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Proposing Method for Airframe Noise Prediction Benefitting Indonesian Aircraft Design

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Abstract. This paper describes the proposal for an airframe noise prediction method that can be used in Indonesian aircraft design research and industry. Since the industry is strategic, whether economically or securely, the country should build their own technology in all phases. Noise assessment is one of the sophisticated procedures in designing and manufacturing aircraft. Indonesia has not developed and manufactured engines, therefore airframe noise prediction is a relevant object to study. This method is proposed to be a utility to improve Indonesian aircraft design specifications. Based on the analogy theory of aeroacoustics, the use of Ffowcs Williams and Hawkings (FWH) equation was chosen to represent noise. The noise prediction method was developed by simulating and modeling in OpenFOAM, an open-source software based on the finite volume method. Its reliability has been proven in research and industrial computational fluid dynamics. The proposed method is developed from CFD and is compatible with using a personal computer device. The algorithm based on boundary conditions and hardware specifications has been built. Each step has been designed to support FWH Equation solver uniquely for this study. Computational domains represent the airflow area overrun a solid object. For the reason of far-field radiation, the domain token is 20 times the dimension of the object, and wall functions are applied. The atmosphere condition of low flight level and low to medium subsonic speed is taken to represent various aircraft designs and configurations. The condition represents the existing Indonesian industry of civil and military flying vehicles, and its possibility to develop.

Keywords: Aeroacoustics; Airframe noise; FWH equation; Indonesian aircraft; OpenFOAM

1. Introduction

Aircraft design is one of the strategic technologies that has already been mastered by the Indonesian aviation industry for decades. While the global development of this industry presents distinct challenges, the implementation of the fly-by-wire system in the N250 aircraft in 1995 serves as evidence of Indonesia's technological advancement in this domain. Recently, the manufacture of N219, R80, and several types of unmanned aircraft convinced the development of the industry. For the purpose of high performance and

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specification, it is recommended to master all phases of aircraft design and manufacturing technology.

A study regarding the high-performance level of the aerospace industry in a developed country showed that research and development is one of the crucial factors. The study, focusing on Mexico, recommends that the country prioritize maintaining and enhancing its research and development efforts to achieve a high-performance level in the aerospace industry (Manzo and Rodríguez, 2022). To Indonesia as well, more advanced design specifications will be achieved by improving appropriate research, especially on contributing responsibility to environment, sustainability, and national security. Establishing a harmonic aerospace ecosystem is also a commitment to Indonesian general development (Birowo *et al.,* 2020). Since all engines that produce major noise in flying vehicles are manufactured abroad, the airframe is a relevant object to be studied in Indonesia. Several methods for predicting airframe noise have been built with specific purposes of aircraft, depending on institutions that support them. This study has justification for developing an airframe noise prediction method to apply simultaneously with the progress of Indonesian aircraft research and technology (Kusumalestari, Soekirno, and Sudibyo, 2019).

The current study proposed key contributions as follows:

- The study supports the purpose of establishing the Indonesian aerospace ecosystem
- The result can be used as part of multidisciplinary conceptual design in manufacturing manned and unmanned aircraft across the nation for the reason of economic strategy
- The result can support military benefit of aircraft design in the mission of national insight and security
- The study is an adding value of responsibility and sustainability of research and development of Indonesian aircraft technology

2. Literature Review

To sustain the environmental issues of green aviation, research on aircraft noise has been conducted in many countries and regions (Ali *et al.,* 2019). For instance, the European Union has a program to reduce aircraft noise from engines and airframes. The ACARE (Advisory Council for Aeronautics Research in Europe) program achieved its target of reducing aircraft noise by 50%, from approximately 150 dB to 75 dB by 2020 and the program aims to further reduce noise levels by more than 65% by 2050 (Kors and Collins, 2020). Since engine and jet burst exhaust noise have been significantly reduced, further reduction will be on the same scale as the airframe noise. It is almost equal to airframe noise on wide-body aircraft when approaching landing (Airbus, 2003). In civil aviation, aircraft noise usually will be reduced to meet a regulation. Out of aircraft design, noise mitigation can be done by several methods, for example, a study on departure trajectory (Suryo *et al.,* 2020). In defence or military technology, the targets are more visionary, such as Unmanned Aerial vehicles (UAV), missiles, and aerial reconnaissance. After overcoming radar as a major barrier, the vision of flying vehicles is to meet the silence of flying owls (Jaworski and Peake, 2020). Nevertheless, from the perspective of aircraft design and manufacture, noise is also identified as a form of energy.

