

Framework for Multi-Fidelity Assessment of Open Rotor Propeller Aeroacoustics

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Aerodynamically generated noise from open rotor aircraft has received immense research interests. Multi-fidelity numerical approaches are in demand for evaluating open rotor propeller noise without compromising computational accuracy and reducing cost. In this paper, propeller noise modelling methods at different fidelity levels are assessed by application to an aircraft propeller configuration at an advance ratio of 0.485 together with tip Reynolds and Mach numbers of 3.7×10^5 and 0.231, respectively. The flow solution of the propeller is obtained using coarse-grid Large Eddy Simulation and then inputted into three acoustic solvers. At higher-fidelity level, Ffowcs-Williams and Hawkings analogy method is employed. Hanson's method and Gutin's method are applied at the medium- and lower -fidelity levels, respectively. Results from the three models are compared correlatively, as well as against existing experimental measurement data. Through the assessment, insight is given into future development of a multi-fidelity model for low-emission open rotor aircraft design. The presented multi-fidelity framework is being developed as part of the Innovate UK, Aerospace Technology Institute (ATI) funded research project – ONEheart (Out of Cycle NExt generation highly efficient air transport).

Nomenclature

c_0	=	reference sound speed
D	=	propeller diameter
dt	=	time step
E	=	total energy
f	=	frequency
P	=	propeller pitch
p	=	pressure
q	=	heat flux
ρ	=	density
T	=	propeller thrust
t	=	time
τ	=	shear stress vector
θ	=	direction angle of acoustic far-field
ω	=	vorticity
y^+	=	dimensionless wall unit

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I. Introduction

One of the requirements for today's aeronautical society is to advance the technologies and aircraft configurations that lower the overall emissions. Numerous aircraft systems architectures with alternative propulsion technologies have been proposed over the last two decades, however, most of these are not mature, and would not be suitable for entry into service (EIS) of 2030/40. One of the technologies that could result in significantly lower emissions, and suitable for EIS of 2030/40, is the open rotor, also known as un-ducted fan (UDF) or propfan engine. Open rotor engines have the potential to enhance fuel efficiency in transport aircraft due to their high propulsive efficiency [1]. This increased efficiency is attributed to reduced kinetic energy losses compared to turbojet and turbofan engines, primarily stemming from open rotors operating at lower fan pressure ratios. Open rotors demonstrate exceptional performance at lower speeds, such as during the climb phase of flight and therefore they appear to be particularly well-suited for shorter missions where a significant portion of the fuel is consumed during the climb phase [1]. As a large percentage of flights/routes are around 1000 nm range, un-ducted fan engines could prove to be a key enabler in lowering emissions [2]. Although open rotor technology holds promise for reducing fuel consumption, it faces difficulties in meeting certification noise requirements without the noise-shielding nacelle [1]. Therefore, our project aims to advance the knowledge of open rotor engines affecting aircraft noise and the environmental impact. The present paper will focus particularly on the propeller noise.

The mechanism of noise generation from a propeller system was illustrated in an early work of Ref. [3]. The aerodynamically generated noise consists of tonal (or discrete) noise and broadband noise. The generation mechanisms of tonal noise are deterministic components of thickness noise, loading noise (non-impulsive loading noise, blade-vortex interaction noise), high-speed impulsive noise and quadrupole noise [4]. Broadband noise is caused by non-deterministic sources of loading noise such as turbulence ingestion noise, and self-noise (trailing edge noise, blade-wake interaction noise, tip vortex formation and laminar vortex shedding) [5]. Although the noise generation mechanisms are well investigated in earlier works by classic aeroacoustic methods, accurate evaluation of the propeller aerodynamic noise is challenging in practical engineering applications.

