BUILDING AND VERIFYING A TOOL FOR CALCULATING THE AERODYNAMIC NOISE OF HELICOPTER ROTORS

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Abstract

This article presents an approach to build and verify a tool for calculating aerodynamic noise characteristics of helicopter rotors. The calculation tool is built on the basis of combining the vortex lattice method and the Formulation 1A of Farrasat, which is one of solutions of the Ffowcs Williams-Hawkings (FW-H) equation. By comparing the obtained result with data from reputable international publications, the calculation tool is verified for accuracy and reliability. The variation and value of the acoustic pressure from this calculation tool are in a good agreement with the international published works. Applying the tool in some specific calculation cases gives appropriate results, thereby giving important recommendations about the safe distance corresponding to the human hearing threshold for rotors with specific geometric dimensions and operating characteristics.

Keywords: *Helicopter rotors; aerodynamic noise; acoustic pressure; vortex lattice method; calculation tool.*

1. Introduction

Helicopters often generate loud noise during horizontal flights and landing maneuvers, creating serious noise pollution, especially in residential areas near the helipad. The rotor is the main part of the helicopter that generates the lift to help its movements, and it is also the object creating the largest aerodynamic noise. The research for the harmful effect reduction of the aerodynamic noise has a very important meaning and is becoming great necessity. Nowadays, there are many studies on the aerodynamic noise of helicopter rotors in the world, and most of these studies apply the Ffowcs Williams-Hawkings (FW-H) equation [1, 2] to describe the noise generation due to the motion of the rotor blade surface in turbulent flows. Many studies use the Computational Fluid Dynamics (CFD) method to estimate the noise of rotors in the near-field based on solving the Reynolds-Averaged Navier-Stokes (RANS) equation [3, 4]. This CFD method has high accuracy but it has a large requirement on computer resources and takes a long time to calculate. Moreover, the CFD method cannot separate the total noise into different noise sources.

Several other studies use the experimental method in the wind tunnel or carry out the experimental flight to measure the aerodynamic noise [5, 6]. In Vietnam, researches

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on aerodynamics of helicopter rotors are increasingly interested and developed. However, many problems related to the aerodynamic noise have not been studied, and there're not many publications which have been published. In the present work, we focus on studying to determine the aerodynamic noise characteristics of helicopter rotors by the vortex lattice method, in order to build a reliable calculation tool for studying and investigating the aerodynamic noise characteristics of different rotors on aircrafts in the future.

2. Building and verifying the calculation tool

2.1. Building the calculation tool

Determining the aerodynamic noise characteristics of rotors is divided into two main problems: the aerodynamic problem and the aerodynamic noise problem in which the pressure distribution calculated from the aerodynamic problem acts as input parameters and the noise source in the aerodynamic noise problem.

For the aerodynamic problem, using the panel method/unsteady vortex lattice method to build a rotor model and calculate the aerodynamic characteristics of the rotor, determine the pressure distribution on the blade surface, the induced velocity and simulate the vortex wake behind rotors (as shown in Fig. 1).

