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THE PROBLEMS OF SELECTING THE POWER PLANT FOR LIGHT PROPELLER-DRIVEN AIRCRAFT AND UNMANNED AERIAL VEHICLE TAKING INTO ACCOUNT THE REQUIREMENTS FOR COMMUNITY NOISE

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***Abstract**: The problem of selecting a propeller-driven power plant including a single propeller and a piston engine for an aircraft taking into account the requirements for community noise is considered. The competitively necessary community noise levels for light propeller-driven aircraft are formulated, focusing on which it is necessary to design modern aircraft that meet the current and future requirements of ICAO. Modern noise reduction technologies are considered and their effectiveness is evaluated. The main parameters when choosing a propeller are its diameter, the number of blades, the configuration (pusher or tractor) and the presence of a duct. When choosing a piston engine you should take into account the higher acoustic efficiency of two-stroke engines compared to four-stroke engines. The use of intake and exhaust mufflers, as well as sound-proofing hoods, significantly affects the mass and size restrictions, so the need to install mufflers and hoods should be determined at the preliminary design stage. The design mode for the design of light propeller-driven aircraft is the take-off power condition, for propeller unmanned aerial vehicle is maximum cruising level flight mode.*

***Keywords:** engine noise, propeller noise, community noise, UAV, light propeller-driven aircraft*

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1. INTRODUCTION

Currently, more and more attention is paid to the environmental performance of aviation engineering. Community noise levels generated by light propeller-driven aircraft (LPDA) are normalized in accordance with the ICAO standard. The maximum permissible noise levels of propeller-driven unmanned aerial vehicles (UAVs) of the aircraft type are currently not regulated, and the low noise of the vehicles is their competitive advantage [1–5]. However, in the future, it is possible to introduce international standards by analogy with the ICAO standards for light propeller-driven aircraft. In this regard, the task of designing LPDAs and UAVS taking into account the requirements for community noise is relevant.

One of the ways to solve the environmental problems of LPDA and UAVS is to switch from piston and turboprop engines to electric engines. Within the framework of the concept for the development of aircraft engine building [6, 7], it is planned that for regional aircraft with a capacity of up to 50 people, the necessary equipment (electric motors and batteries of acceptable weight) it will be available within the next 10 years. The hybrid scheme which involves the generation of electricity on board by means of a piston or turboprop engine, allows you to circumvent this restriction and is the most promising for LPDAs and UAVS within 5-7 years.

When using electric power plants the main sources of community noise will be propeller [8–12], airframe noise [13–15], and additional noise sources in the real configuration, in particular, „blade-wake“ interaction noise for the pushing configuration of the propeller [16, 17].

Currently, piston engines are used as the drive of the LPDA and UAV propellers, while providing low specific fuel consumption and a long flight time. In contrast to electric piston engines, during operation, they generate significant noise, the role of which in the overall community noise created by the aircraft depends on a different parameters [18, 19], both constructive and the direction of noise propagation and the power condition of the power plant (PP).

The developers of LPDA and UAVs not designing PP, their task is to select an optimal power plant, and its coordination with the aircraft, taking into account the acoustic characteristics of the piston engine and propeller, as well as taking into account the aeroacoustics effects in real configurations PP on a/c.

The purpose of the work is to consider the problem of selecting PP for LPDA and UAVs taking into account the requirements for community noise, as well as to analyze the main parameters of power plants that affect the noise level of the aircraft as a whole. At the same time, the issues of aerodynamic design of light propeller-driven aircraft are discussed in detail in [20–23] and are not considered in the framework of this paper. The optimal aerodynamic design of propellers is discussed in Ref. [24–31], and the process of aeroacoustics optimization of the blade profiles is discussed in detail in Ref. [32].

2. COMPETITIVE COMMUNITY NOISE LEVELS OF LIGHT PROPELLER-DRIVEN AIRCRAFT

When forming requirements for developed and prospective aircraft, it is also necessary to formulate requirements for maximum permissible community noise levels on the basis of known data on the noise levels of operated aircraft that have previously received a type certificate. For this purpose, the EASA certification test database was analyzed. The results of the analysis of inventory values by community noise levels of operated light propeller-driven aircraft certified in accordance with paragraphs 6.3, 10.4a and 10.4b of ICAO standard are presented in Table 1 [33].

It can be seen that some aircraft were certified with almost zero margin, the maximum margin reaches 20 dBA, and the average margin for all aircraft considered in the EASA database is 6 dBA for modern aircraft certified according to the requirements of p 10.4b. Therefore, the maximum permissible community noise level of the designed aircraft should be set at least 6 dBA lower than the value of paragraph 10.4b of the ICAO standard (Tab. 1).

