Fast prediction method of aircraft noise with distributed propulsion in the far field

B Chen¹, A A Yakovlev¹,* and P A Moshkov²

¹Department of Aero Engines, Moscow Aviation Institute (National Research University), 4 Volokolamskoe Highway, 125993, Moscow, Russian Federation
²Department of External Loads, IRKUT Corporation Regional Aircraft, 26 Leninskaya Sloboda Street, 115280, Moscow, Russian Federation

*E-mail: yakovlevaa@mai.ru

Abstract. Based on the known methods for calculating the propeller noise, a fast prediction method of the distributed propulsion noise is proposed. The method takes into account only the component of tonal noise from the load. To test the adequacy of the model, the GL-10 model was used, a concept of an aircraft developed by National Aeronautics and Space Administration to test distributed propulsion as well as vertical take-off and landing maneuvers. The comparison showed a good agreement between the results obtained and the data for the GL-10 model.

1. Introduction

The problem of distributed propulsion noise has been reviewed for advanced regional short-takeoff and landing aircraft has recently become more and more relevant [1-3]. The economic and environmental aspects of the use of such power plants in civil aviation are considered [4-6]. On the one hand, such a design can provide significant fuel savings and improve take-off and landing characteristics, and on the other, propeller-driven aircraft are quite noisy aircraft in relation to jet aircraft with turbofan engines at the same take-off masses. These factors lead to the task of finding the optimal configuration in which the relative position of the propellers relative to the airframe could lead to reduced community noise.

When considering the noise of an aircraft with a distributed power plant, it is customary to distinguish isolated propeller noise. Some questions about noise reduction of an engine-propeller power plant were discussed in [7-9]. Methods for reducing of single propellers noise and a semi empirical method for calculating noise [10-12]. Software for calculating the propeller noise [13-15]. The known complexes of algorithms and programs for estimating the aircraft community noise [16-18]. The results of experimental studies of propellers noise [19,20]. The problems of numerical simulation of single propellers noise are considered in [21-23]. The problem of propellers noise in the conditions of real configuration of power plants on aircraft is devoted [24-26], airframe noise [19], aeroacoustics effects in real configurations due to scattering of the power plant noise on the airframe elements in [27-29].

Currently, many papers have been published on the problem of numerical modeling of propeller noise, including in a real configuration and the study of aeroacoustics effects in real aircraft configurations. At the same time, for a short take-off and landing aircraft, the dominant noise sources will be the propellers. Of the components of the propeller noise on take-off condition power, tonal noise from the load usually dominates. The aim of this work is to develop fast prediction method of aircraft noise with distributed propulsion in the far field.
2. Methods and calculations

The acoustic model focuses on the propeller noise. Broadband noise is not considered in this model. Tonal noise components are caused by loading noise and thickness noise. A model designed for fast calculating far-field noise, so the detailed geometry of the propeller blade profile is unknown. It is also known that in the take-off mode of the power plant, the thickness noise is insignificant [8]. Therefore, the proposed model calculates only the tonal loading noise.

The main equation is the linear wave equation (1). It is driven in a moving medium in such a way that the observer and the axial position of the propeller are fixed relative to the coordinate system, and the flow moves along the $x$ axis with the velocity of flight $V$. Therefore, the pressure disturbances $p$ of the observer is periodic at the blade passing frequency (BPF) and the Doppler Effect does not appear at this frequency.

\[
\nabla^2 p - \frac{1}{c_0^2} \frac{D^2 p}{t^2} = \nabla \cdot F = -Q
\]

\[
Dp \frac{\partial}{\partial t} - V \frac{\partial}{\partial x} Dp \frac{\partial}{\partial t} = -V \frac{\partial}{\partial x} (2)
\]

The equation (2) is the convective derivative. It includes a minus sign because the sign convention, typical in propeller acoustics, is used, i.e. that the $x$-axis is positive in the direction flight.

In the equation (1) $F$ is force per unit volume acting on the fluid and can be used to represent the blade loading as acoustic sources.