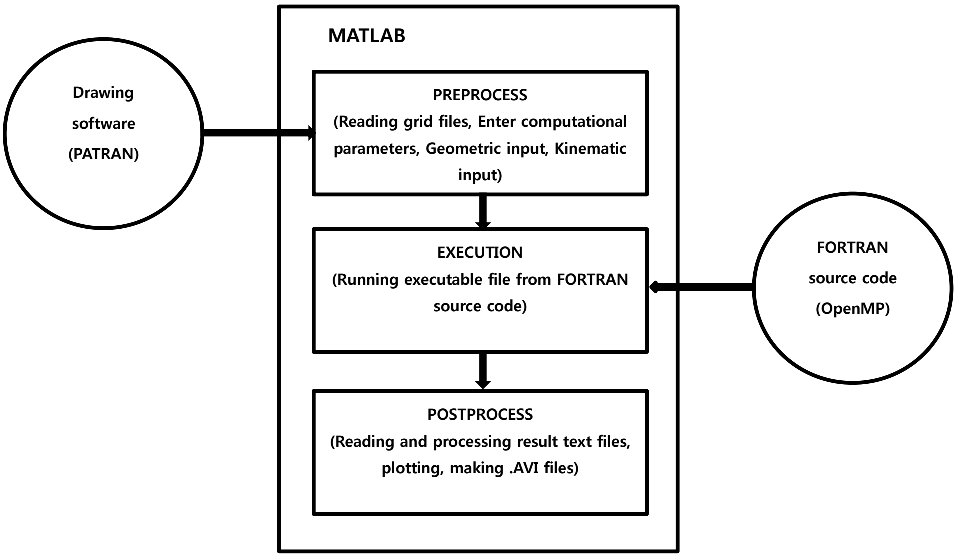


Fig. 1. Scheme for calculating aerodynamics of helicopter rotors / UAV.

The input of geometric dimensions, meshing and defining mesh indexes are conducted on Patran software. The code programming for calculating the aerodynamics of rotors by the panel method or the unsteady vortex lattice method is performed on the Fortran/Matlab software. The Matlab software is also used to input data, calculate and simulate, process results. This program for calculating the aerodynamics (schematic in

Fig. 1) can be applied for many aerodynamic objects such as flat wings, rotors, delta wings or flapping wings with thin wing or 3D wing models. The building models, setting boundary conditions, calculating and verifying results of aerodynamic problems are presented in works [7-10].

For the aerodynamic noise problem, according to the research of Ffowcs Williams-Hawkings [1], the aerodynamic noise generated by the motion of the rotor included main components: the thickness noise (TN - the noise due to the motion of the rotor in the rotation plane); the loading noise (LN - the noise caused by aerodynamic loads acting on the blade surface); the blade vortex interaction noise (BVI - the noise caused by the interaction between blades and the vortex) and the high-speed impulsive noise (HSI - the noise caused by the high-speed motion of blade components, usually at the tips). Here, TN and LN are lower harmonic noise sources; BVI and HSI are impulsive noise sources. Lower harmonic noise occurs during all flight conditions. Impulsive noise only occurs during certain flight conditions, e.g., BVI generates by helicopter rotors in descending flight and HSI generates by helicopter rotors in high-speed forward flight [11]. In this article, we only consider helicopter in low-speed forward flight (v = 51.631 m/s) and in hover. Then, the aerodynamic noise generated by helicopter rotors only included the thickness noise and the loading noise; BVI and HSI can be neglected.

The acoustic pressure is determined by using the Formulation 1A of Farrasat [2], which is one of solutions of the FW-H equation. The noise source is the mesh elements that make up the rotor blades with a pressure distribution varying with flight time. The input data includes: the pressure distribution on the blade surface, the area of the vortex elements, the coordinates of collocation points, the value of the normal vector at each collocation point, the index of the panel components... are taken from the aerodynamic problem.

Formulation 1A of Farrasat [2] is given by:

$$p'(x,t) = p'_T(x,t) + p'_L(x,t) \tag{1}$$

where $p'(x,t)$ is the total acoustic pressure at observers; $p'_T(x,t)$ and $p'_L(x,t)$ are the pressure causing thickness noise and loading noise, respectively. For an arbitrary observer, thickness noise and loading noise can be written as:

$$p'_T(x,t) = p'_{TN}(x,t) + p'_{TF}(x,t) \tag{2}$$

$$p'_L(x,t) = p'_{LN}(x,t) + p'_{LF}(x,t) \tag{3}$$

where the subscripts N, F stand for near-field and far-field noise determined by the expressions:

$$p'_{TF}(x,t) = \frac{1}{4\pi}\int_{f=0}\left[\frac{\rho_0 \dot{v}_n}{r(1-M_r)^2} + \frac{\rho_0 v_n \hat{r}_1 \dot{M}_1}{r(1-M_r)^3}\right]_{ret} dS \tag{4}$$

$$p'_{TN}(x,t) = \frac{1}{4\pi}\int_{f=0}\left[\frac{\rho_0 c v_n (M_r - M^2)}{r^2(1-M_r)^3}\right]_{ret} dS \tag{5}$$