Over the past two decades, research on propeller noise has been revived with support from government programmes, aircraft manufacturers, and research institutions. Numerical methods at different fidelity levels have been developed and applied to evaluate propeller aerodynamics and the generated noise. Low-fidelity models present considerable computational efficiency by making assumptions to ignore insignificant aeroacoustic sources. Gutin's Method offers a simplified approach for estimating propeller noise produced from a single source at the propeller hub [8]. The method focuses on the sound pressure generated by the propeller based on its thrust, power consumption, diameter, number of blades and tip Mach number. The observer's position is calculated by the distance and angle relative to the propeller hub. The method uses Bessel functions to calculate noise attenuation at higher harmonics. It does not consider detailed propeller geometry and, however, is limited by the Bessel function and is best suited for propellers with less than five blades, harmonics under six and blade tip Mach number between 0.3 and 0.8 [6]. In addition, Hanson's model incorporates key parameters from Gutin's work, focusing on lift, drag, and displacement or volume noise for each blade element [9,10]. It computes sound pressure in the frequency domain through integration along the propeller radius, using far-field equations and considering the Doppler effect. Acoustic wavenumber and phase alignment factors account for geometry effects like sweep and lean. This model considers aeroacoustic non-compactness for thickness and loading noise in the form of lift and drag. It accommodates complex propeller geometries such as sweep and twist without requiring time-dependent aerodynamic solutions, reducing computational complexity. The reconstruction of the governing equations to the frequency domain oversimplifies the blade geometry which results in loss of information but is less significant for capturing higher harmonics but is computationally less expensive [11]. Moreover, Farassat's Model involves integrating loading and thickness noise along the surface to compute time and space-dependent sound pressures [6,7]. It considers local surface pressure and local angles describing the relationship between acting pressures and the observer vector. Key elements of this model include the time-dependent observer vector, which points from the observer to varying points on the rotating surface, the projection of the local Mach number on this vector, and the local normal velocity component.

Although these low-fidelity models present considerable computational efficiency, some of the noise sources may not be ignored for modern large transport aircraft at transonic cruise Mach numbers. Therefore, this research aims to develop a multi-fidelity framework for modelling open rotor noise, considering evaluation accuracy as well as computational costs. In this paper, three aero-acoustic models at high-, medium- and low-fidelity levels are applied to a simplified propeller configuration through which their capacities are assessed and compared correlatively.

II. Multi-Fidelity Framework and Methodology

Propeller aeroacoustics is well described by compressible Navier-Stokes equation together with the state equation of an ideal gas. These governing equations can be written in a form using Cartesian coordinates [12],

$$\begin{aligned}
 \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{U}) &= S_m, \\
 \frac{\partial(\rho u)}{\partial t} + \nabla \cdot (\rho u \mathbf{U}) &= -\frac{\partial p}{\partial x} + \nabla \cdot \tau_x + F_x, \\
 \frac{\partial(\rho v)}{\partial t} + \nabla \cdot (\rho v \mathbf{U}) &= -\frac{\partial p}{\partial y} + \nabla \cdot \tau_y + F_y, \\
 \frac{\partial(\rho w)}{\partial t} + \nabla \cdot (\rho w \mathbf{U}) &= -\frac{\partial p}{\partial z} + \nabla \cdot \tau_z + F_z, \\
 \frac{\partial(\rho E)}{\partial t} + \nabla \cdot (\rho E \mathbf{U}) &= q - \nabla \cdot (\rho \mathbf{U}) + \nabla \cdot (\tau \mathbf{U}) + S_q
 \end{aligned} \tag{1}$$

where $\mathbf{U} = (u, v, w)$. S_m and S_q represent source terms for mass and heat, respectively. F_x , F_y , and F_z represent source terms for body forces in coordinate directions. Based on Eq. 1, physics-informed methods for propeller aeroacoustic modelling were developed and can be categorized by their fidelity levels (see Fig. 1). At the top fidelity level is Direct Aeroacoustic Simulation (DAS) method, which solves Eq. 1 directly or using turbulence models [12]. In DAS, the propeller aerodynamics and the resulted noise are achieved simultaneously. Therefore, DAS is capable of modelling the near-field aeroacoustics, including multi-component and flow-acoustic interactions [13,14].

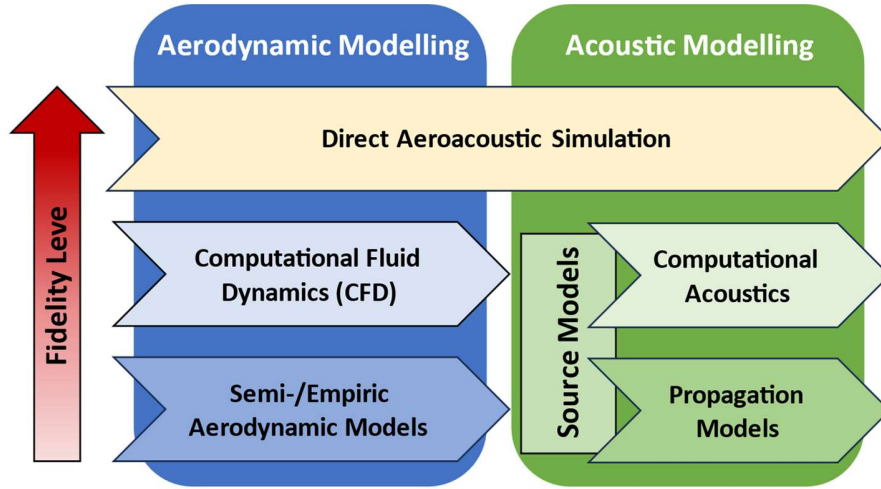


Fig. 1 Demonstration of aerodynamic and acoustic modelling approaches against fidelity levels.