Then using the Fourier transform, we describe the sources of $Q$ and pressure disturbances in harmonic form (3)-(4).

\[
Q(x, y, z, t) = \sum_{m=-\infty}^{\infty} Q_m(x, y, z)e^{-im\Omega t}
\]

\[
p(x, y, z, t) = \sum_{m=-\infty}^{\infty} P_m(x, y, z)e^{-im\Omega t}
\]

In the study [30] a solution for radiated noise is obtained in the equation (5):

\[
P_n(x, y, z) = \iiint \frac{Q_m(x_0, y_0, z_0)e^{i\beta|\mathbf{r}|}}{4\pi S}dx_0dy_0dz_0
\]

where $k_m = mB\Omega/c_0$ is harmonic wave number, $c0$ is sound speed, $B$ is blade number, $\Omega$ is propeller rotation rate, $x, y, z$ are observer coordinates, $x_0, y_0, z_0$ are source coordinates, equation (6)-(8).

\[
S = \sqrt{(x-x_0)^2 + \beta^2 \left[ (y-y_0)^2 + (z-z_0)^2 \right]}
\]

\[
\sigma = [M(x-x_0)+S]/\beta^2
\]

\[
\beta^2 = 1-M^2
\]

At the angle of attack $\alpha$, the coordinates of the source can be expressed as the coordinates of the propeller (figure 1) in (9):
For an arbitrary point on the blade $S$ and $\sigma$ can be expressed as follows (10)-(11):

\[
S \approx S_0 - \frac{1}{S_0} (x \cos \alpha + \beta^2 R \sin \phi \sin \alpha) x'_0 + \frac{1}{S_0} (x \sin \alpha + \beta^2 R \sin \phi \cos \alpha) r_0 \sin \phi_0 - \beta^2 R \cos \phi_0 \cos \phi_0
\]

\[
\sigma = \frac{1}{\beta^2} (Mx + S_0) - \frac{1}{S_0} \left( \frac{x + MS_0}{\beta^2} \cos \alpha + R \sin \phi \sin \alpha \right) x'_0 \left. - \frac{R}{S_0} \cos \phi_0 \cos \phi_0 + \frac{1}{S_0} \left( \frac{x + MS_0}{\beta^2} \sin \alpha - R \sin \phi \cos \alpha \sin \phi_0 \right) \right.
\]

\[
= r - \frac{\cos \theta'}{1 - M \cos \theta} x'_0 - \frac{\sin \theta'}{1 - M \cos \theta} r_0 \cos (\phi' - \phi_0)
\]

\[(11)\]

**Figure 1.** Coordinate systems of the source and observer.

The cumbersome expression (11) can be simplified by noting that observer angles in the flight system and in the propeller system are related by the following expression (figure 2) in (12).

\[
\begin{aligned}
\cos \theta' &= \cos \theta \cos \alpha + \sin \theta \sin \phi \sin \alpha, \\
\sin \theta' \cos \phi' &= \sin \theta \cos \phi, \\
\sin \theta' \sin \phi' &= -\cos \theta \sin \alpha + \sin \theta \sin \phi \cos \alpha.
\end{aligned}
\]

\[(12)\]
Figure 2. Observer coordinates; visual and retarded system.

Substituting (11) and (12) in expression (5) we get (13):

\[
P_m = \iiint \frac{e^{i k \alpha}}{4\pi r(1-M \cos \theta)} Q_m \exp \left[-i k_m (x_0', \cos \theta' + r_0 \sin \theta' \cos(\phi' - \phi_0))\right] r_0 d\phi_0 dx_0' dr_0
\]  

(13)

Equation (14) represents wave number that includes the Doppler factor.

\[
k_m = \frac{mB\Omega}{c_0 (1-M \cos \theta)} = \frac{k_m}{(1-M \cos \theta)}
\]  

(14)

The load force on each blade consists of an axial and tangential (15):

\[
F = (F_x, 0, F_\phi)
\]  

(15)

They also change over time according to the harmonic law. Therefore, they can be decomposed into a Fourier series at (16) and (17):

\[
F_x = \sum_{m=-\infty}^{\infty} \sum_{k=-\infty}^{\infty} F_{x;k} \exp \left[-i \pm (n-k) \Omega t \exp(i n\phi_0)\right]
\]  

(16)

\[
F_\phi = \sum_{m=-\infty}^{\infty} \sum_{k=-\infty}^{\infty} F_{\phi;k} \exp \left[-i \pm (n-k) \Omega t \exp(i n\phi_0)\right]
\]  

(17)

Where ‘+’ denotes counter clockwise, ‘–’ denotes clockwise. If the number of blades is B, then the sum of the forces on the propeller is written as equations (18) and (19):

\[
F_{x;e} = \sum_{m=-\infty}^{\infty} \sum_{k=-\infty}^{\infty} F_{x;k} \exp \left[-imB\Omega t \exp(i(\pm mB + k)\phi_0)\right]
\]  