$$p'_{LF}(x,t) = \frac{1}{4\pi c}\int_{f=0}\left[\frac{\dot{p}\cos(\theta)}{r(1-M_r)^2} + \frac{p\cos(\theta)\hat{r}_1 \dot{M}_1}{r(1-M_r)^3}\right]_{ret} dS \tag{6}$$

$$p'_{LN}(x,t) = \frac{1}{4\pi}\int_{f=0}\left[\frac{p(\cos(\theta) - M_i n_i)}{r^2(1-M_r)^2} + \frac{p\cos(\theta)(M_r - M^2)}{r^2(1-M_r)^3}\right]_{ret} dS \tag{7}$$

$$\tau = t - \frac{r}{c} = t - \frac{|\boldsymbol{x} - \boldsymbol{y}|}{c} \tag{8}$$

where p is the pressure at source points; c is the speed of sound; ρ_0 is the airflow density; t is the time at observers (microphones); τ is the retarded time when the noise is emitted from the source to the observer; $M_r = \dot{M}_1 \hat{r}_1$ is the Mach number of source in radiation direction; v_n is the local normal velocity to blade surface; the subscripts n and r represent terms in the normal and emission directions with the blade surface; the subscripts n and r represent terms in the normal and emission directions with the blade surface; $r = |\boldsymbol{x} - \boldsymbol{y}|$ is the distance between observer and source, $\boldsymbol{x}$ is the observer position vector, $\boldsymbol{y}$ is the source position vector. $f = 0$ is a function describing the blade surface (source surface); $\cos(\theta) = \boldsymbol{n} \cdot \hat{\boldsymbol{r}}$, with θ used to denote the angle between the normal vector $\boldsymbol{n}$ to the emission surface and the radiation direction $\boldsymbol{r}$ at the time of emission [2, 4].

2.2. Verifying the calculation tool

Verifying obtained results with the experimental data from the works of Conner D.A. [12] and Brentner K.S. [13], the experimental object is a rotor model of a helicopter UH-1H with a scale of ¼. The experiment was conducted in the acoustic chamber of the Langley 4 wind tunnel (7-Meter Tunnel). The experimental rotor included 2 blades of standard rectangular shape and with specific parameters shown in Table 1. The rotor operates in a wind tunnel at wind speed of 100 knots (51.631 m/s) and rotates with an angular speed of 1296 rpm. The noise characteristic parameters were measured by microphones from 1 ÷ 8 arranged in the wind tunnel in both the near-field and far-field. However, the works [12] and [13] published only the obtained results at the mic. 4 with coordinate $x = -3.27$ m, $y = 2.16$ m, $z = -0.17$ m and at the mic. 5 with coordinate $x = -3.28$ m, $y = -2.23$ m, $z = -0.17$ m (Fig. 2).

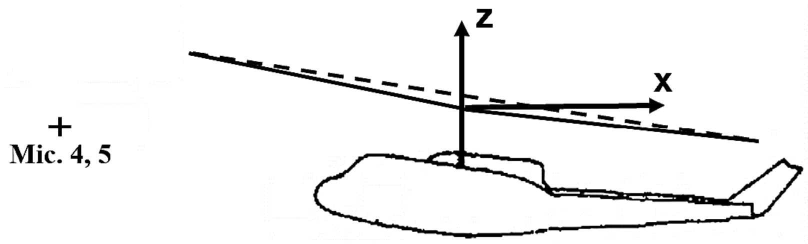


Fig. 2. Positions of mic. 4 and 5 in vertical projection plane [9].

Microphones 4 and 5 are located symmetrically about the XZ plane and Conner D.A. oriented to measure the acoustic pressure in the far-field. And in the calculational model, rotors are built, meshed and determined indexes in Patran software with the geometric parameters input corresponding to the experimental rotor's dimensions, with the blade airfoil 3D with profile NACA0012 (Fig. 3 and Table 1).