2.1. Indonesian Aircraft Industry

For a couple of years, aircraft design and manufacture in Indonesia have been developing many types of flying vehicles. Aircraft such as N219 and R80 have already been produced to get involved in regional transportation with small to medium numbers of passengers. Today, air transport is Indonesia's most popular regional public transportation (Badan Pusat Statistik, 2024). Furthermore, since the country is an archipelago, flight with advanced aircraft models such as wing-in-ground effect and amphibia are feasible to develop. UAVs such as Minibe, Ruppel Bomber, Male, and other drones with different missions are also developed by government and private institutions. For purposes such as farming, mapping, or other non-military applications, UAVs are typically optimized for economic and environmental performance. For military purposes, UAVs are expected to be more specified and have better performance. For instance, weaponized drones and kamikaze drones are designed to have a far operation range, long-life battery, and fast velocity. The operational range of the drone developed and manufactured in Indonesia could reach 50 km and a maximum velocity of 250 km/jam or about 0.2 M, where M is for Mach number. The life of batteries varies, starting from 180 minutes to 900 minutes to 24 hours. Under research and development, the specifications and performance of the vehicles may be improved. Many studies on noise reduction in Indonesia have been published. For instance, using composite material to absorb sound (Zulkarnain *et al.,* 2023). More advanced research on optimization energy has also been studied (Akbar *et al.,* 2022). Further, the Indonesian research program needs to improve to reduce noise from the conceptual design stage.

2.2. Airframe Noise Prediction

In general, noise will be directly proportional to the reduction of aerodynamic performance and power efficiency of the aircraft (Glegg and Devenport, 2017). However, more specific studies on airframe noise could increase power consumption as noise is reduced (Hirschberg and Rienstra, 2004). These could be different when the design is blended wing body aircraft, flying wing, wing in ground aircraft, or other shape. To avoid more expensive modifications in the manufacturing phase, noise prediction should be implemented in the very early phase of design. Thus, to perform optimization, study and treatment should be conducted in the phase of conceptual design and multidisciplinary mode (Sahai, 2016; Hosder, 2004). According to this phase, the basic shape of clean wing or clean aircraft is applied. The geometry is calculated when the type and function of the aircraft to be built are determined (Kundu, Price, and Riordan, 2019; Raymer, 2018). An early study by Brooks and Hodgson describes noise generated from trailing edge of a clean wing in their research. The study shows the field of noise around trailing edge with a condition of low Mach number and boundary condition flow is fully turbulent (Glegg and Devenport, 2017). The advancement of relevant studies utilizing computation will be described in the next subsection of this paper, as well as existing methods.

The study of noise from aerodynamic flows was originally formulated by Lighthill in an equation derived from the properties of flow continuity and momentum conservation, mainly caused by turbulence. The formula is developed by applying fluctuation of aeroacoustics pressure tensor, $\boldsymbol{T}_{ij}$, as an analogy of vibration in classical acoustics. With the development of aeroacoustics research, Lighthill's equation was modified to resume the formula approaching the real conditions of each case. One of those equations is the Ffowcs Williams and Hawkings (FWH) Equation. While Lighthill's formula only represents turbulence in open areas, FWH complements the term of the boundary layer from Curle's model, and the arbitrary motion of aerofoil surface (Nitzkorski and Mahesh, 2015; Mendez, 2013). In general, the equation is described as follows:

$$4\pi a^2(\rho(x,t)-\rho_o)=\int\left[\frac{\partial^2\boldsymbol{T}_{ij}}{\partial x_i\partial x_j}\right]df-\int\frac{\partial}{\partial x_i}\left(p_{ij}\delta(f)\frac{\partial f}{\partial x_j}\right)+\int\frac{\partial}{\partial t}\left(\rho_0\boldsymbol{v}_i\delta(f)\frac{\partial f}{\partial x_i}\right) \quad (1)$$