(18)

\[
F_{\phi;e} = \sum_{m=-\infty}^{\infty} \sum_{k=-\infty}^{\infty} F_{\phi;k} \exp \left[-imB\Omega t \exp(i(\pm mB + k)\phi_0)\right]
\]  

(19)

In cylindrical coordinates, the divergence has the form (ignoring the radial term):
If we replace (20) with (13) to get the full expression of the pressure wave [31] at (21):

\[ p(\sigma,t) = \sum_{m=-\infty}^{\infty} \sum_{k=-\infty}^{\infty} P_{mk} \exp\left[ ik_{\theta} \sigma_{0} + (\pm mB + k)(\phi' - \frac{\pi}{2}) - mB\Omega t \right] \] (21)

where

\[ P_{mk} = \frac{iB}{4\pi r(1 - M \cos \theta)} \left[ \frac{BF_{sk} \cos \theta'}{1 - M \cos \theta} \right] \frac{F_{sk}}{r_{eff}} \left[ J_{\pm mB + k} \left( \frac{mB\Omega \sin \theta' r_{eff}}{1 - M \cos \theta} \right) \right] \] (22)

where \( r_{eff} \) is effective blade radius.

Equation (22) describes the loading noise of propeller in the far field. If the load on the propeller is steady, then \( k=0 \), and if not, then \( k \neq 0 \), and includes the effects of periodic axial movement of the source and changes in the direction of force. For counter clockwise rotation of the screw, the \( +mB \) mode is positive and \( k=-1 \) dominates. For clockwise rotation of the propeller, the mode \( -mB \) is exclamation and \( k=1 \) dominates [32].

Finally, the noise of a distributed power plant at the observation point is a superposition of the sound fields of several propellers and can be estimated using the following expression (23):

\[ P(t) = \sum_{n=1}^{N} \sum_{m=-\infty}^{\infty} \sum_{k=-\infty}^{\infty} P_{mnk} \exp\left[ ik_{n} \sigma_{0} + (\pm mB + k)(\phi' - \frac{\pi}{2} + \phi_{n}) - mB\Omega t \right] \] (23)

where \( N \) – number of blades, \( \phi_{n} \) – relative angle of blade installation. It is angle of blade installation of \( n \)-th propeller relative to the reference propeller.

3. Results and discussion

The GL-10 is a 50% scale vehicle concept developed by NASA to combine long endurance with vertical take-off and landing (VTOL) technology [33]. Figure 3a shows the GL-10 in hover mode. The distributed engines power plant (DEP) system includes eight propellers along the wing and two propellers along the tail. A wing- and tail-tilt command allows the propulsion system to act as a set of rotors during takeoff and landing operations. Midflight transition occurs to enter a conventional operating state during forward flight. Each propeller is composed of three AeroNaut 16×8 computer aided manufacturing (CAM) folding carbon blades with a diameter of 0.4064 m. Figure 3b is a schematic of the propeller locations relative to the vehicle’s roll axis. Notice that the propellers are mounted on a swept wing with angle of 10.6°.

Figure 4 shows a comparison of the calculation results using the proposed method with the calculation presented in reference [34]. You can see that the results are in good agreement with each other. The differences can be explained by the assumptions of the developed method which does not take into account thickness and vortex noise.
Figure 3. GL-10 in (a) hover mode and (b) top view of the forward flight configuration [34].

Figure 4. GL-10 noise maps for various combinations of propeller rotation directions ('+' denotes counter clockwise, '-' denotes clockwise). The results are obtained for the propeller speed 8000 rpm, flight altitude 30 m, angle of attack 0°, flight Mach number 0.1, $\phi_{1.10}$=0°. The graph on the left is the result from [34], the right is the result of the new author’s method. Contours are normalized by the maximum level per case.
4. Conclusion
Fast prediction method of a distributed propulsion noise that takes into account only the load noise is proposed. This method does not require a detailed description of the blade geometry [35-37]. At the same time, the method takes into account the direction of propeller rotation and their phase angle.

This method will allow for a quick analysis of distributed power plants even at the stage of solving the problem of alignment.

Verification of the calculation method based on open sources was performed. A good agreement was obtained with the data of other authors.