Table 1. Geometric parameters of the rotor model

№	Geometric parameters	Value
1	Number of blades n_{blade}	2
2	Rotor radius R, m	1.829
3	Rotor rig radius R_{cutout}, m	0.1554
4	Blade chord c, m	0.1334
5	Pitch angle, deg	9
6	Angular speed ω, rpm	1296
7	Blade airfoil	NACA0012
8	Blade twist, deg	10.9^{o}

Accordingly, rotors include 2 blades, modeled by 680 panels with 760 nodes. After 600 calculation steps (time step dt = 0.00046296 s) corresponding to 6 revolutions, the obtained results of aerodynamics (Problem 1) are shown in Fig. 3 and Fig. 4.

Figure 3 shows the vortex wake behind rotors during motion. The time-dependent lift coefficient in this calculational model has the value of $1.2 \cdot 10^{-3} \div 5.1 \cdot 10^{-3}$ and the average value of $C_T = 0.00315$ (Fig. 4).

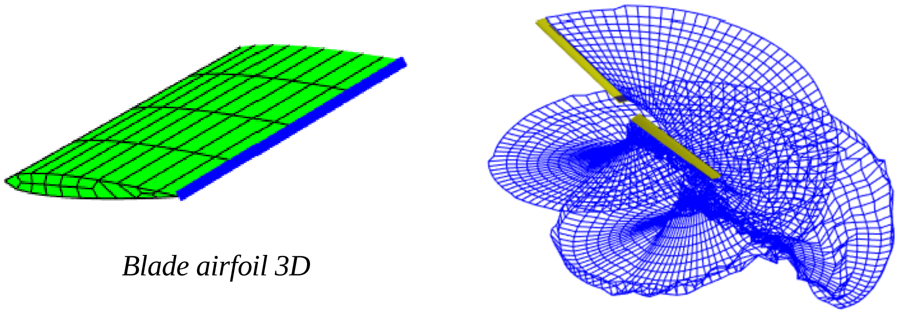


Fig. 3. Votex wake behind rotors.

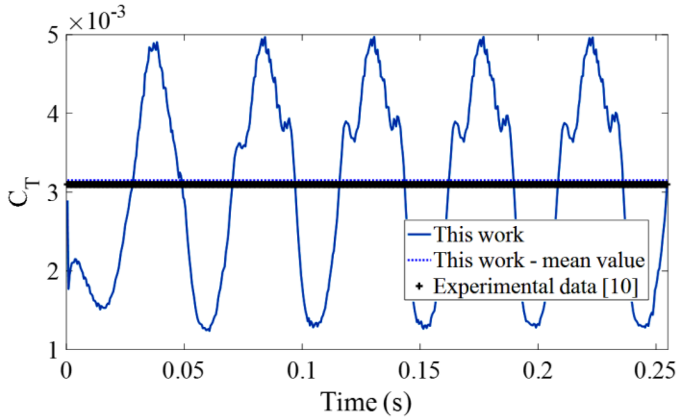


Fig. 4. The variation of the time-dependent lift coefficient of rotors.

The average lift coefficient value of rotors in the experimental model of Conner D.A. ([12] - Table II, page 9) of $C_T = 0.0031$. The difference between the lift coefficient values of this calculational model and the experimental rotor model of Conner D.A. [12] is relatively small ($\varepsilon = 1.6\%$). In addition, the results of the pressure distribution at the blade elements, the values of the normal vectors, the area of the blade elements, the local speed at the collocation points on the blade, etc. are saved in the data file .DAT and input into the computational program of the noise problem, which is written on the basis of equations (1) ÷ (8).

Results of the acoustic pressure at mic. 4 position with coordinates $x = -3.27$ m, $y = 2.16$ m, $z = -0.17$ m obtained from this calculation tool, the experimental model [12] and the calculational model of Brentner K.S. [13] are shown in Fig. 5. It is found that the variation and value of the acoustic pressure from this calculation tool are in a good agreement with the published data in works [12] and [13].