Requirements of ICAO standard Chapters	p 6.3	p 10.4a	p 10.4b
Minimum margin, dBA	0.1	0.1	0.1
Maximum margin, dBA	18.6	20	17.4
Average margin, dBA	4.6	7.5	6

Tab. 1: Minimum, maximum and average noise levels of light propeller-driven aircrafts certified in accordance with Chapters 6 and 10 of ICAO standard

3. THE METHOD OF SELECTING THE POWER PLANT TAKING INTO ACCOUNT THE NOISE RESTRICTIONS

One of the important tasks in the design of light propeller-driven aircraft and unmanned aerial vehicle is selecting of the power plant. First, the engine (one or two) of the required power is selected and propeller is selected to it, so that the power plant provides the specified flight performance of a/c. In general, the best engine is the one where the sum of the mass of the geared engine and the fuel required to provide a given flight time is minimal.

The schematic diagram of the selecting of power plant for LPDA and UAVS taking into account the requirements for community noise is considered on Fig. 1.

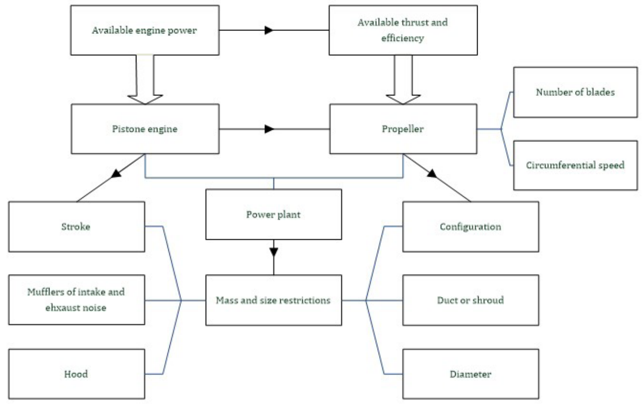

Fig. 1: Schematic diagram of the selecting of power plant for light propeller-driven aircraft and UAVS taking into account the requirements for community noise

Mass and size restrictions for a piston engine are associated with the need to install mufflers in the intake and exhaust channels, as well as hoods. Under the influence of the engine stroke in the framework of the proposed scheme, the influence of the stroke on the engine power on the one hand and on the acoustic efficiency on the other hand is meant. With the same available power, a two-stroke engine will be significantly smaller and lighter than a four-stroke engine, but significantly noisier in the absence of mufflers and hoods due to higher acoustic efficiency.

The main parameters that affect the propeller noise are circumferential speed, number of blades, diameter, configuration (tractor or pushing), as well as the presence of duct (or shroud).

When selecting the propeller to the engine, the required diameter is first determined. Approximately, the propeller diameter can be determined by the statistical formula [23]:

$$d = k_d \sqrt[4]{\frac{N_e}{V \Delta n_m^2}} \tag{1}$$

where

Ne –available engine power (HP),
n_m – propeller speed (rpm),
Δ – relative density of air, equal to the ratio of air density at a given height to air density at ground level,
k_d – empirical coefficient is selected depending on the type of propeller (see Tab. 2).
V – cruise flight speed (km/h)

Type of propeller	Material			
	Tree		Metal	
	Number of blades			
	2	4	2	3
High-speed	98	82	96	89
Rate of climb	110	92	108	103
Economy	104	89	103	99

Tab. 2: The values of the kd coefficient according to the data of the work [23]

When selecting the propeller diameter also need to consider design constraints:

- strength condition [24] (***nd<90*** m/s, where ***n*** is propeller speed (rps)),
- tip Mach number should not exceed 0.9,
- distance from the blade tip to the ground not less than 250 mm [23],
- distance from the propeller tip to any part of the aircraft lying in the plane of rotation of the propeller is not less than 200 mm.

Modern propellers are made of composite materials, so there are no mass restrictions associated with the number of blades. The number of blades affects the propeller noise and its efficiency. For small-sized propellers operating at low Reynolds numbers the use of a larger number of blades in the design significantly reduces the efficiency.

To improve the aerodynamic characteristics of the propeller and, as a result, the a/c flight performance, in some cases, it is advisable to enclose the propeller in duct (or shroud).

Also note that the circumferential speed of the ducted propeller is less than in the case of an isolated propeller, with the same thrust, which can lead to a significant reduction propeller noise. The duct can significantly effect on directivity pattern of the propeller.

Under the influence of the configuration on the propeller noise in the framework of the scheme presented on Fig. 1, two effects are understood. Firstly, it is the work of the propeller in the wake of the upstream parts of the airframe, and secondly, the location of the power plant above the wing is possible, which can provide a significant noise reduction due to the scattering of the power plant noise on the elements of the airframe.

