propellers in a ring are commonly used as thrusters. Axial fans work by drawing air into the fan and moving it in a parallel direction along the axis of the blades. The simplicity of their design and efficiency make them a popular means of creating propulsion for aircraft.

Axial fans consist of one or more rows of blades (impellers) attached to a central hub (hub). An intermediate guide apparatus may be placed between the rows of blades. An inlet guide apparatus may be located in front of the first impeller. Behind the last impeller, there may be a straightening device. Intermediate, inlet guide, and straightening apparatuses are designed to change the air direction. There are three main types of axial fan design: propeller fans, tubular axial fans, and vane axial fans. Propeller fans are simple low-pressure axial fans that move large volumes of air at low pressure. Tubular axial fans (ducted propellers) are propeller fans enclosed in a cylindrical housing (duct) to direct the airflow better. Bladed axial fans are equipped with guide vanes at the fan outlet to improve efficiency and control airflow direction. They are designed for high pressures.

Today, UAV designs with engines in tubular axial fans with propellers in a ring have become increasingly common [2]. Indeed, this type of propulsion system is more efficient than a propeller fan [3], which makes it possible to gain UAV dimensions, and it is also safer and more reliable in operation since a solid pipe encloses the impellers. Increased efficiency allows even such fans to install protective grilles in front and behind the propeller, contributing to increased reliability and safety in the operation of UAVs. The fan's operation principle is based on creating a pressure difference between its inlet and outlet. The fan blades rotate at a speed, creating a low pressure at the inlet and a high pressure at the outlet. This pressure difference creates the movement of the air mass flow through the fan and generates thrust for the propulsion of the aircraft.

2. Main steps of the aerodynamic calculation of axial fans

Typically, the aerodynamic calculation of axial fans consists of the following main steps [4]:

1. Selection of the design scheme and determination of the design parameters of the fan, including diameter and speed, based on the given values of pressure, capacity, and pressure losses in the elements that make up the electric propulsor.

2. Calculate flow, flow kinematics, and velocity triangles in front of and behind the blade crowns along the radius. Determination of the geometry of the blade crowns (profiling) allows the realization of the given flow at the design point at the lowest pressure losses, i.e., with the highest efficiency.

3. Calculate the aerodynamic characteristic of the fan in the operating range of variation of its performance.

4. Calculation of aerodynamic characteristics of fans in their regulation.

One of the most important metrics that aircraft designers focus on is its aerodynamic characteristics [5]. The main parameters of aerodynamics are air flow, thrust, performance, static and dynamic pressure, energy consumption, and power. In general, the characteristic of an air fan is the dependence of the total pressure, shaft power, and efficiency on the air flow rate at a constant rotational speed of the impeller of known size and known air density and aerodynamic scheme, i.e., the totality of the geometric configuration of the flow part and impeller. The aerodynamic characteristics of the propulsor are necessary both at the design stage and its testing. Aerodynamic characteristics are distinguished between absolute (pressure, performance, power, etc.) and relative in dimensionless parameters when, for example, the pressure coefficient is used instead of pressure, the performance coefficient instead of performance, and the power coefficient instead of power.

Due to the variety of requirements that developers impose on UAVs, it is often necessary to develop an aerodynamic scheme [6] that ensures the fabrication of a fan propulsor that maximally satisfies the conditions of its layout and application.

The relationship between aerodynamic parameters can be seen if the expression for the thrust F of a fan propulsor using the equation of quantity of motion [7] is represented in this form:

$$F = \int_S \rho v_{out} \left(v_{out} - v \right) dS, \tag{1}$$

where v_{out} is the velocity at the thruster outlet, m/s;

v is the velocity of the UAV, m/s;

ρ is the air density, kg/m^3;

S is the channel area, m^2.

It is more convenient to consider the value of these parameters in Figure 1 for the simplest case of the propulsor with one fan when the diameter of the inlet channel [8] and the outlet channel are the same, and the pressure outside the outlet channel is equal to the atmospheric pressure.