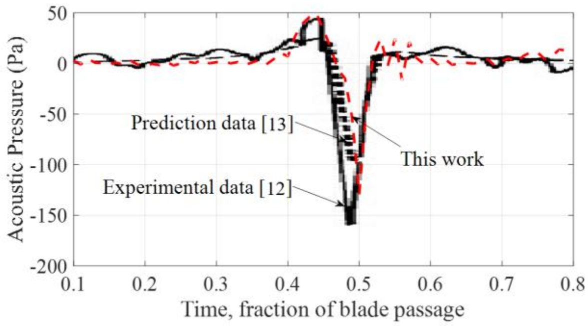


Fig. 5. Variation of the time-dependent acoustic pressure in 1 period.

Using the FFT transformation (Fast Fourier Transform) as a mapping an acoustic pressure signal in the time domain onto its spectrum in the frequency domain. Then the sound spectrum diagram at mic. 4 obtained from this calculational model are shown in Fig. 6. The value of the sound pressure level obtained from this calculation tool is in a good agreement with the experimental data [12], especially in the low frequency domain. The maximum values of the sound pressure level (SPL) obtained from this calculation tool and from the works [12, 13] are 118 dB, 115 dB and 112 dB, respectively, the error is less than 3%.

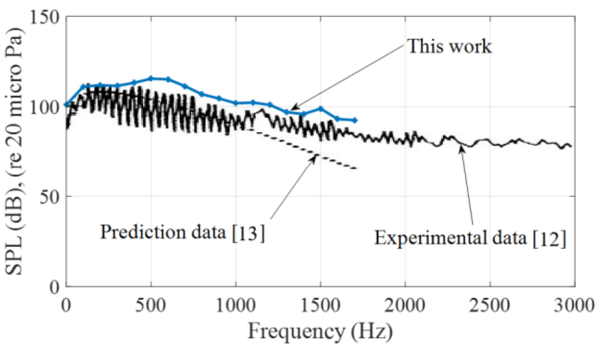
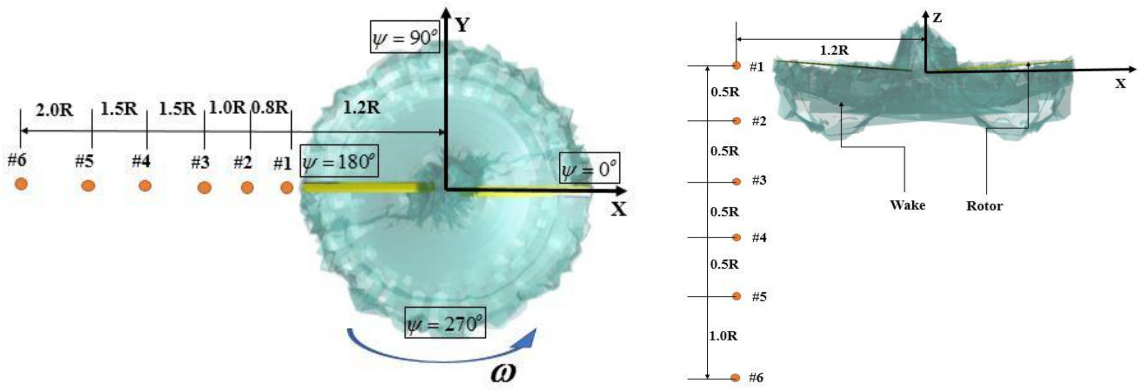


Fig. 6. The Sound spectrum diagram.

The obtained results and verification show that the calculation tool for calculating aerodynamics and aerodynamic noise characteristics of helicopter rotors presenting in this work is reliable and gives accurate results.

3. Calculating aerodynamic noise characteristics of rotors

Using the verified calculation tool above, carry out calculating and investigating the aerodynamic noise characteristics of helicopter rotors in hover. Microphone positions for determining aerodynamic noise parameters such as the acoustic pressure, the sound pressure level and acoustic pressure components (thickness noise, loading noise) are shown in Fig. 7.



