The Concept of Acoustic Design of Propeller-Driven Fixed-Wing Aircrafts

Petr Moshkov[1,*], and *Mikhail* Pogosyan[1]

[1]Moscow Aviation Institute (National Research University), Moscow, Russia

Abstract. The article proposes the concept of acoustic design of propeller-driven fixed wing aircraft, i.e., taking into account the required acoustic characteristics. The scheme of research and development work at various stage of the project necessary for the implementation of this concept is proposed. A schematic diagram of computational studies in the framework of the acoustic design process of propeller-driven fixed-wing aircraft is proposed. A schematic diagram of the choice of a propeller-driven power plant is considered, taking into account the required acoustic characteristics.

1 Introduction

The problem of reducing the noise impact of aircraft-type propeller aircraft is relevant due to the availability of international ICAO standards [1] and aviation regulations (AP-36, CS-36) [2] regulating the maximum permissible community noise levels of light and heavy propeller-driven aircraft. Meeting the requirements of these documents is a prerequisite for obtaining a type certificate for an aircraft. Periodically, the noise requirements on the terrain of propeller aircraft are tightened.

Another aspect of this problem is related to the need to reduce the noise of propeller–driven unmanned aerial vehicles (UAV) aircraft of both civil and special purpose. Low noise levels of civil-purpose UAVs are currently a competitive advantage of the device, but in the future, it is possible to develop and implement international standards regulating the maximum permissible community noise levels of such devices. For special-purpose UAVS, low community noise levels on provide a low degree of acoustic signature, and, as a result, increase the survivability of the device.

According to the requirements of the national standard of the Russian Federation GOST R 58849-2020 [3], the created aviation equipment must meet the requirements of the customer, the requirements for airworthiness and environmental protection from the effects of aviation and ensure the possibility of its effective and safe use.

Thus, minimizing the noise impact of aviation equipment on the environment is one of the priority tasks of design department [4] when designing modern aircraft-type propeller aircraft. To solve this problem, it is necessary to implement the acoustic design concept in the design department, ensuring the achievement of the required (target) acoustic

* Corresponding author: moshkov89@bk.ru

characteristics of the aircraft. The development of such a concept is the purpose of this work

2 The scheme of R&D in the acoustic design of propeller-driven fixed-wing aircrafts

When designing a propeller-driven aircraft, taking into account the community noise requirements, the task of the design department is to formulate correct and practical requirements for the noise of the power plant elements, as well as its integration into the layout of the aircraft. At the same time, it is necessary to perform a number of computational and experimental studies accompanying the development of a new aircraft at various stages of the project.

Suppliers of engines and propellers independently carry out research and development (R&D) to the extent necessary to meet the requirements of the Aircraft Developer. Among these R&D, we will highlight the following main areas:

– Development of a silencer for the exhaust noise of an internal combustion engine (ICE), taking into account the permissible overall dimensions when installed on the aircraft and the required efficiency in the characteristic power condition of the power plant (PP). To do this, computational studies are carried out, prototypes of silencers are made and their tests are carried out.

– Design and experimental studies for the purpose of designing the profile of the propeller blade according to the criterion of minimum acoustic radiation power with the minimum possible profile thickness and required aerodynamic characteristics (take-off thrust and efficiency in cruising flight mode);

– Bench and/or laboratory acoustic tests of propellers, engines and the power plant as a whole in the volume necessary for the implementation of the project.

Engine and propeller suppliers transmit data on noise levels in the far sound field to design department in the form of 1/3-octave and narrowband spectrum of sound pressure levels measured for different observation angles. These data are used for a refined assessment of the overall sound field of the projected aircraft, taking into account the configuration of the PP.

A schematic diagram of the acoustic design process performed at various stages of the design of propeller-driven fixed-wing aircrafts is shown in Fig. 1 [5].