References
[1] Kim H D, Perry A T and Ansell P J 2018 A Review of distributed electric propulsion concepts for air vehicle technology. Proc. AIAA/IEEE Electric Aircraft Technol. Symp. (9-11 July 2018, Cincinnati, Ohio, USA) AIAA 2018-4998 p 21
[2] Schäfer A W et al. 2018 Technological, economic and environmental prospects of all-electric aircraft. Nature Energy 4 160 https://doi.org/10.1038/s41560-018-0294-x
[3] Gordin M V and Palkin V A 2019 Concepts of aircraft engines for advanced passenger aircraft Aviation engines 3(4) 7 [In Russian]
[4] Varyukhin A N, Ismagilov F R, Vavilov V Ye, Ayguzina V V and Gordin M V 2019 Design of an electric generator for an aircraft with a hybrid power system. 26th Int. Workshop on Electric Drives: Improvement in Efficiency of Electric Drives (30 Jan-02 Feb, Moscow, Russia, Institute of Electrical and Electronics Engineers Inc.) p 8664225
[5] Fioriti M, Corpino S, Vaschetto S and Premoli G 2020 Design of hybrid electric heavy fuel male ISR UAV enabling technologies for military operations. Aircr. Eng. Aerosp. Tec. 92(5) 745 https://doi.org/10.1108/AEAT-05-2019-0109
[6] Riboldi C E D, Trainelli L, Mariani L, Rolando A and Salucci F 2020 Predicting the effect of electric and hybrid-electric aviation on acoustic pollution. Noise Mapp. 7 35 https://doi.org/10.1515/noise-2020-0004
[7] Moshkov P A, Samokhin V F and Yakovlev A A 2017 Engine-propeller power plant aircraft community noise reduction key methods. JEAS. 12(S9) 8601 https://doi.org/10.3923/jeasci.2017.8601.8606
[8] Moshkov P A and Samokhin V F 2018 Integral model of noise of an engine-propeller power plant. JOEP. 91(2) 332 https://doi.org/10.1007/s10891-018-1753-8
[9] Samokhin V.F. 2012 Semiempirical method for estimating the noise of a propeller. JOEP. 85 1157 https://doi.org/10.1108/10891-012-0758-y
[10] Campos L and Lau F 2006 On propeller acoustics design synthesis using source distributions along blade span. Proc. 12th Aeroacoustics Conf. (08 May-10 May, Cambridge, Massachusetts, USA) AIAA 2006-2605 https://doi.org/10.2514/6.2006-2605
[11] Timushev S, Yakovlev A, Klimenko D, Aksenov V, Gavrilyuk V and Moshkov P 2020 CFD-CAA Approach for sound generation and propagation in the UAV propeller with subsonic flow. Proc. QUIET DRONES Int. e-Symp. on UAV/UAS 10 (19 October – 21 October, Paris, France) p 518
[12] Moshkov P A 2020 Study of vortex noise of rotating blades. Herald of the Bauman Moscow State Technical University. Series Natural Sciences. 2(89) https://doi.org/10.18698/1812-3368-2020-2-85-98
[13] Kuznetsov V M 2003 Noise control problems of passenger airplanes (a review). Acoust. Phys. 49(3) 241 https://doi.org/10.1134/1.1574351
[14] Bertsch L, Dobrzyński W and Guérin S T 2010 Tool development for low-noise aircraft design. J. Aircraft. 47(2) 694 https://doi.org/10.2514/1.43188
[15] Filippone A 2014 Aircraft noise prediction. Prog. Aerosp Sci. 68 27 https://doi.org/10.1016/j.paerosci.2014.02.001
[16] Arntzen M, Rizzi S A, Visser H G and Simons D G 2014 Framework for simulating aircraft
flyover noise through nonstandard atmospheres. J. Aircraft. 51(3) 956
https://doi.org/10.2514/1.C032049

[17] Arntzen M, Heblig J I and Simons D G 2014 Weather-dependent airport noise contour prediction concept based on ray tracing. J. Aircraft. 51(5) 1351 https://doi.org/10.2514/1.C032149

[18] Dmitriev V G and Samokhin V F 2014 Complex of algorithms and programs for calculation of aircraft noise. TsAGI Science Journal 45(3-4) 367 https://doi.org/10.1615/TsAGISciJ.2014011838

[19] Moshkov P, Samokhin V and Yakovlev A 2019 About the community noise problem of the light propeller aircraft. Akustika 34 66 https://doi.org/10.36336/akustika20193466

[20] Moshkov P, Ostrivok N, Samokhin V and Valiev A 2019 Study of Ptero-G0 UAV Noise with Level Flight Conditions. Proc. 25th AIAA/CEAS Aeroacoustics Conf. (20-23 May 2019, Delft, The Netherlands) AIAA 2019-2514

[21] Titarev V A, Faranosov G A, Chernyshev S A and Batrakov A S 2018 Numerical modeling of the influence of the relative positions of a propeller and pylon on turboprop aircraft noise. Acoust. Phys. 64(6) 760 https://doi.org/10.1134/S1063771018060118