While the lefthand side of Equation 1 represents fluctuating momentum as a total noise source, the righthand side consists of several terms. The first term, diffusion term, represents noise generated by turbulence in an open area that is far enough from the solid surface within the observed area. The second term represents noise from convection flow shearing on the boundary layer on a solid surface. The third term represents the arbitrary motion of the solid surface within the aerodynamic flow, for example an aircraft's wing motion in the atmosphere. Constant a is the speed of sound in reference medium, variable ρ is density, variable p is pressure, $\boldsymbol{v}$ is a vector of velocity in 3D, $\boldsymbol{x}$ represents location in 3D, t is identifying time, while the Dirac function (δ) has exact value for $f = 0$, otherwise zero. Notation f is a function representing the surface of semipermeable element volume which is solved by Gauss theorem. $\boldsymbol{T_{ij}}$ is Lighthill's or aeroacoustics pressure tensor described as:

$$\boldsymbol{T_{ij}} = \rho \boldsymbol{v_i} \boldsymbol{v_j} + \boldsymbol{p_{ij}} - a_0^2 \rho \delta_{ij} \tag{2}$$

The first term of the righthand side of Equation 2, usually named Reynold's Stress, contains vector velocity of a volume element and vector velocity of the main flow. The first and second terms represent pressure inside the element volume of flow, and the third term represents pressure around the element. Physical illustrations of FWH derivation are described by Zinoviev to compare it with other equation of the analogy, however, experiments to validate the equation begin after it (Zinoviev, 2002).

2.3. Existing Methods of Noise Prediction

To analyze the implementation of the FWH equation in the currently proposed method had been issued (Kusumalestari *et al.,* 2019). The specific form of the equation was also studied by Spalart and Shur (2009) and by Jarozs, Czajka, and Golaś (2016), which applied FWH to different objects and conditions (Jarozs, Czajka, and Golaś, 2016; Spalart and Shur, 2009). One of the recent studies using the equation is carried out by Al Hawwary and Wang (2020). The method is built to predict noise sourcing from jet streams in low subsonic ($v < 0.3\ M$) conditions. The result shows good agreement with experimental data (Al Hawwary and Wang, 2020). Recent implementation of the equation on part of airframe is a study of high lift devices noise from wings of N219 Indonesian aircraft at BRIN (*Badan Riset dan Inovasi Nasional*), an Indonesian Research Centre. The equation is implemented on Fluent Ansys CFD software with large eddy simulation method. The result identifies good agreement between the computational model and existing data in a confined frequency range (Soemaryanto *et al.,* 2021).

Recent research on noise prediction methods includes dissertations by Sahai (2016), and Bertsch (2013), Hosder (2004). Hosder worked on predicting noise in clean wing conditions by defining a new noise scale based on the sound source within the near field area. The study demonstrates that noise production is highly dependent on the lift coefficient (C_L); specifically, as the lift coefficient increases, the generated noise also increases (Hosder, 2004). Hosder's method is a part of an aerodynamic project of aircraft design research at Virginia Polytechnic Institute and State University and is prepared to be integrated into NASA's (National Aeronautics and Space Administration) program of ANOPP (Aircraft Noise Prediction Program).

A study by Bertsch in 2013, utilizes computational aeroacoustics (CAA) software rather than computational fluid dynamic (CFD) and is appropriate for both compressible and incompressible fluid flow, this means is applicable for low and high subsonic speed. The method, named PANAM (Parametric Aircraft Noise Analysis Module), is compatible with assessing environmental and economic performance of different flying vehicles under various scenarios. By applying the Bertsch method to a comprehensive program of conceptual aircraft design, the correlation between the geometry shape of aerofoil and noise emission can be described (Bertsch, 2013).

Another study on predicting noise in conceptual design phase was delivered by Sahai in 2016, named INSTANT (ILR Noise Simulation and Assessment), where ILS stands for Instrument Landing System. In this study, noise prediction is referred to as psychoacoustics phenomena. The study utilizes CAA software and is applicable for low subsonic speed. The result of the study shows that for wider aerofoil surfaces, airframe noise will increase (Sahai, 2016). The method was built to be integrated with MICADO (Multidisciplinary Integrated Conceptual Aircraft Design and Optimazion) program held by RWTH (*Rheinisch-Westfälische Technische Hochschule*) for aircraft design.