Case 1 **Case 2**

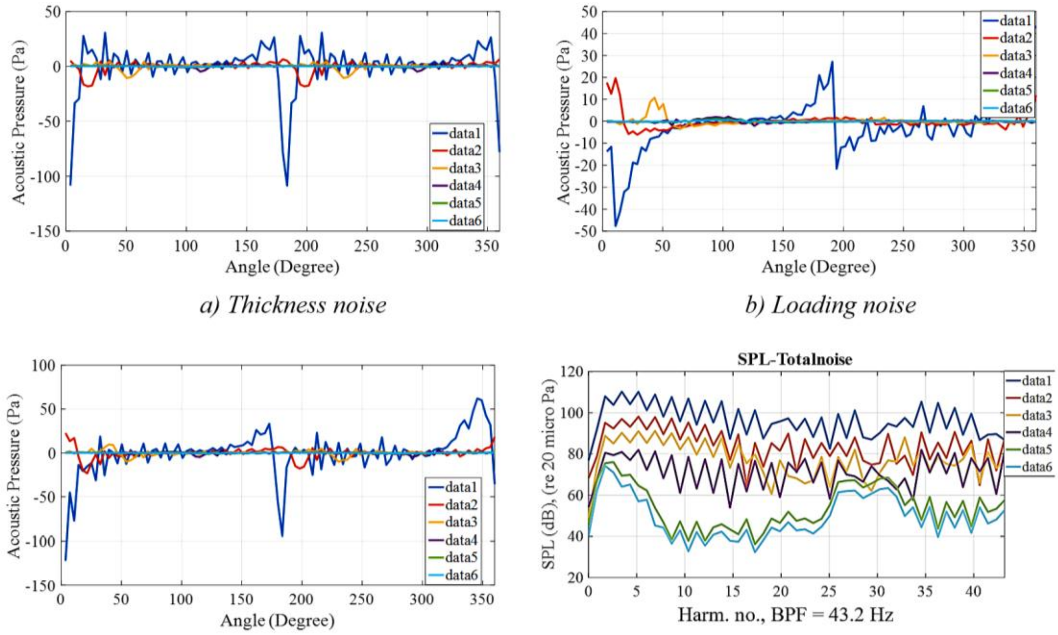
Fig. 7. Microphone positions for measuring aerodynamic noise parameters.

In case 1, observers from #1 to #6 are in the horizontal direction, and in case 2, observers are in the vertical direction. The observers's coordinates in each case are presented in Table 2.

Table 2. Coordinates of observers in case 1 and 2

№	Case 1	Case 2
#1	(-1.2×R, 0, -0.01×R)	(-1.2×R, 0, -0.01×R)
#2	(-2.0×R, 0, -0.01×R)	(-1.2×R, 0, -0.5×R)
#3	(-3.0×R, 0, -0.01×R)	(-1.2×R, 0, -1.0×R)
#4	(-4.5×R, 0, -0.01×R)	(-1.2×R, 0, -1.5×R)
#5	(-6.0×R, 0, -0.01×R)	(-1.2×R, 0, -2.0×R)
#6	(-8.0×R, 0, -0.01×R)	(-1.2×R, 0, -3.0×R)

The acoustic pressure and the sound spectrum in case 1 are determined and shown in Fig. 8. The results show that in the horizontal direction when observers are gradually moved father away from the rotor, the acoustic pressure decreases (both thickness noise and loading noise components). Similarly, the SPL also decreases with increasing distance from the rotor center, and when the observer located on the distance futher than 3R from the rotor center (>3R), the SPL value is less than 80 dB, which is within the safe hearing threshold for humans (Fig. 8d). The observers in the case 1 are located on the rotor plane, so the acoustic pressure of the thickness noise component here has a larger value than the acoustic pressure of the loadingness noise component. This is consistent with the research results in many other specialized documents.