For engineering applications, hybrid methods are often used though with a lower fidelity. This type of methods decouples the hydrodynamic and acoustic components of the propeller aeroacoustic field [13]. Flow component is often obtained through aerodynamic modelling approaches and then the corresponding acoustic component is calculated based on the flow results. Computational Fluid Dynamics (CFD) has shown good capabilities of providing detailed flow solutions to capture major acoustic sources, while semi-/empirical models have been used at further lower fidelity levels to estimate predominant aerodynamics which informs the corresponding acoustic sources [15]. On the other hand, Lighthill's acoustic analogy and its extended approaches have shown good capability of computing the resulting acoustic field [17]. Other acoustic models further simplify acoustic sources based on related assumptions of the propeller aeroacoustics [6-8]. These low-fidelity acoustic models can significantly save computational costs and show great advantage in industrial applications. However, they may underestimate some of the noise sources.

In this paper, we focus mainly on the acoustic models used in the hybrid method. Three acoustic models are assessed at respective high-, medium- and low-fidelity levels. Flow data, informing these three acoustic solvers, are achieved from same flow modelling. The flow solver is described below, followed by three acoustic models.

A. Flow solver

Propeller aerodynamic simulation is performed in a general purpose CFD solver, ANSYS Fluent (v231). This solver has shown a good efficacy in resolving propeller aerodynamics at the same Reynolds and Mach number regime as the present simulation [14]. Coarse-grid Large Eddy Simulation (LES) is performed in compressible form and WALE subgrid model is employed to model the turbulence effect. In addition, the Coupled Scheme is applied to the computation so that this numerical method is capable for extended cases with higher Mach numbers.

B. High-fidelity acoustic solver by Ffowcs-Williams and Hawkings analogy

Acoustic analogy obtains the governing equations of aeroacoustic sources and their far-field propagation by rewriting Eq. 1 into the form of wave equation [17]. Ffowcs-Williams and Hawkings (FWH) analogy belongs to this class and is known for considering the existence and motions of sliding surfaces. The FWH equation is expressed as [18],

$$\frac{\partial^2 \rho}{\partial t^2} - c_0^2 \nabla^2 \rho = \frac{\partial^2}{\partial x_i \partial x_j} (T_{ij} H(g)) - \frac{\partial}{\partial x_i} (\rho u_i u_n \delta(g)) + \frac{\partial}{\partial t} (\rho u_n \delta(g)) \quad (2)$$

where T_{ij} is Lighthill stress tensor, $H(g)$ represents the Heaviside function with a value of 0 for $g < 0$ (interior domain) and 1 for $g > 0$ (exterior domain), and the velocity of fluid normal to the surface is represented by u_n . The three terms on the right hand represent acoustic sources due to turbulence shear stress, momentum, and volume fluctuations respectively. The acoustics at far-field receivers can be evaluated by surface integrals of the FWH equation using the free-space Green's function.

For conditions with lower Mach numbers ($Ma < 0.3$), the contribution of turbulence shear stress is limited while momentum and volumetric fluctuations produced by solid surfaces are regarded as dominant sound sources [19]. Therefore, only solid surfaces (i.e. surfaces of the propeller configuration) are taken into surface integrals due to low Mach number condition in the present case. The FWH calculation is conducted in ANSYS Fluent (v231).

C. Medium-fidelity acoustic solver by Hanson's method

Hanson's method considers discrete component of propeller noise whilst ignoring broadband noise [9,10]. The discrete component is produced as a result of the rotational motion of the propeller blades. The main sources of noise that generate the discrete component are thickness noise and loading noise. With these lines, the noise harmonic is calculated using the sum of two components: one associated with the force dipole as the loading component, and the other associated with the volume displacement. These two terms are obtained by surface integrals of the propeller volume and aerodynamic loading along radial and chordwise directions.