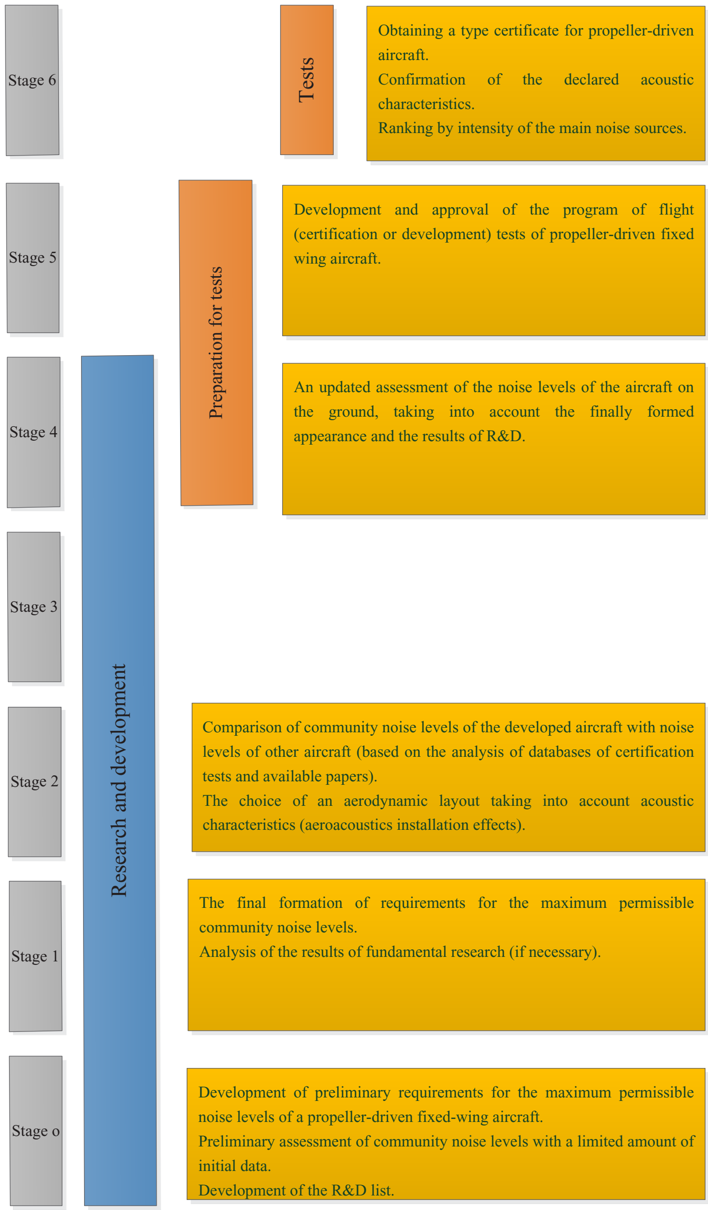

Fig. 1. The scheme of R&D in the acoustic design of propeller-driven fixed-wing aircrafts.

At Stage 0 ("Preliminary Analysis"), a preliminary analysis of the possibility of creating an aircraft is performed, its concept is formed. Preliminary requirements for the maximum permissible noise levels of the aircraft are being developed, and a preliminary assessment of noise levels is being carried out with a limited amount of initial data. The decomposition of noise indicators is performed for a preliminary assessment of the contribution of individual components in the formation of the overall sound field of the aircraft. At this stage, the list of R&D necessary to achieve the targets for community noise during the implementation of the concept of a new aircraft is justified and formed. Among such R&D, we note:

https://doi.org/10.1051/e3sconf/202344601006

– Numerical and experimental studies of aeroacoustics effects when integrating a power plant into an aircraft configuration;

– Improvement of algorithms and programs for assessing aircraft community noise, etc.

The result of the search and applied R&D is a list of technologies with the sixth level of readiness, providing with a probability of 80% the required level of acoustic perfection of the aircraft.

At stage 1 ("Development of a draft proposal") the requirements for the maximum permissible community noise levels of the aircraft are finally formed, and the results of fundamental research work carried out, if necessary, by industry institutes (TsAGI, CIAM, Keldysh Institute of Applied Mathematics etc) in the field of aeroacoustics, necessary for the implementation of the project.