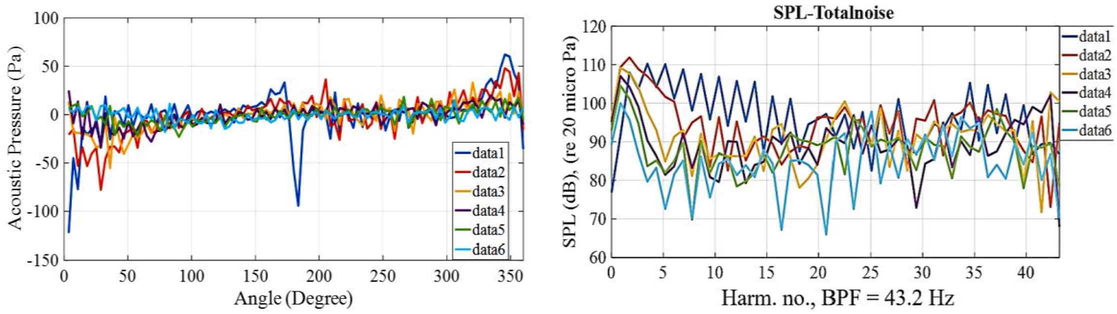
a) Thickness noise *b) Loading noise*

c) Total noise *d) SPL Case 1*

Fig. 8. Aerodynamic noise characteristics in case 1.

In case 2, when observers are gradually distributed father away from the rotor in the vertical direction, the obtained acoustic pressure value and the sound spectrum diagram are shown in Fig. 9. Accordingly, similar to case 1, at observers closer to the rotor, a high acoustic pressure and a high sound pressure level were obtained. In the vertical direction, the observer located on the distance futher than or equal 2R from the rotor centre, the obtained SPL is within the safe hearing threshold for humans.

In addition, comparing the obtained results in both survey cases shows that the further away from the rotor, the sound pressure level reduction in the vertical direction is larger than that in the horizontal direction. This shows that the thickness noise component propagates away in the horizontal direction on the rotor plane, and the loadingness noise component has a downward direction and has a faster extinguishing rate.



a) Total noise *b) SPL Case 2*

Fig. 9. Aerodynamic noise characteristics in case 2.

4. Conclusion

In this article, a tool for calculating aerodynamic noise characteristics of helicopter rotors by the vortex lattice method was built. The calculation tool is verified by comparing with experimental and prediction data in reputable international publications, ensuring accuracy and reliability. By using the tool in specific calculation cases and conditions (hover, according to case 1 and case 2), based on obtained results and surveys, the authors have made important recommendations about the safe distance corresponding to the human hearing threshold for rotors with specific geometric dimensions and operating characteristics.

References

[1] Ffowcs Williams J. and Hawkings D., "Sound Generation by Turbulence and Surfaces in Arbitrary Motion", *Mathematical and Physical Sciences (1934-1990)*, Vol. 264 (1151), pp. 321-342, 1969, DOI: 10.2307/73790

[2] F. Farassat (2007), "Derivation of Formulations 1 and 1A of Farassat", NASA/TM-2007-214853, https://ntrs.nasa.gov/citations/20070010579

[3] Takashi AOYAMA, Choongmo YANG, Natsuki KONDO and Shigeru SAITO, "Fundamental CFD Analysis on Main-Rotor/Tail-Rotor interaction noise of helicopter", Japan Aerospace Exploration Agency, Chofu, Tokyo, 2004, Vol. 53, pp. 215-220, doi: https://doi.org/10.11345/nctam.53.215

[4] A N Kusyumov, S A Mikhailov, S A Kusyumov, K V Fayzullin, G N Barakos, "Numerical Simulation of Aeroacoustics of Hovering Helicopter Rotor", *Materials Science and Engineering*, 449, 2018, DOI: 10.1088/1757-899X/449/1/012017

[5] Stepanov R., Pakhov V., Bozhenko A., Batrakov A., “Experimental and numerical study of rotor aeroacoustics”, *International Journal of Aeroacoustics*, 16(6), pp. 460-475, 2017, DOI: 10.1177/1475472X17730447

[6] Zhe Ning, Hui Hu, “An Experimental Study on the Aerodynamics and Aeroacoustic Characteristics of Small Propellers of UAV Applications”, *54th AIAA Aerospace Sciences Meeting,* San Diego, California, USA, 2016, DOI: 10.2514/6.2016-1785

[7] Phạm Thành Đồng, Nguyễn Anh Tuấn, Đặng Ngọc Thanh, Phạm Vũ Uy, “Xây dựng mô hình tính toán các đặc trưng khí động của cánh quay trực thăng”, *Tạp chí Khoa học và Kỹ thuật,* Đại học Kỹ thuật Lê Quý Đôn, số 185, 2017.