Table 1 Existing latest noise prediction methods

Noise Source & Flight Speed	Tools	Mathematical Approach	Computational Method	Method/ Researcher
clean aircraft conceptual design phase low subsonic (< 0.3 M)	specific CAA in Virginia Polytechnic Institute & State University, USA	FW-Hall and *(k-ω)SST* turbulent model	solved in average value (RANS)	(Hosder, 2004) Note: applicable to ANOPP, aircraft noise prediction by NASA
all components conceptual design phase low & medium subsonic (< 0.3 M)	field simulation	using existing noise model and flight trajectory simulator from the Institute of Aerodynamics and Flow Technology, Braunschweig, Germany		PANAM (Bertsch, 2013)
all components conceptual design phase low subsonic (< 0.3 M)	field simulation	using airframe and engine noise simulator from RWTH, Aachen, Germany		INSTANT (2) (Sahai, 2016) Note: applicable to MICADO, aircraft design program by RWTH
rotor blade assessment phase low subsonic (< 0.3 M)	CFD OpenFOAM using Zeus HPC 24 core in AGH University of Science & Technology, Poland	FWH and Spalart-Allmaras turbulent model	solved in average value	Jarozs, Czajka, and Golaś, 2016)
airframe and jet assessment phase transonic (0.8 - 1.2 M)	CFD hpMusic using high-specification computers at the University of Kansas	FWH and turbulent flow simulation	solved in direct value (LES)	Al Hawwary and Wang (2020) Note: part of USA Department of Defense project
clean aircraft conceptual design phase low subsonic (< 0.3 M)	CFD OpenFOAM using PC	FWH and Spalart-Allmaras turbulent model	solved in average value	PROPOSED METHOD

In many research issues based on fluid dynamics or similar studies, open-source software is not as widely used as commercial software. For more specialized fields such as aeroacoustics, there are still far fewer. In research assessing the reliability of open-source software for academic and industrial studies, Shademan and the team compared OpenFOAM, an open-source software, with one of the popular commercial software. The results show very good agreement between booth simulation performance dynamic flow. (Shademan, Barron, and Balachandar, 2013). OpenFOAM has already been used as an aerodynamics research tool in industrial environments, including automotive and aviation. Thus, the advantage of OpenFOAM is not only because it can be used for free, but also because it is reliable for performing fluid dynamics computations (Tofany, 2023; Marbona, 2018; Jasak, Jemcov, and Tukovic, 2017). Initially, this proposed method begins with a brief study on the probability of utilizing OpenFOAM to build an FWH solver (Kusumalestari *et al.*, 2020). One reference of this study is research by Jarozs and team in 2016. In this research, OpenFOAM is utilized to build a method and solve the FWH for low speed on the Mach scale, namely < 0.3 M. The solid object chosen for an obstacle in the aerodynamic flow is a double cylinder, and the observer is placed in nearfield area. Overall, the model shows good agreement between OpenFOAM calculation results, and the experiments (Jarozs, Czajka, and Golaś, 2016). Resumes of existing recent methods are described in Table 1. Older methods have already been developed and are referred to by those newer methods.

In addition, in applying FWH as a governing equation to solve the computational noise model, a turbulence model is needed. Considering there is no general model for turbulence, analyzing a proper turbulence model for fluid flow cases is very important (Sodja and Podgornik, 2007). In a technical study conducted by NASA in 1997, four turbulence models were compared to show their specifications. Generally, it is concluded that *(k-ω)SST* has advantages over other models. In terms of computational performance, certain criteria and conditions, Spalart-Allmaras has advantages over the other models, as far as it is not used for jet stream simulations. This model is suitable for transition conditions between laminar and turbulent that occur in most areas around the aerofoil. Using one equation for modeling also makes this model more efficient and requires a smaller number of grids than other models to reach the same accuracy (Bardina, Huang, and Coakley, 1997). Another consideration is that the Spalart-Allmaras model has been tested quite well for modeling turbulence in compressible flow conditions as well, namely at speeds higher than 0.3 Mach (Raje, 2015).

3. Proposed Method

The proposed method is depicted in Figure 1. To aim for wide possibilities in applying the method on various flying vehicles and to be implemented in the conceptual design phase, the method uses a clean wing as a solid object. Based on the configuration of the current Indonesian aircraft design, a flight speed of 0.2 M is taken at the first condition. The sound radiation is assumed to be singular, whereas reflecting radiation is neglected.