At stage 2 ("Development of a preliminary design"), the development and detailing of the aircraft concept is carried out, including an analysis of the technical level of perfection of the aircraft and a comparison of community noise levels of the aircraft being developed with noise levels of other operated (based on the analysis of databases of EASA, ICAO certification tests) and promising aircraft (based on available publications). The preferred configuration of the aircraft is selected and the possibility of achieving the targets is confirmed.

At stage 3 ("Development of a technical project"), work in the field of aeroacoustics is not envisaged within the framework of the proposed concept, however, the process of improving computational algorithms and programs for assessing aircraft community noise in the design departments is continuous. It is also worth noting that when designing aircraft, often part of the work of the preliminary design is transferred to the stage of the technical project. And it is also possible to design an aircraft within the framework of a "preliminary design / technical project" combining stages 2 and 3.

At stage 4 ("Development of working design documentation"), the appearance of the aircraft is finally formed, technical and technological solutions are being developed to ensure the fulfillment of the operational and technical requirements imposed on the aircraft. All R&D is being completed to ensure the creation of the main units. The assessment of community noise levels of the designed aircraft is carried out, taking into account the final appearance and obtaining the results of the R&D performed (including the results of acoustic tests of propellers, engines and power plants in general). Work on the stage ends with the submission of an application to the certifying authorities (when designing a propeller-driven aircraft).

At stage 5 ("Production of an experimental aircraft"), a program of certification acoustic tests of propeller-driven aircraft is developed and approved in accordance with the requirements of ICAO regulatory documents, or a program of special (finishing) flight tests to assess the community noise of fixed-wing UAVs.

At stage 6 ("Flight tests and certification of the aircraft"), the aircraft is tested, the aircraft is confirmed to the requirements of regulatory documents. The test results are used to assess the compliance of the aircraft with the declared acoustic characteristics and ranking by intensity of the main noise sources. Validation of computational methods for assessing community noise is performed. On the basis of the R&D carried out within the framework of the project, the document "Principles of acoustic design" is being developed to provide scientific and technical groundwork for the design of similar aircraft.

The design of modern aircraft, engines and propellers is carried out using modern CALS-technologies, which reduce the time of aircraft creation by automating the design process [6].

3 Schematic diagram of computational studies in the acoustic design of propeller-driven fixed-wing aircrafts

The schematic diagram of computational studies in the implementation of the concept of acoustic design of aircraft-type propeller aircraft is considered in Fig. 2 [7]. The targets for community noise of propeller-driven aircrafts are formulated for the take-off operating mode of the power plant. For propeller-driven UAVs, special requirements for community noise are formulated for the mode of cruising level flight with maximum speed. Competitive requirements for noise in the terrain of light propeller aircraft are formulated by the authors in Ref. [8].

On the basis of a preliminary assessment of the community noise of a propeller-driven aircraft as a superposition of the sound fields of the main sources and the requirements for the maximum permissible community noise levels, the decomposition of the noise indicators of the main sources is carried out taking into account the number of engines and their layout, propeller, airframe, etc. And the requirements for the maximum permissible noise levels generated when working separately by the engine and the propeller are formulated. To ensure the required noise parameters of the main sources, noise reduction methods are selected. The contribution of the installation effects in the formation of the general sound field of the aircraft is taken into account and, if necessary, methods are used to level these effects.

Verification of targets for community noise and final validation of the software [9, 10] used at various stages of the project to assess community noise is carried out on the basis of an in-flight experiment, the compliance of the aircraft with the targets for community noise is determined, the main noise sources are ranked by intensity.

Currently, much attention is paid to the numerical simulation of noise of various types of propellers (ducted propeller, open rotor etc). However, the existing commercial software is ineffective in solving such tasks [11], and interested organizations: MAI (NRU), TsAGI, Keldysh Institute of Applied Mathematics, AVIC Aerodynamics Research Institute and others independently develop their own software for the correct formulation of numerical aeroacoustics experiments [12–16]. The advantage of numerical modeling is the ability to take into account all parameters that affect the noise levels of the propeller, including installation effects.