An expression for the thrust F of the fan propulsor through the parameters in the outlet channel cross-section using Bernoulli's equation:

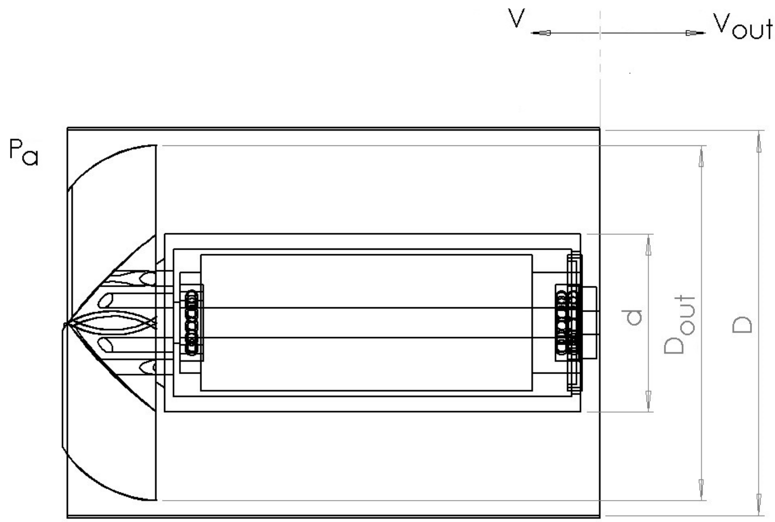

Figure 1. Channel fan in section: p_a – atmospheric pressure; D – channel diameter, D_{out} – fan diameter ($D_{out} < D$), d – sleeve diameter

$$S = \frac{\pi D^2}{4},\ u = \frac{d}{D},\ S_{out} = \frac{\pi D_{out}{}^2}{4}$$

$$F = \int_S \rho v_{out} v \left(\sqrt{\frac{2(p_{out} - p_a)}{\rho v^2} - \left(\frac{v_{out}}{v}\right)^2} - 1 \right) dS. \qquad (2)$$

Expression (2) makes it possible to determine the propulsor's real thrust during its testing [9]. For practical application, this formula can be further simplified by neglecting the small value of the $\frac{v_{out}}{v}$ ratio, the change in velocity v_{out} along section *S*, and the change in density ρ in the propulsion path. In this case, the equation for thrust *F*, in order to reveal the regularities of influence of the main parameters on it, will be written in the following form:

$$F = \frac{\pi D^2}{4}\left(1 - u^2\right)\rho C_{in}\left(v_{out} - v\right) = \rho Q\left(v_{out} - v\right), \qquad (3)$$

where Q – air flow rate, m^3/s;

u – relative diameter of the impeller hub;

C_{in} – axial component of the airflow velocity at the air inlet, m/s.

Flow velocity, defined as the volume of air moved per unit of time, is a fundamental performance indicator for axial fans. The required flow rate depends on the specific aircraft application [10].

In practice, thrust is not specified for one mode of aircraft operation in calculations but for several, e.g., cruising speed [11] and in place.

For fans, a distinction is made between static and dynamic pressure. Static pressure is related to its force, which puts the head of air generated by the fan. Static pressure determines the back pressure the fan may encounter when pumping air through itself. This parameter is measured in pascals (Pa). The optimal static pressure value is chosen based on the specific design of the drone and depends on the fan design and impeller speed. The higher the value, the better the fan works in high-drag conditions.

Dynamic pressure is the most important parameter, as it affects the fan's ability to overcome the resistance created by various obstacles when pumping air through itself. The higher the dynamic pressure value, the more resistance it can overcome and the more air it can move. It is measured in pascals (Pa).

Losses in the fan duct P_{can} occur due to friction, leakage, and turbulence. Inefficiencies caused by air resistance, turbulence, or improper blade design can increase energy consumption. Friction losses usually occur on blade surfaces and other moving parts. They can be minimized by high artistry and the use of low-friction materials. Air leakage around the fan blades and housing can reduce adequate flow and increase energy consumption. Improper installation of fan blades can lead to turbulent airflow inside the duct, which increases duct drag and reduces propulsion efficiency.