In this paper, the Hanson's method is performed using a code by ESDU [23]. The calculation employs steady lift and drag coefficients, $\overline{C_L}$ and $\overline{C_D}$, at 10 radial stations of the propeller blade. Provided that $\overline{C_L}$ and $\overline{C_D}$ are variants against the radial stations, the relations between $\overline{C_L}$, $\overline{C_D}$ and $\overline{T}$, $\overline{Q}$ can be expressed as,

$$\begin{aligned} \overline{T} &= 2 \times \int_0^R \frac{1}{2} \rho_\infty U(r)^2 \cdot \overline{C_L}(r) \cdot c(r) dr \text{ [N]} \\ \overline{Q} &= 2 \times \int_0^R \frac{1}{2} \rho_\infty U(r)^2 \cdot \overline{C_D}(r) \cdot c(r) \cdot r dr \text{ [N} \cdot \text{m]} \end{aligned} \quad (2)$$

where r denotes distance between the radial station and the propeller centre, $U(r)$ refers to local reference velocity considered to be $U(r) = \sqrt{U_\infty^2 + n^2 r^2}$, and $c(r)$ is the chord length of the radial station. For propeller blades with small relative angles between flow and the blade, it can be approximated that $\overline{C_L}$ is proportional to the relative angles and $\overline{C_D}$ is constant. Despite this $\overline{C_L}$ and $\overline{C_D}$ can be obtained from the flow simulation, they are calculated using this approximation in Section III to reduce computational costs.

D. Low-fidelity acoustic solver by Gutin's method

Gutin's method attributes noise directly to the steady and fluctuating lift and drag forces on the propeller [6,8]. The base for the Gutin's method is provided by the Gutin first harmonic sound pressure level. The Gutin theory assumes that the blade loads are concentrated at a single point on the blade. It then gives a straight method of estimating the peak harmonic sound pressure levels from isolated rotors and propellers. The data are based on static measurements, mostly from rigs, from which the effect of ground reflection has been removed. The sound pressure level of the first harmonic of the blade passage frequency is,

$$\text{SPL}_{\text{BPF}} = I_1 + I_3 + I_4 + I_4 + I_5 \quad (3)$$

where I_1 to I_5 are five components of the first harmonic sound pressure level in terms of non-dimensional parameters. Arithmetic summation of these components gives an estimate of the first harmonic sound pressure level. Higher harmonic sound pressure levels are estimated using the relationship,

$$SPL_m = I_1 + I_6 + I_7 \quad (4)$$

where I_6 and I_7 are corrections which should be added to the first harmonic sound pressure level to obtain estimates of higher harmonic sound pressure levels.

In this paper, the Gutin's method is performed using a code by ESDU [24], where the load point is assumed to be 0.8 times the blade radius from the centre of the propeller disc. The calculation uses propeller steady thrust and power $\bar{P}$. $\bar{P}$ is calculated from the torque results as $\bar{P} = \bar{Q} \cdot n$ in Watts. It is worth noting that results from the Gutin's method are valid at limited directions, $90^\circ \leq \theta \leq 120^\circ$ about the propeller axis [24].

III. Benchmark Configuration and Flow Modelling

In this section, the employed propeller configuration and the flight condition are described, followed by the numerical setup of the flow modelling. Finally, the obtained flow results are presented.

A. Benchmark configuration of a simplified propeller

An aircraft propeller configuration is employed here to assess multi-fidelity aeroacoustic methods. This configuration has been used by previous experimental and numerical research on aircraft propeller noise generation and control mechanism [13,20,21]. As shown in figure 2, this configuration consists of a Mejzlik[®] 2-blade propeller installed at the front of a cylindrical pylon. The propeller presents Clark-Y airfoil cross-sections, with 9 inches in diameter (D) and pitch (P) respectively. The pylon is streamlined at its tail part, with a total length of 400 mm and maximum diameter of 54 mm. Same geometry, dimension, and installation were applied in previous numerical works [20, 21]. Distributions of the blade's chord c and twist angle at the aforementioned 10 radial stations along the radius R are presented in figure 3.

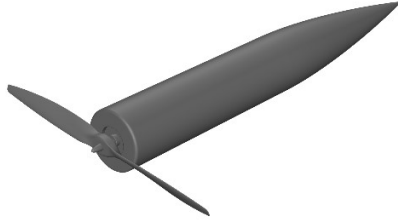


Fig. 2 Demonstration of the simplified open rotor configuration.