Note also that the placement of the power plant in the wake of the fuselage can provide positive interference, which can lead to a decrease in the required engine power for the flight. When the propeller is located in a pushing configuration an increase in tonal noise should be expected compared to the case of an isolated propeller due to the appearance of an additional noise source so called the „blade-wake" interaction noise.

4. EVALUATION OF THE INFLUENCE OF THE NUMBER OF BLADES AND DIAMETER ON PROPELLER NOISE

Until now, the authors have limited the possibilities of reducing the propeller noise by changing the geometry of the blade profile (i.e., aeroacoustics optimization) to 3 dB [34]. In Ref. [35] aeroacoustics optimization of the blade profile of a 6-bladed propeller in the framework of a numerical experiment led to a reduction in overall noise level of the propeller by 5 dB. Thus by changing the sweep of the blade to achieve noise reduction 2 dBA [36], but due to changes in the tip shape of the blade, you can reduce the noise level by 1-2 dB.

Aeroacoustics optimization of the blade profile is a time-consuming process and does not guarantee, ultimately, a significant reduction in noise levels in the aircraft configuration. The most effective way to ensure the design of a low-noise propeller is to optimize it in terms of changing the number of blades and diameter.

According to semiempirical model of propeller noise [37, 38], the components of the propeller noise from aerodynamic loads and thickness can be calculated using expressions (2) and (3) sound power sources.

For load noise:

$$\boldsymbol{W_{\overline{P}} = c_1 \frac{\rho a^3}{c_0^3}\left[\alpha^2 + \frac{\beta}{(2\pi\overline{r})^2}\right]\frac{M_{cir}^2}{z^3 b_э} n^6 d^8} \tag{2}$$

For thickness noise:

$$\boldsymbol{W_{\overline{u_n}} = c_2 \frac{\rho a^3}{c_0^3}\left(1 + \frac{M_{flight}^2}{M_{cir}^2}\right)\left(1 - \frac{\sin(2\pi a M_{cir} z^{-1})}{2\pi a M_{cir} z^{-1}}\right)\frac{1}{b_{eff}} n^4 d^6 z \overline{a}^2 \overline{s}^2} \tag{3}$$

where

M_{cir} – Mach number of the circumferential speed (tip Mach number),
M_{flight} – flight Mach number,
α – thrust coefficient,
β – Power coefficient,
c_1, c_2 – empirical coefficients,
d – propeller diameter (m),
a – maximum thickness of the aerodynamic profile of the blade at the effective radius (m),
$\overline{a}$ – relative thickness of blade profile,
$\overline{s}$ – coefficient of the unfolded area of blade,
$\overline{r}$ – relative radius of propeller,
c_0 – sound speed (m/s),
z – number of blades,
b_{eff} – blade chord in the effective cross-section (m),
ρ – air density (kg/m^3),
n – propeller speed (rps).

In take-off power condition the noise from the aerodynamic load dominates so when designing light propeller-driven aircraft that are certified for community noise in take-off mode, it is very important to take into account this component of the tonal propeller noise. Analyzing the expression (2) it can be seen that the sound power of the load noise depends on the thrust in the degree of 2 and on the tip Mach number in the degree of 8.

Based on the analysis of semiempirical model of propeller noise [34, 35], the authors proposed a simple correlations that allow to evaluate the influence of diameter and number of blades on load noise when the condition of a constant thrust propellers consider, and when you save the aerodynamic similarity and constant tip Mach number [39].

The calculated change in the sound power level noise from load is written as:

$$\boldsymbol{\Delta L_W = 20lg\frac{d_1}{d_2} + 50lg\frac{z_1}{z_2}} \tag{4}$$

In Ref. [40], the results of assessing the influence of the number of blades on the propeller noise based on numerical modeling as a function of the tip Mach number were presented. The calculation is performed for the far field in the direction of the expected maximum radiation in the plane of rotation of the propellers. It can be seen that at the tip Mach number of 0.75, the noise level of the 7-bladed propeller is 12 dB lower than for the 3-bladed propeller. At a Mach number of 0.9, the effect is reduced to 4 dB, which is associated with an increase in the contribution of the thickness noise component.