The airflow rate is the volume of air that passes through the fan per unit of time. The unit of measurement is cubic meters per second (m^3/s). The airflow rate depends on factors such as fan blade speed, shape and number of blades, inlet and outlet pressure, and air temperature. At a given air flow rate Q, the fan should develop such a total pressure p_v that provides the airhead with kinetic energy $E_k = \frac{\rho v_{out}^{\ \ 2}}{2}$, overcoming the channel resistance at the channel inlet $\varnothing p_{in}$ and outlet $\varnothing p_{out}$, as well as overcoming possible pressure losses $\varnothing p_{ins}$ associated with the placement of auxiliary elements of the channel design: rudders, grids, rod mimics for noise reduction, etc. The fan should also overcome possible pressure losses Δp_ins associated with placing auxiliary elements of the channel design: rudders, grids, rod mimics for noise reduction, etc., and overcoming possible pressure losses Δp_ins. In addition, changes in air density due to temperature fluctuations can also affect fan performance. Increasing the rotational speed or blade pitch can increase the flow rate, but these adjustments also affect other parameters, such as power and efficiency. Considering these variables during the design phase is important to ensure consistent performance under different operating conditions.

Considering the optimum balance between pressure rise and flow velocity in the design is critical [12]. If the fan generates too little pressure, it will have difficulty moving air through the system, reducing efficiency. On the other hand, excessive pressure can lead to unnecessary energy consumption and noise. Choosing the correct blade design, fan speed, and operating conditions will ensure that the pressure increase is sufficient to overcome the resistance of moving air through itself without compromising efficiency while maintaining the desired flow rate.

The channel resistance in the general case is represented as follows:

$$p_v = \frac{\rho v_{out}^{\ \ 2}}{2} + \Delta p_{in} + \Delta p_{out} + \Delta p_{ins}, \tag{4}$$

with the channel resistance coefficients being a set:

$$\zeta = \{\zeta_2, \zeta_{in}, \zeta_{out}, \zeta_{ins}\}, \tag{5}$$

where $\zeta_2 = \frac{E_k}{\frac{\rho c_{in}^{\ 2}}{2}}$; $\zeta_{in} = \frac{\Delta p_{in}}{\frac{\rho c_{in}^{\ 2}}{2}}$; $\zeta_{out} = \frac{\Delta p_{out}}{\frac{\rho c_{in}^{\ 2}}{2}}$; $\zeta_{ins} = \frac{\Delta p_{ins}}{\frac{\rho c_{in}^{\ 2}}{2}}$.

Airflow exit area of the fan, taking into account the sleeve size:

$$S_{out} = \frac{\pi D^2}{4}\left(1 - u^2\right). \tag{6}$$

The ratio of the average velocities (areas) of the airflow exit from the propeller nozzle and from the fan:

$$n_S = \frac{S}{S_{out}} = \frac{C_{in}}{v_{out}} = \sqrt{\frac{1}{\zeta_2}} \tag{7}$$

and therefore, the channel resistance in the general case

$$p_v = \left(\zeta_{sum} + \frac{1}{n_S{}^2} \right) \frac{\rho C_{out}{}^2}{2} = \left(1 + \zeta_{sum}\, n_S{}^2 \right) \frac{\rho v_{out}{}^2}{2}, \tag{8}$$

where $\zeta_{sum} = \zeta_{in} + \zeta_{out} + \zeta_{ins}$.

When calculating fans for aircraft, taking into account their typical design, the influence of the air flow's compressibility can be neglected.

The dynamic pressure of the flow on the fan associated with the movement of the aircraft is taken into account using the coefficient of utilization of this pressure α, where $\alpha < 1$, the value of which depends mainly on the layout and type of air intake, the velocity ratio $\frac{C_{in}}{v}$ and the location of the propulsor in the duct. When the aircraft moves at velocity v, the dynamic pressure $\frac{\rho v^2}{2}$ or its part $\frac{\alpha \rho v^2}{2}$ also participates in overcoming the duct resistance and the total fan pressure p_v, when $\frac{C_{in}}{v} \geq 1$, the coefficient α is in the range of $\alpha = 0{,}85 \ldots 0{,}95$.