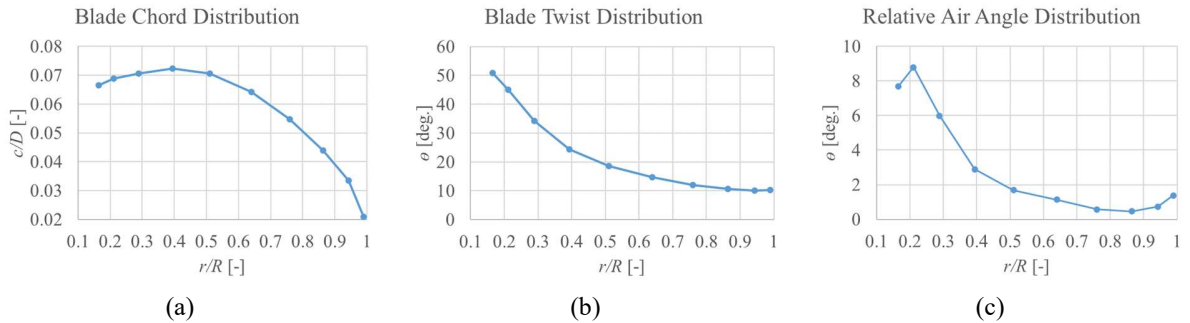


Fig. 3 (a) blade chord distribution, (b) blade twist distribution and (c) relative air angle distribution of the propeller blade in present geometric and flow configuration.

In the present work, the propeller is prescribed with a rotating speed of 6500 rev/min and a forward-flight speed of 12 m/s, corresponding to an advance ratio of 0.485. And Reynolds and Mach numbers are then defined respectively as $Re_n = nD^2/\nu_0 = 3.7 \times 10^5$ and $Ma_n = \pi nD/c_0 = 0.231$, where n is the rotational frequency in revolutions per second, ν_0 denotes freestream kinetic viscosity, and c_0 as sound speed. In this flow condition, flow over the open rotor is characterised by full turbulence and limited compressibility. As shown in figure 3c, the relative air angle at various blade positions is resulted to be 0.465° to 8.794° . Owing to Clark-Y airfoil characteristics, $\overline{C_L}$ at blade sections is approximately proportional to the flow angle and $\overline{C_D}$ is constant.

B. Setup of flow modelling

As shown in figure 4a, the propeller configuration is placed in a computation domain, whose dimensions are $9.21D \times 6.58D \times 6.58D$ in streamwise, spanwise, and transverse directions, respectively. Three-dimensional Cartesian coordinates are used to describe the domain space, where the coordinate origin o is placed $0.90D$ mm downstream to the propeller and the coordinate axes, x , y , and z , are parallel to the streamwise, spanwise, and transverse directions, respectively. Non-slip wall boundary condition is applied to the surfaces of the configuration, pressure far-field boundary condition to the upstream and downstream boundaries to generate the free stream, and pressure outlet boundary condition to the rest boundaries. Moreover, a general non-reflective boundary condition (NRBC) is used at all outer boundaries using Riemann's method.

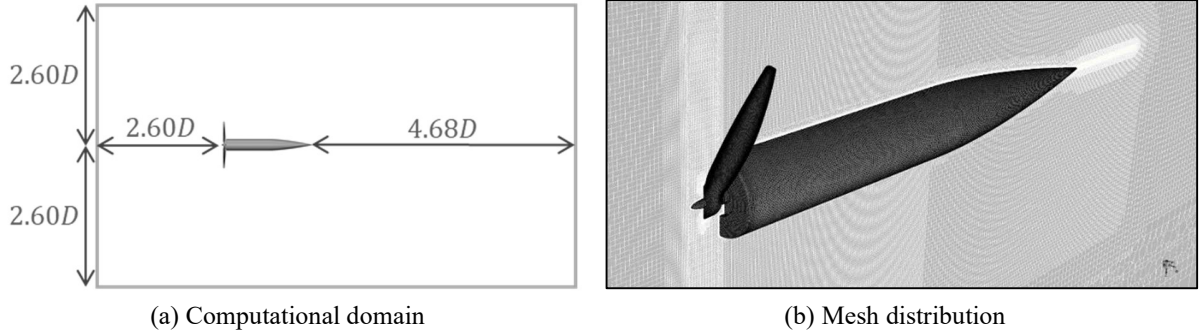


Fig. 4 Demonstration of the computational domain (dimensions not to scale) and mesh distribution.

The computational domain is discretized by poly-hex cells. As shown in figure 4b, cells close to the configuration surfaces and those in the wake region are refined. The size of surface meshes is $y^+ \leq 1$ with $\Delta_{x,z}^+ = 36 - 200$ in dimensionless wall unit, referring to previous numerical works using coarse-grid LES [14]. Although the present cell count is coarser than that for a wall-resolved LES, it is efficient in resolving energy-containing eddies so that most of the turbulent kinetic energy is resolved and the computational cost is reduced [14]. For time marching, the solution is advanced with a physical time step of 1×10^{-5} s, corresponding to 0.39° of the propeller rotating angle.