[8] Thanh Dong Pham, Anh Tuan Nguyen, Ngoc Thanh Dang and Vu Uy Pham, "On the aerodynamic interactions analysis between the main rotor and the helicopter fuselage", *Proceedings of International Symposium on Applied Science 2019*, Vol. 3, pp. 123-132, 2020, ISSN: 2515-1770. Published: May 14, 2020, Kalpa Publications in Engineering. https://doi.org/10.29007/3m41

[9] Anh Tuan Nguyen, Jong-Seob Han and Jae-Hung Han, “Effect of body aerodynamics on the dynamic flight stability of the hawkmoth Manduca sexta”, *Bioinspiration & Biomimetics,* ISSN: 1748-3190, Vol. 12, No. 1, 2016, DOI: 10.1088/1748-3190/12/1/016007

[10] Pham Thanh Dong, Nguyen AnhTuan, Dang Ngoc Thanh, Pham Vu Uy, “Numerical Method to Study Helicopter Main Rotor-fuselage Aerodynamic Interaction”, *International Conference on Fluid Machinery and Automation Systems 2018 (ICFMAS2018)*/Ta Quang Buu Library, Hanoi University of Science and Technology (HUST).

[11] Eric Greenwood, “Fundamental Rotorcraft Acoustic Modeling from Experiments (FRAME)”, Dissertation submitted to the Faculty of the Graduate School of the University of Maryland, College Park in partial fulfillment of the requirements for the degree of Doctor of Philosophy 2011, https://drum.lib.umd.edu/handle/1903/11518.

[12] Conner, David A.; and Hoad, Danny R., “Reduction of High-speed Impulsive Noise by Blade Planform Modification of a Model Helicopter Rotor”, NASA Technical Memorandum-84553, AVRADCOM TR 82-B-6, 1982. https://ntrs.nasa.gov/api/citations/19830007880/downloads/19830007880.pdf

[13] Kenneth S. Brentner, “A Computer Program Ilzcorporutilzg Reulistic Blude Motiolzs ulzd Advulzced Acozcstic Formahtion”, NASA Technical Memorandum-87721, NASA Langley Research Center Hampton, VA 23665-5225, 1986. https://ntrs.nasa.gov/citations/19870001317

NGHIÊN CỨU XÂY DỰNG VÀ KIỂM CHỨNG CÔNG CỤ TÍNH TOÁN TIẾNG ỒN KHÍ ĐỘNG CỦA CÁNH QUAY TRỰC THĂNG

Lê Quang Quyền, Phạm Thành Đồng, Nguyễn Anh Tuấn, Vũ Quốc Trụ

Tóm tắt: *Bài báo trình bày cách tiếp cận xây dựng và kiểm chứng công cụ tính toán đặc trưng tiếng ồn khí động của cánh quay trực thăng. Công cụ được xây dựng trên cơ sở kết hợp phương pháp xoáy và công thức 1A của phương trình Ffowcs Williams-Hawkings (FW-H). Bằng cách so sánh kết quả tính toán với số liệu từ công trình nghiên cứu uy tín nước ngoài, công cụ tính toán được kiểm chứng tính chính xác và độ tin cậy. Kết quả tính toán cho thấy quy luật biến thiên và giá trị áp suất âm từ công cụ tính toán của nhóm tác giả rất tương đồng với các số liệu công bố quốc tế. Áp dụng công cụ trong một số trường hợp tính toán cụ thể cho kết quả phù hợp, từ đó đưa ra được các khuyến cáo có ý nghĩa quan trọng về khoảng cách an toàn ứng với ngưỡng nghe giới hạn của con người đối với cánh quay có kích thước hình học và đặc điểm hoạt động cụ thể.*

Từ khóa: Cánh quay trực thăng; tiếng ồn khí động; áp suất âm thanh; phương pháp xoáy; công cụ tính toán.

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