Taking into account the pressure utilization factor α, the required fan pressure p_v will be:

$$p_v = \left(\zeta_{sum} + \frac{1}{n_S{}^2} \right) \frac{\rho C_{out}{}^2}{2} - \frac{\alpha \rho v^2}{2}. \tag{9}$$

The power requirements for axial fan design are key to the design process. Power consumption has a direct impact on both operating costs and the overall performance of the aircraft. Understanding the power requirements of an axial fan involves a clear understanding of the forces acting during its operation. The power required by an axial fan is directly proportional to flow rate and pressure rise and inversely proportional to efficiency. Higher flow rates and pressure rise increase the power requirements, while higher efficiency reduces the power required. Power N consumed by the fan:

$$N = \frac{Qp_v}{\eta}, \tag{10}$$

where η – is the efficiency of the fan.

Thrust F through velocity v_{out}:

$$F = \rho Q\left(v_{out} - v\right). \tag{11}$$

Knowledge of air density is an important factor in engineering design. It is used in various engineering applications where the effects associated with the movement of liquids and gases must be considered. An understanding of air density is fundamental in the design and operation of aircraft. Air density varies at different altitudes, affecting the aircraft's air resistance and lift. Air density at different altitudes depends on pressure, temperature, and humidity. The higher the flight altitude, the lower the pressure and temperature, and the air density decreases. It is known that at sea level, air density is about 1.2 kg/m³. At an altitude of 3 km, the air density already decreases to 0.9 kg/m³, and at an altitude of 6 km – to 0.6 kg/m³. According to the above formulas, the aerodynamic parameters of the aircraft are in direct dependence on the air density ρ, i.e., at an altitude of 6 km, the air density ρ is twice less than on the ground, so the thrust, for example, will be reduced by half, and to maintain speed at an altitude of 6 km requires, for example, power twice as much as on the ground. The thrust characteristic in calculations can be used in absolute values (H) or as dimensionless relative values, such as specific thrust (kg of thrust per one kg of air) or thrust factor $\bar{F}$.

The thrust coefficient $\bar{F}$ through the speed of the aircraft:

$$\bar{F} = \frac{F}{\frac{\rho v^2}{2}\frac{\pi D^2}{4}\left(1 - u^2\right)}. \tag{12}$$

Flow velocity at the fan outlet v_{out} through the draft factor $\bar{F}$:

$$v_{out} = \frac{v}{2}\left(1 + \sqrt{1 + \frac{2\bar{F}}{n_S}}\right). \tag{13}$$

Substituting v_{out} from (13) into (8), the total fan pressure through the thrust coefficient:

$$p_v = \frac{\rho v_{out}^{\ 2}}{2}\left[\frac{1+\zeta_{sum}\, n_S^{\ 2}}{4}\left(1+\sqrt{1+\frac{2\bar{F}}{n_S}}\right)^2 - \alpha\right]. \tag{14}$$

Through the traction coefficient, the performance formula is as follows:

$$Q = \frac{F\, n_S}{\bar{F}\rho v}\left(1+\sqrt{1+\frac{2\bar{F}}{n_S}}\right) . \tag{15}$$

Efficiency is one of the most important parameters in axial fan design, as it directly affects energy consumption and operating costs. Efficiency indicates how efficiently the fan converts input power into practical air movement work. The overall efficiency of an axial fan is affected by several factors, categorized as mechanical or aerodynamic efficiency. Mechanical efficiency refers to the efficiency of the fan's mechanical components, such as the motor and bearings. High-quality components such as magnetic bearings can significantly reduce mechanical losses. Aerodynamic efficiency refers to how efficiently the fan blades convert rotational energy into airflow. The design of the blade is crucial here, with factors such as angle of attack and blade shape playing an important role.

The energy consumption of a fan is directly related to its efficiency of operation and may depend on various factors, including blade design, material of manufacture, technical parameters of the fan, and others. The optimal combination of energy consumption and fan performance is one of the main tasks in aircraft design.