C. Aerodynamic results

The aerodynamic loading on the propeller surfaces is obtained by the LES calculation and validated against the experimental measurements [20]. The streamwise component of the aerodynamic loading is regarded as propeller thrust T and the moment of the aerodynamic loading about x -axis is regarded as propeller torque Q . Table 1 presents the time-averaged values of the mean thrust $\bar{T}$ and torque $\bar{Q}$, comparing against the experimental measurements [20]. The averaging is conducted using a sampling time corresponding to two rotating cycles with a sampling frequency of 5×10^4 Hz together. The differences between the LES and experimental results are small, no larger than 3.57%, verifying the present LES capable of modelling propeller's aerodynamic loading.

Table 1 Time-averaged values of propeller thrust and moment.

Method	Present LES	Exp. [20]	Difference
$\bar{T}$ [N]	2.9205	2.8197	+3.57%
$\bar{Q}$ [N·m]	0.0964	0.0976	-1.23%

Figure 5 shows the distributions of instantaneous vorticity magnitude on an iso-surface of normalized Q-criterion $Q = 0.3$ and, in addition, on a mid-plane $y = 0$ m. It demonstrates that the flow field is characterized by significant

tip vortices generated over the blade ends and small-scale eddies detached from the blade trailing edges. These vortical structures move downstream with the main flow and dissipate to form the propeller wake.

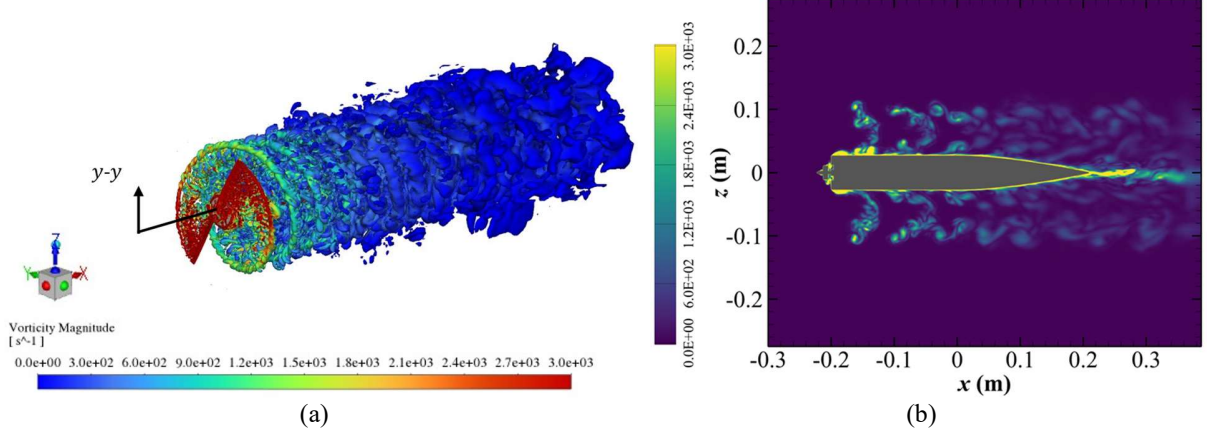


Fig. 5 Distributions of vorticity magnitudes on (a) iso-surfaces of normalized Q-criterion $Q = 0.3$ and (b) mid-plane $y = 0$ [m].

Figure 6 shows the distributions of instantaneous velocity components on the mid-plane $y = 0$ m, where u , v , and w denote respectively the velocity components in x , y , and z directions. It can be seen that a jet flow with high u -magnitudes is induced by the propeller and bounded by the tip vortices. High v -magnitudes are observed in the jet flow and tip vortices with opposite signs about the rotating axis, whilst the w -magnitudes are relatively lower. Therefore, it is implied that the radial velocity of the jet flow is smallest, then the tangential velocity and the axial velocity.