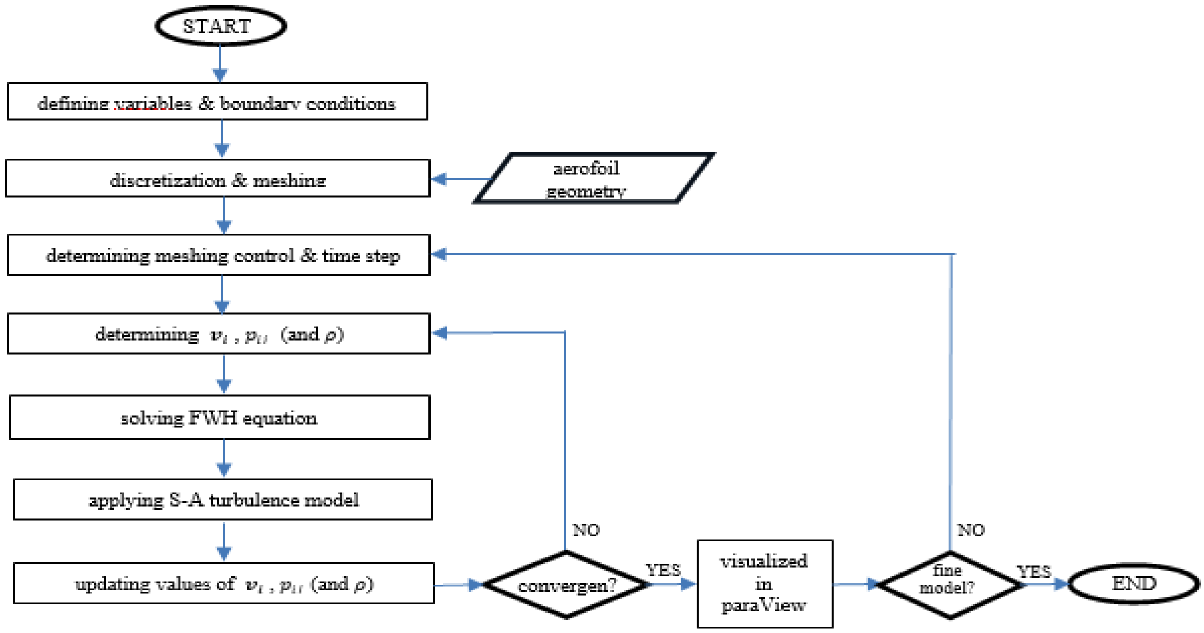

Figure 1 The proposed method is built in OpenFOAM, implementing the FWH equation, and Spalart-Allmaras turbulent model, visualized in ParaView, for conditions of low to medium subsonic speed

To build the method in OpenFOAM, at least three directories must be made, "0" directory, "constant" directory, and "system" directory. The first is where pressure (p), density (ρ), and vector of velocities ($\boldsymbol{v}_x$, $\boldsymbol{v}_y$, $\boldsymbol{v}_z$) are declared. Meshing and discretization of the computational domain are figured in the second directory, while geometry is taken from a given file (in .stl format). Characteristics flow used in the equation is also defined in this directory in the mode of Newtonian flow and Spalart-Allmaras turbulence model. The solver of the FWH equation is designed from existing flow equation solvers, combined with aeroacoustics pressure tensor, $\boldsymbol{T}_{ij}$, and completed by the Spalart-Allmaras turbulence model. The solver computes each element's volume and iterates within the domain as large as 20 times of solid object. Compared to Jarozs's study, this proposed method uses wall function and y+ of 50 to identify noise around the far field area. Visualization of geometry and the computational domain is seen in paraView application, as well as analysis the result.

4. Discussion

4.1. The Boundary Condition of Indonesian Aircraft Design

In the proposed method's algorithm, the setting of boundary conditions is crucial for the successful execution and performance of the model. A Mach number of 0.2 will be selected, and incompressible flow conditions will be applied as required. Furthermore, up to 0.4 M will apply to probability of improvement. In the second condition, the flow is given to be compressible and ρ should be considered as a variable. Both conditions represent the Indonesian aircraft performance for UAVs, vehicles with wing-in-ground effects, most regional aircraft, and military aircraft with special missions to fly at low altitudes above the ground, where the noise source is close enough to the listener. Height from sea level to 5000 ft, with relevant ambient temperature, density, and pressure, considered as noise will affect the population on the ground. Reynolds number of 10^6 is taken representing atmosphere. An aerofoil type with probability to be applied on common aircraft and a new design of electric power is set to be the solid object within the flow.