Three factors influence energy consumption:

– blade shape and size. The design of the fan blades, including their pitch, curvature, and length, significantly affects the power required. Larger blades or blades with steeper angles require more power to move the same air volume;

– motor characteristics. The type of motor selected also plays a role. High-efficiency motors can reduce power consumption, while underpowered motors may not achieve the required performance.

The generalized external propulsor efficiency η_{outs} is designed to account for losses in the channel and the degree to which the kinetic energy of motion is utilized. Its physical meaning is the extent to which η_{outs}

reflects the ratio of helpful power associated with aircraft motion to the pneumatic power of the flow through the propulsor:

$$\eta_{outs} = \frac{\sqrt{1+\frac{2\bar{F}}{n_S}}-1}{\frac{1+\zeta_{sum}\,n_S^{\,2}}{4}\left(1+\sqrt{1+\frac{2\bar{F}}{n_S}}\right)^2-\alpha}. \tag{16}$$

The power through η_{outs} is expressed as follows:

$$N = \frac{Fv}{\eta\eta_{outs}}. \tag{17}$$

The method of determining the propeller parameters when only the fan diameter is known does not allow for judgment of the minimum possible power required to drive the fan. In contrast to the propeller, the built-in fan-driver has a maximum η_{outs} due to pressure losses associated with its location in the channel. This leads to the necessity of finding the optimal parameters of the realizable fan corresponding to the minimum possible power of its drive.

As can be seen from the above formulas, the propulsion fan is calculated for one optimal speed, considering some factors. If the speed changes, the resistance coefficient of the channel or the rotation speed of the propulsion fan changes, and the thrust force, power consumption, and other parameters change. These changes must be considered when selecting or fabricating the right fan. From the equation $\partial\partial\eta_{outs}/\partial\bar{F}$ for a given n_S, the optimum diameter D_{opt} of the propulsion fan can be found:

$$\bar{F}_{opt} = 2\sqrt{1-\frac{\alpha}{1+\zeta_{sum}\,n_S^{\,2}}}\left(1+\sqrt{1-\frac{\alpha}{1+\zeta_{sum}\,n_S^{\,2}}}\right)n_S. \tag{18}$$

$$D_{opt} = \frac{4F}{\pi\rho(1-u^2)\,n_S v^2\left(1+\sqrt{1-\frac{\alpha}{1+\zeta_{sum}\,n_S^{\,2}}}\right)\sqrt{1-\frac{\alpha}{1+\zeta_{sum}\,n_S^{\,2}}}}. \tag{19}$$

The optimum airflow rate v_{out_opt} corresponding to the optimum diameter D_{opt} given v and n_S:

$$v_{out\_opt} = v\left(1+\sqrt{1-\frac{\alpha}{1+\zeta_{sum}\, n_S{}^2}}\right). \qquad (20)$$

The physical meaning of the optimal value of D_{opt} at a given n_S is as follows. D reduction at a given thrust increases the air velocity behind the fan. In this case, due to the increase in losses, the required p_v increases and Q decreases since the increase in airflow velocity behind the fan is less than the decrease in the area of the passage flow. When D increases, the opposite is true. The minimum of the product $p_v Q$ corresponds to D_{opt}, which increases with decreasing n_S. This decreases flow velocities, decreases pressure losses, and increases maximum η_{outs}. Figure 2 shows the $F_{opt}(\zeta)$ dependence graph at different n_S with lines of equal values of $\left(\frac{v_{out}}{v}\right)_{opt}$ corresponding to F_{opt}, where $\left(\frac{v_{out}}{v}\right)_{opt} = 1,85$.