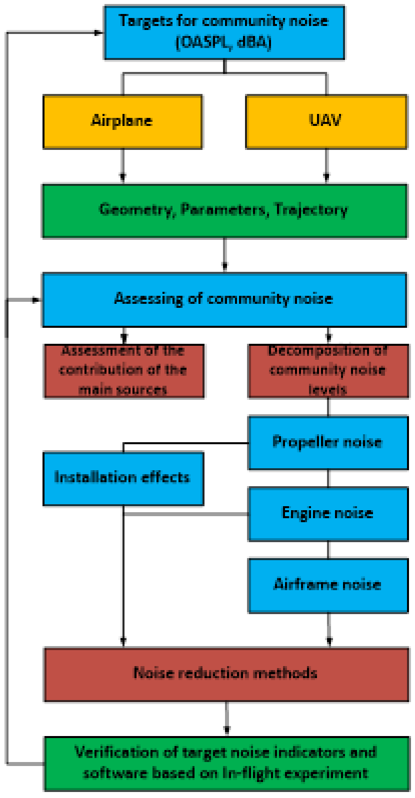

Fig. 2. Schematic diagram of computational studies in the framework of the acoustic design process of propeller-driven fixed-wing aircrafts.

4 Schematic diagram of the choice of a power plant for aircraft-type propeller aircraft, taking into account the required acoustic characteristics

One of the important tasks in the design of propeller-driven fixed-wing aircrafts is the choice of a power plant [17]. First, an engine of the required power is selected and a propeller is selected to it, so that the power plant provides the required flight characteristics of the device. In general, the best engine is the one in which the sum of the mass of the geared engine and the fuel required to ensure a given flight time is minimal.

The schematic diagram of the choice of a power plant for an airplane-type propeller aircraft, taking into account the required acoustic characteristics, is considered in Fig.3. In fact, within the framework of the proposed scheme, all the main factors affecting the noise of an isolated propeller-driven power plant are considered.

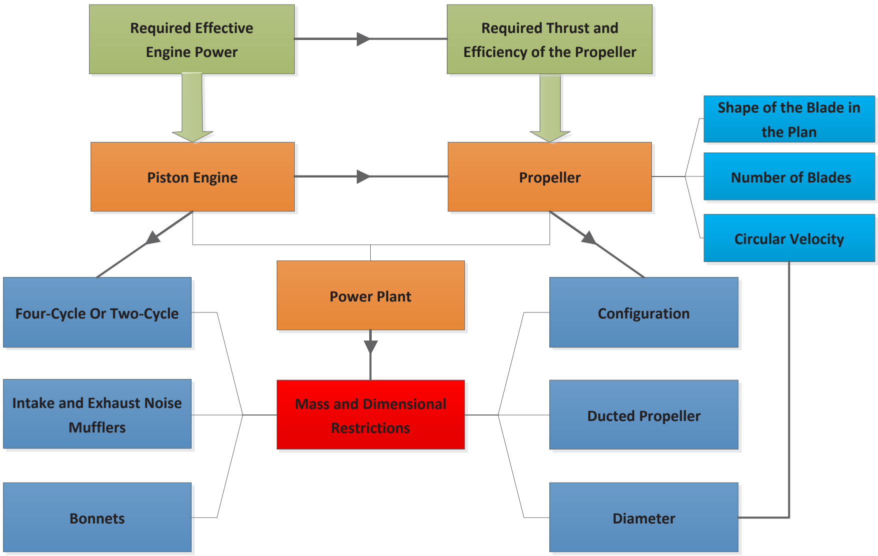

Fig. 3. Schematic diagram of the choice of a power plant for propeller-driven fixed-wing aircrafts, taking into account the required acoustic characteristics.