4.2. Descritization and Meshing

In Indonesia today, computers with very high specifications for aircraft design are only owned by large institutions. If the nation is projecting aeroacoustics research and aircraft design can be further developed, the research should be carried out by many institutions, especially academic researchers. Therefore, it is important to determine optimal precision in discretization and meshing to optimize the calculation (Alimin, 1995). To optimize aircraft design process, clean wing geometry is used to apply in stage of conceptual design (Hosder, 2010). An aerofoil with one meter length is selected as the solid object within the aerodynamic flow. This proposed method uses 1,500,000 volume elements to represent the computational domain. The width of the domain is set to 20 times the aerofoil geometry.

4.3. Meshing Control and Time Step

To optimize the accuracy and a load of computational tasks, utilizing mesh control and time steps is important. This study uses "`snappyHexMesh`" dictionary to improve the number of grids through the aerofoil geometry surface. Inside the dictionary code, the minimum level of mesh refinement is set to be twice, and maximum level is set to be four times. To monitor the calculation of the program, time step is set as least as possible where the program is still controllable, and the value could be changed while analyzing. These calculations are determined on consideration of hardware capabilites, which is using personal computer.

4.4. Solving $\boldsymbol{v}$, p, (and ρ) of FWH Equation

In this case, the solver is designed to be hybrid and therefore can be used for pressure-based cases for incompressible flows and density base for compressible flows. The temperature gradient is not calculated, because, in the case of sound propagation, the atmosphere is assumed to be homogenic. This calculation is still in the subsonic range for the chosen flow velocity. The calculation of the density base with the temperature gradient only needs to be applied if the flight speed enters transonic, supersonic, and hypersonic. This solver solves the pressure-velocity couple equation for unstable flow conditions, and turbulence transient flows, as the characteristics of FWH equation.

4.5. Applying Spalart-Allmaras Turbulence Model

To close the solution of the equation, the turbulence model of Spalart-Allmaras has been chosen. In this study of aircraft design and its condition in Indonesia, no special turbulence model is required. This model was selected based on the analysis from Bardina's research on several turbulence models. The Spalart-Allmaras model is considered more efficient for numerical applications because it requires relatively fewer grids than other models. The use of one equation also makes this model more efficient than a model that uses two equations. This model is suitable for the transition conditions between laminar and turbulent, which occur in most areas around the aerofoil (Bardina, Huang, and Coakley, 1997).

4.6. The Use of ParaView for Visualization and Analysis

The visualization of aerofoil geometric shapes in the computational domain is shown in the paraView application, which is also taken from open source. This software can also be utilized to analyse the results of noise prediction calculations which is computed by OpenFOAM. If Indonesia wants to develop aircraft design research, then consideration of appropriate and efficient tools is needed.

4.7. The Advantage of the Proposed Method to Indonesia

Comparing the proposed with the existing methods, the use of equipment for computational aeroacoustic, or high specification of industrial computers is not needed. Utilizing open-source software with high conformity performance is another advantage. Whether a similar method has been built, or or whether it is compatible with the Indonesian design and manufacturing industry of aircraft still needs to be studied. The use of methods that utilize foreign equipment certainly will cost and threaten national security when applied to military aircraft.

4.8. Harmonize with global development and regulation

Additionally, in developing the method for airframe noise prediction, it is important to consider the future prospects of Indonesian aviation. Supporting the ongoing development of the Indonesian aviation ecosystem should be a key consideration. Updated regulations by the International Civil Aviation Organization (ICAO) and the Directorate General of Civil Aviation of Indonesia should be followed. A review of Molin on airframe noise modelling and prediction in an issued paper and a study by Guo and Thomas on future work of airframe noise prediction should be taken as an outline (Guo and Thomas, 2022; Molin, 2019).

5. Conclusions and Future Works

A method to predict airframe noise has been proposed. The method benefits Indonesian aircraft design research and industry for consideration of strategic economy, security and sustainability. The core of the proposed method is an algorithm with nine steps including aerofoil geometry determination. Compared to previously reviewed methods, the proposed method may be more time-consuming; however, it requires simpler equipment. The future work to carry out is calculating the time-consuming of process in a personal computer with 8 cores and 32 RAM. Since the proposed method can be supported by simpler computational equipment, it opens up opportunities for other researchers to further develop this study.

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