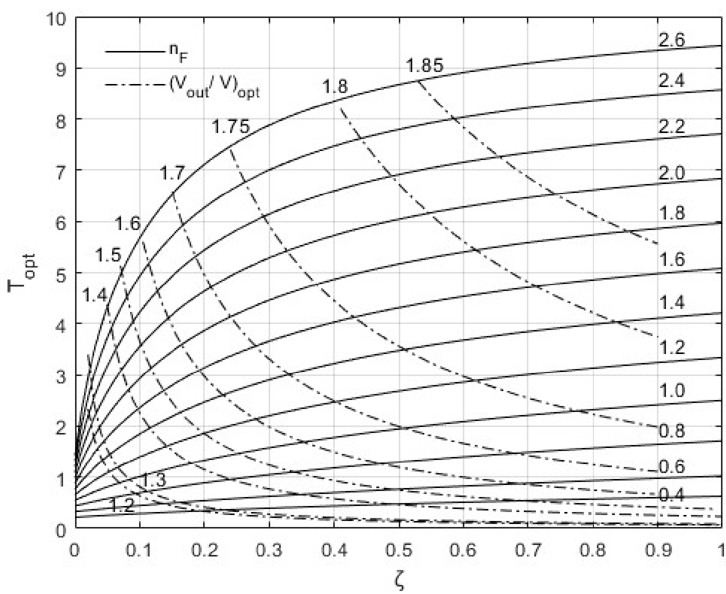

Figure 2. Effect of losses and area ratio on the optimum diameter of the electric motor

The physical meaning of the optimal value of n_S and its variation is as follows. Given F and v, an increase in n_S results in the need to reduce the velocity v_{out}, but to a lesser extent. At the same time, Q increases, and the pressure p_v decreases due to the reduction of the kinetic energy of the airflow. When n_S decreases, the opposite is true. The minimum of the product $p_v Q$ corresponds to the optimum n_S. However, the exact change of the product $p_v Q$ with the change of n_S at small values of the loss factor ζ occurs in the region of large values of n_S, and at large values of ζ – in the region of small values of n_S.

In the case when a ready-made axial fan is selected for an aircraft, it is necessary to take into account the following:

– when analyzing the aerodynamic characteristics of axial ventilators, it is necessary to take into account the case when the electric motor is located in front of the impeller, and the wheel hub goes outside the housing in the axial direction (Figure 1), the dynamic pressure is calculated by the flow exit velocity, determined by the area swept by the blades (total area calculated by the wheel diameter, excluding the area occupied by the wheel hub);

In foreign catalogs, the dynamic pressure of axial fans is determined by the total area, i.e., by the area swept by the wheel. The difference in static pressures established by these methods begins to affect noticeably at the relative diameter of the hub $u > 0.4$ (the ratio of the diameter of the hub to the diameter of the fan). If this is not considered, the selected fan may not give the expected performance in a given design.

When selecting a fan according to the catalog, it is necessary to pay attention to the following:

– whether the power specified in the characteristics is the fan power or the power consumed by the fan motor from the power supply;

– does the electric motor complete the fan and have a power reserve for inrush currents and low air temperatures?

A testing and verification phase usually completes the design of a fan propulsor. Once the propulsor is designed, testing and verifying the flow rate is critical to ensure that it meets the intended specifications. Computational fluid dynamics (CFD) modeling is commonly used to predict airflow characteristics, but physical testing in controlled environments remains the gold standard for performance verification.

3. Conclusions

1. Thus, the aerodynamic characteristics of axial fans play a key role in aircraft flight support.

2. Calculation of aerodynamic characteristics of the axial fan is advisable to carry out in the following order: the choice of design scheme of the fan, flow kinematics, calculation of the aerodynamic characteristics of the fan in the operating range of variation of its performance, calculation of aerodynamic characteristics of fans in their regulation.

3. For the axial fan should distinguish between static and dynamic pressure.

4. Consideration of the optimal relationship between pressure rise and flow velocity in the design of an axial fan is crucial.

5. Power requirements for axial fan design are key in the design process.

6. Knowledge of air density is an important factor in axial fan design.

7. Efficiency is one of the most important parameters in axial fan design as it directly affects energy consumption and operating cost.

8. The method of determining propeller parameters, when only the diameter of the fan is known, does not allow a judgment of the minimum possible power required to drive the fan.

9. Testing and verification of airflow is critical to ensure that the axial fan meets the specified characteristics.

10. The optimal combination of all these components will ensure high operational efficiency and meet the designers' expectations for aircraft quality.

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