Evaluation of the effectiveness of various methods of reducing the noise of the propeller and piston engine is presented by the authors in Ref. [18].

Mass and dimensional limitations for a piston engine are associated with the need to install mufflers in the intake and exhaust channels, as well as bonnets, which can be very difficult on propeller-driven fixed-wing aircrafts. Under the influence of the engine stroke in the framework of the proposed scheme, the influence of the engine stroke on the acoustic efficiency of the power plant is implied. The acoustic efficiency of two-stroke engines is significantly higher than that of four-stroke engines with the same available power. With the same available power, a two-stroke engine will be significantly smaller and lighter than a four-stroke one, but significantly noisier due to the higher acoustic efficiency of such engines.

The main parameters affecting the noise of an isolated propeller are the circular velocity, the number of blades, the diameter, the shape of the blade in plan, as well as the presence of duct (ducted propeller).

Modern propellers are made of composite materials [19], so there are no mass restrictions related to the number of blades. For small-sized propellers operating at low Reynolds numbers, the use of a larger number of blades in the design is impractical due to a significant decrease in efficiency with an increase in the number of blades.

To improve the aerodynamic characteristics of the propeller and, as a consequence, the flight performance of the aircraft, in some cases it is advisable to enclose the propeller in duct.

The profile efficiency of the propeller itself operating in the duct, due to the higher speed in the plane of rotation at high power load, is significantly higher than that of the same propeller without a duct. Therefore, with a sufficiently large power load, the advantage in terms of thrust of a ducted propeller mover compared to a propeller without a duct may be significantly greater than could be expected due to the axial efficiency of the system. This effect is especially significant when, due to structural or strength limitations, a propeller without a duct cannot be made optimal (the size of either the diameter, or the number of revolutions, or the coating is insufficient for a given power). In these cases, due to overload, the propeller blades without a duct flow (partially or completely) with a flow separation and, consequently, with a low-profile efficiency. At the same time, studies show that the optimal design parameters and the rotational speed of the ducted propeller at the same power load are significantly lower than that of a propeller without a duct, which makes the ducted propeller optimal, and the flow of the blades continuous to large power loads.

Also note that the circular velocity 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 in the noise levels of the propeller, primarily at the frequency of the first tone and a change in the directivity pattern of acoustic radiation.

The choice of a propeller for propeller-driven fixed-wing aircrafts includes the choice of the design mode, the diameter and profile of the propeller blade, the pitch or ranges of its installation. The propeller selection is performed by successive approximations [20, 21]. This issue is not considered in the framework of this work

5 Conclusion

To solve the problem of reducing the noise impact of propeller-driven fixed-wing aircrafts on the environment, it is necessary to implement the concept of acoustic design. In this paper, a list of the main R&D necessary for the implementation of this concept at various stages of the project is formulated from the "preliminary analysis" stage, at which preliminary requirements for maximum permissible community noise levels are formulated to the "flight tests and certification of the aircraft" stage, at which the claimed acoustic characteristics of the aircraft are confirmed.

References

1. Environmental Protection. Annex 16 to the Convention on International Civil Aviation, Montreal. Canada. ICAO, **1** Aircraft Noise (2011)
2. CS-36 Certification Specifications, Acceptable Means of Compliance and Guidance Material for Aircraft Noise. Amendment 6 (2021) https://www.easa.europa.eu/en/document-library/certification-specifications/cs-36-amendment-6
3. GOST R 58849-2020 (2020) Civil aircraft. Development procedures. General provisions.
4. M.A. Pogosyan, P.A. Moshkov, Modern problems of aeroacoustics of propeller-driven fixed-wing aircrafts. J. of Dyn. and Vib., **9**, 6-15 (2023) doi: 10.18287/2409-4579-2023-9-1-6-15
5. P.A. Moshkov, V.F. Samokhin, Problems of light propeller-driven airplane design with regard to community noise requirements. MAI Aerospace J., **28**, 19-34 (2021) doi: 10.34759/vst-2021-1-19-34
6. M.A. Pogosyan, A.G. Bratukhin, E.P. Savel’evskikh, D.Y. Strelets, V.A. Zlygarev, CALS technology in the creation of the SSJ100 airplane. Russ. Eng. Res., **37**, 694-700 (2017) doi: 10.3103/S1068798X17080159
7. P. Moshkov, E. Toropylina, Assessment of the use of electric power plants on the propeller-driven aircraft noise, J. Aerosp. Sys., **6**, 101-106 (2023) doi: 10.1007/s42401-022-00167-5
8. V.G. Dmitriev, V.F. Samokhin, P.A. Moshkov, Acoustics of Light Propeller-Driven Aircraft. Polyot, **3**, 3-12 (2022)