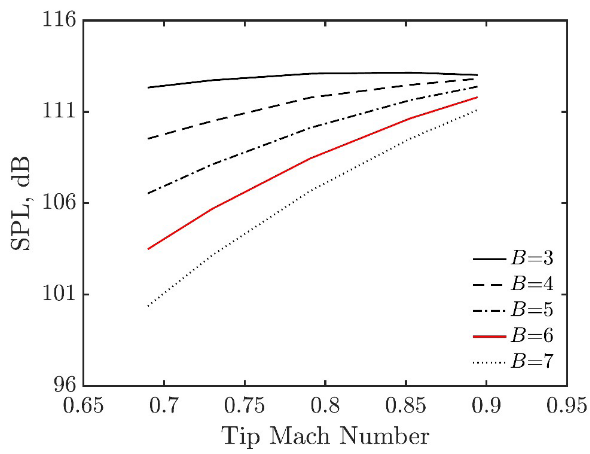

Fig. 2: The influence of the number of blades and tip Mach number on the propeller noise according to the results of a numerical study in the direction of 90° in the far field [40]

Note that in practice, when acoustic finishing of aircraft in operation, the number of blades increases, as a rule, by one with an insignificant change in diameter. To estimate the influence of the number of blades and the diameter in this case it is convenient to use the expression (4).

5. EVALUATION OF THE INFLUENCE OF EXHAUST MUFFLERS AND HOODS

Based on the analysis of the EASA database of acoustic certification tests of LPDA presented in Ref. [33] the following conclusions are made about the effect of exhaust mufflers on the community noise levels of LPDA.

- When installing mufflers in the engine exhaust system the community noise levels of LPDA are reduced by an amount from 1.7 to 10.3 dBA and on average by 4.6 dBA.
- If there are mufflers in the exhaust path sometimes new more efficient mufflers are installed to reduce the noise of the aircraft during operation. Their efficiency is higher than reference ones by 2.5–5.2 dBA, and on average by 3.7 dBA as part of LPDA power plant.

In the absence of exhaust mufflers in the exhaust path, the use of hoods is not advisable from the point of view of noise reduction.

Thus it can be stated that the average efficiency of standard exhaust mufflers in the power plant is 4.6 dBA. The maximum efficiency muffler will reduce the noise levels of PP by 10.3 dBA. When choosing a piston engine, it is necessary to choose the engine with the lowest available power, however, fully providing the required level of a/c flight performances.

6. EFFECT OF THE PUSHING CONFIGURATION ON THE PROPELLER NOISE

When the propeller is positioned in the pushing configuration an additional noise source due to the aerodynamic interaction „blade-wake". Graph of the dependence of the reduction in the overall noise level of the propeller (***ΔL***) when it moves downstream by a normalized distance ***x/c*** (the ratio of the distance x to the average aerodynamic chord of the wing ***c*** (pylon or empennage)) are shown in Fig. 3.

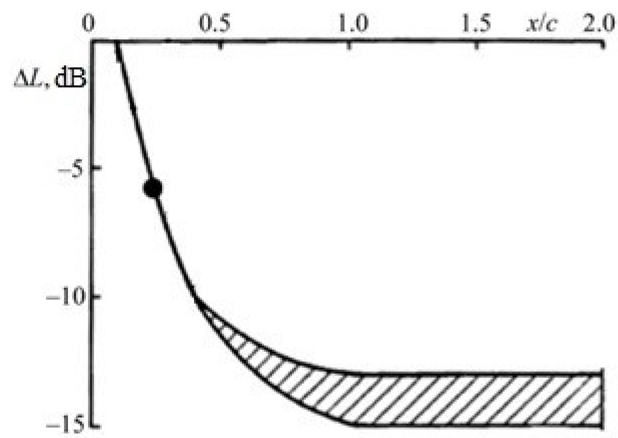

Fig. 3: Graph of the attenuation of the propeller noise with increase spacing between the propeller and wing

It can be seen that to offset the effect of the pushing configuration the propeller should be positioned downstream at a distance of more than one average aerodynamic chord above the located wing (pylon or empennage).

Another way to reduce the propeller noise is pylon blowing In order to compensate for the deficit of speed in the wake. When the flow velocity profile is fully aligned in the wake of the pylon, it is possible to ensure that the noise levels of the pusher propeller are at the level of the isolated propeller.

7. CONCLUSION

The problem of selecting a power plant for light propeller-driven aircraft and unmanned aerial vehicle taking into account the requirements for community noise is considered. The competitively necessary noise levels are formulated which should be used in the design of light propeller-driven aircraft. The influence of different design parameters on the propeller noise is considered. In particular, it is shown that when placing the propeller in the pushing configuration, it is necessary to take into account an additional source of noise, called the „blade-wake" interaction noise. When the propeller is located downstream for a distance of more than one average aerodynamic chord of the wing (pylon or empennage), the noise levels of the pushing propeller become comparable to the noise levels of the isolated propellers. The average efficiency of modern piston engine exhaust silencers is 4.6 dBA as part of the power plant.

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