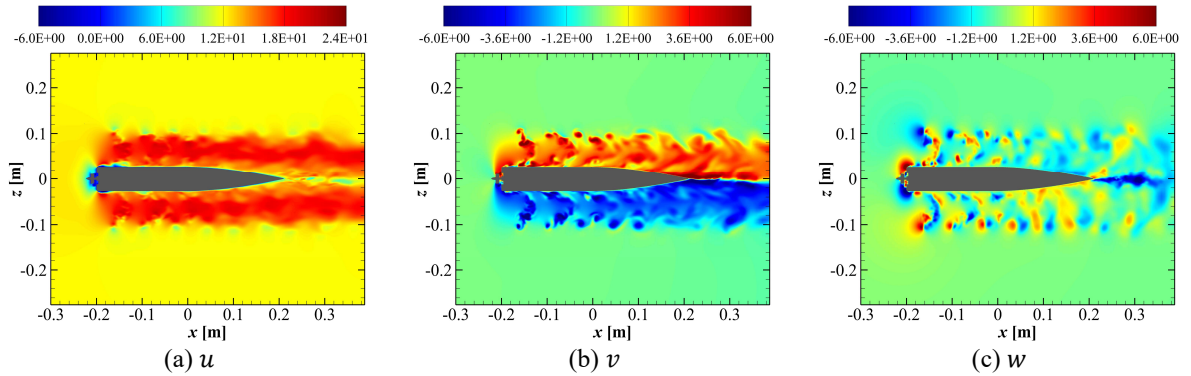


Fig. 6 Distribution of instantaneous velocity components on mid-plane $y = 0$ [m].

Figure 7 presents distributions of instantaneous pressure p over the propeller blades' front and rear surfaces. Lower and higher p -magnitudes are observed respectively on the front and rear surfaces, which result in the propeller thrust. In addition, low p -magnitudes are spotted at the mid-blade on the front surfaces, suggesting instantaneous flow separation over the front surfaces, which may lead to higher drag and be responsible of the larger torque.

IV. Acoustic Modelling and Results

In this section, results of the induced far-field acoustics obtained from the three acoustic methods are presented and compared with each other. A polar array of acoustic receivers is placed at 1.75 m distant from the propeller centre to record the acoustic signals at far field. This distance corresponds to $7.66D$, which is considered to be sufficiently far and has been used in previous studies [12-14, 20]. These receivers are demonstrated in Fig. 8.

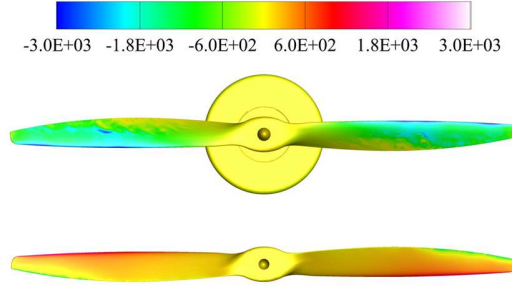


Fig. 7 Distribution of instantaneous pressure p [pa] over propeller front and rear surfaces.

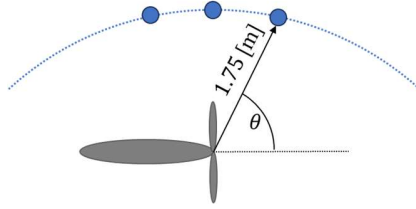


Fig. 8 Illustration of the far-field microphone locations related to the propeller configuration.

A. Evaluation of tonal noise

Tonal component of propeller noise is associated with propeller rotation and is featured by tones at the blade passing frequency (BPF) and its positive integer multiple. Figure 9 presents the spectra of blade passing tone measured in two directions, $\theta = 90^\circ$ and 120° . The tone's magnitude is described by sound pressure level (SPL) and the frequency is normalized by BPF. Here, SPL is defined as,

$$\text{SPL} = 10 \times \log_{10}(p_a^2/p_0^2) \text{ [dB]} \quad (5)$$

where p_a [pa] is sound pressure and $p_0 = 2 \times 10^{-5}$ [pa] is the reference sound pressure. The FWH method captures the first harmonic well, and fairly the second harmonic, but overestimates the higher harmonics. This overestimation is possibly because the LES overestimates high-frequency fluctuations over the propeller blade. In addition, Hanson's method performs surprisingly well for predicting the blade passing tone, with slight underestimation for higher harmonics. Moreover, the Gutin's method offers a good prediction for the first harmonic but less accurate at higher harmonics which is known [24].