9. L. Bertsch, Noise Prediction within Conceptual Aircraft Design. PhD Thesis (2013) doi: 10.34912/n0is3-d3sign
10. V.G. Dmitriev, V.F. Samokhin, Complex of algorithms and programs for calculation of aircraft noise. TsAGI Sci. J., **45**, 367-388 (2014) doi: 10.1615/TsAGISciJ.2014011838
11. M.K. Herniczek, D. Feszty, S. Meslioui, J. Park, Applicability of Early Acoustic Theory for Modern Propeller Design. 23rd AIAA/CEAS Aeroacoustics Conf., AIAA 2017-3865 (2017) doi: 10.2514/6.2017-3865
12. S. Timushev, A. Yakovlev, P. Moshkov, Numerical simulation of the light aircraft propeller noise under static condition. Akustika, **41**, 100-106, (2021) doi: 10.36336/akustika202141100
13. M.A. Pogosyan, S.F. Timushev, P.A. Moshkov, A.A. Yakovlev, Simulation of isolated propeller noise using acoustic-vortex method. JSFI, **10**, 21–30 (2023) doi: 10.14529/jsfi230102
14. V.G. Bobkov, T.K. Kozubskaya, L.N. Kudryavtseva, V.O. Tsvetkova, Hybrid dynamic mesh redistribution – immersed boundary method for acoustic simulation of flow around a propeller. JSFI, **9**, 69-84 (2022) doi: 10.14529/jsfi220407
15. V.F. Kopiev, V.A. Titarev, I.V. Belyaev, Development of a methodology for propeller noise calculation on high-performance computer. TsAGI Sci. J., **45**, 293-327 (2014) doi: 10.1615/TsAGISciJ.2014011857
16. H. Jiang et al, Toward high-efficiency low-noise propellers: A numerical and experimental study. Phys. Fluids, **34**, 076116 (2022) doi: 10.1063/5.0098891
17. P. Moshkov, V. Samokhin, A. Yakovlev, C. Bolun, The problems of selecting the power plant for light propeller-driven aircraft and unmanned aerial vehicle taking into account the requirements for community noise. Akustika, **39**, 164-169 (2021) doi: 10.36336/akustika202139162
18. P.A. Moshkov, V.F. Samokhin, A.A. Yakovlev, Engine-propeller power plant aircraft community noise reduction key methods. AIP Conf. Proc., **1952**, 020059 (2018) doi: 10.1063/1.5032021
19. A.Z. Dwi, H. Syamsudin, Manufacturing Fiberglass-Epoxy LSU-03 Aircraft Propeller Using Hand Lay-up and Vacuum Assisted Resin Transfer Moulding (VARTM) Methods. IOP Conf. Series: Materials Sci. and Eng., **645**, 012018 (2019) doi:10.1088/1757-899X/645/1/012018
20. V.G. Gainutdinov, N.V. Levshonkov, Design of highly efficient propeller blades. Russian Aeronautics, **56**, 111-116 (2013) doi: 10.3103/S1068799813020013
21. T.Y. Gainutdinova, A.V. Gainutdinova, Algorithm of calculating the light airplane flight performance and rational design airscrew parameters at the preliminary design stage. Russian Aeronautics, **59**, 364-370, (2016) doi: 10.3103/S1068799816030119