[22] Abalakin I V, Bakhvalov P A, Bobkov V G, Kozubskaya T K and Anikin V A 2016 Numerical investigation of the aerodynamic and acoustical properties of a shrouded rotor. Fluid Dyn. 51(3) 419 https://doi.org/10.1134/S0015462816030145

[23] Abalakin I V, Bahvalov P A, Bobkov V G, Kozubskaya T K and Anikin V A 2016 Numerical simulation of aerodynamic and acoustic characteristics of a ducted rotor. Mathematical Models and Computer Simulations 8(3) 309 https://doi.org/10.1134/S2070048216030030

[24] Oleson R D and Patrick H 1998 Small aircraft propeller noise with ducted propeller. Proc. 4th AIAA/CEAS Aeroacoustics Conf. (02 June-04 June. Toulouse, France) AIAA 98-2284

[25] Malgoezar A MN, Vieira A, Snellen M, Simons D G and Veldhuis L LM 2019 Experimental characterization of noise radiation from a ducted propeller of an unmanned aerial vehicle. Int. J. Aeroacoust. 18(4-5) 372 https://doi.org/10.1177/1475472X19852952

[26] Belyaev I, Kopiev V, Skvortsov R, Pankratov I, Titarev V and Zaytsev M 2015 Comparison of rotor noise measurement results in large-scale and small-scale anechoic facilities. Proc. 21st AIAA/CEAS Aeroacoustics Conf. (22-26 June, Dallas, TX) AIAA 2015-2986

[27] Vieira A, Snellen M, Malgoezar A M N, Merino-Martinez R and Simons D G 2019 Analysis of shielding of propeller noise using beamforming and predictions. JASA. 146(2) 1085 https://doi.org/10.1121/1.5121398

[28] Ostrivok N and Denisov S 2016 Mean Flow Effect on Shielding of Noncompact Aviation Noise Sources. Proc. 22d AIAA/CEAS Aeroacoustics Conf. (30 May-1 June, Lyon, France) AIAA 2016-3014 https://doi.org/10.2514/6.2016-3014

[29] Denisov S L, Kopiev V F, Ostrivok N N. et al. 2020 Using the Correlation Model of Random Quadrupoles of Sources to Calculate the Efficiency of Turbulent Jet Noise Screening with Geometric Diffraction Theory. Acoust. Phys. 66(5) 528 https://doi.org/10.1134/S1063771020050024

[30] Goldstein M E 1976 Aeroacoustics (New York: McGraw-Hill International Book Company) p 293

[31] Hanson D B 1995 Sound from a propeller at angle of attack: a new theoretical viewpoint. Proc. R. Soc. Lond. A 449(1936) 315 https://doi.org/10.1098/rspa.1995.0046

[32] Krejsa E 1990 Prediction of the noise from a propeller at angle of attack. Proc. 13th Aeroacoustics Conf. (22 October-24 October, Tallahassee, FL, USA) AIAA 1990-3954

[33] Rothhaar P, Murphy P, Bacon B, Gregory I, Grauer J, Busan R and Croom M 2014 NASA Langley Distributed Propulsion VTOL Tilt-Wing Aircraft Testing, Modeling, Simulation, Control, and Flight Test Development. Proc 14th AIAA Aviation Tech., Integration, and Operations Conf. (16 June-20 June Atlanta, GA,USA) AIAA 2014-2999

[34] Pascioni K, Rizzi S A 2018 Tonal Noise Prediction of a Distributed Propulsion Unmanned Aerial Vehicle. Proc. 2018 AIAA/CEAS Aeroacoustics Conf. (25-29 Atlanta, Georgia, USA) AIAA
[35] Song X, Yu P, Bai J, Han X and Peng J 2020 Aerodynamic and aeroacoustic optimization of propeller based on Hanson noise model. *JNPU*. 38(4) 685 https://doi.org/10.1051/jnwp/20203840685

[36] Okoyenta A R, Wu H, Liu X and Jiang W 2020 A Short Survey on Green’s Function for Acoustic Problems. *JTCA*. 28(2) 1950025 https://doi.org/10.1142/S2591728519500257

[37] Kotwicz Herniczek M T, Feszty D, Meslioui S A, Park J and Nitzsche F 2019 Evaluation of acoustic frequency methods for the prediction of propeller noise. *AIAA J.* 57(6) 1 https://doi.org/10.2514/1.J056658