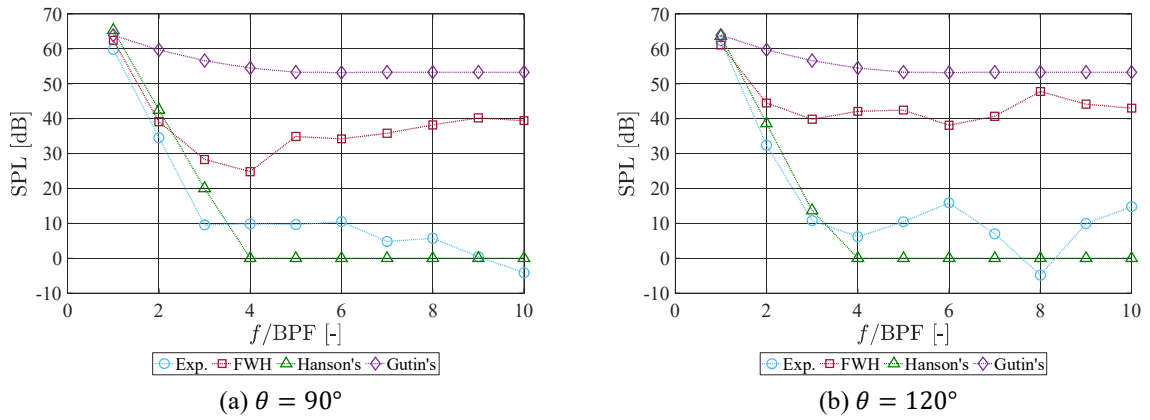


Fig. 9 Spectra of tonal noise at (a) $\theta = 90^\circ$ and (b) $\theta = 120^\circ$, experimental data cited from Ref. [20].

Figure 10 presents the directivity of blade passing tone at first two harmonics. The FWH method shows a good capacity of predicting the first harmonic. However, for the second harmonic, the FWH method presents fair accuracy at $\theta < 110^\circ$ but overestimation at $\theta > 110^\circ$. In addition, the Hanson's method shows good agreement with the experimental data except slight overestimation at $\theta < 100^\circ$. Moreover, the Gutin's method presents decent accuracy for the first harmonic prediction within its valid direction range ($90^\circ \leq \theta \leq 120^\circ$).

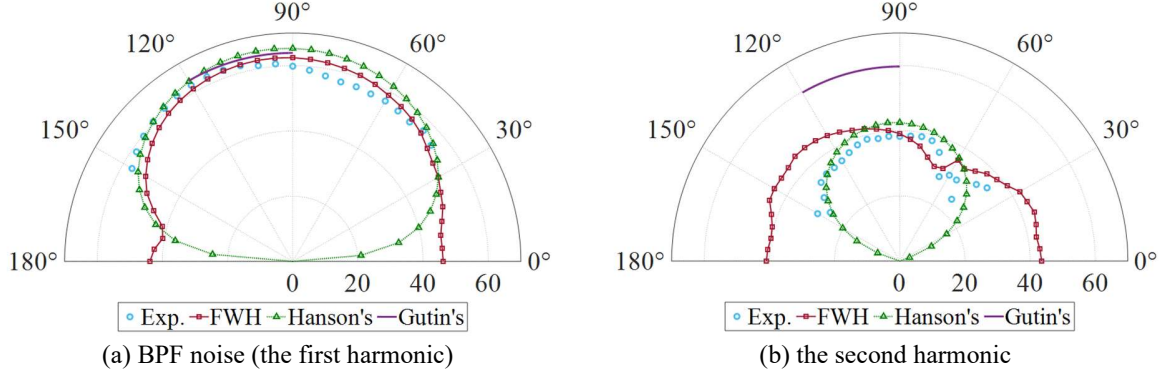


Fig. 10 Directivity of blade passing tone [dB]: (a) the first harmonic and (b) the second harmonic, experimental measurements cited from Ref. [20]

B. Evaluation of overall noise

Overall sound pressure level (OASPL) is used to describe the magnitude of overall propeller noise. OASPL is defined by the integration of sound pressure over a broad frequency range as,

$$\text{OASPL} = 10 \times \log_{10} \left(\int p_a^2 df / p_0^2 \right) [\text{dB}] \quad (6)$$

For the FWH results, the integration frequency range is set the same as that in the experimental work [20]. For the Hanson's and Gutin's results, OASPL is calculated by the summation of first 10 harmonics of the blade passing tone. Fig. 11 presents the directivity of overall propeller noise in OASPL. The FWH results show good agreement with the experimental measurements. On contrary, the Hanson's method is relatively capable of predicting OASPL mainly in the vertical direction, $60^\circ \leq \theta \leq 120^\circ$, but presents less accuracy out of this direction region. This is possibly because Hanson's method considers the tonal component of propeller noise whilst it ignores the broadband component. The broadband noise may make significant contribution in the streamwise direction. Moreover, the Gutin's method works fairly at $90^\circ \leq \theta \leq 120^\circ$.

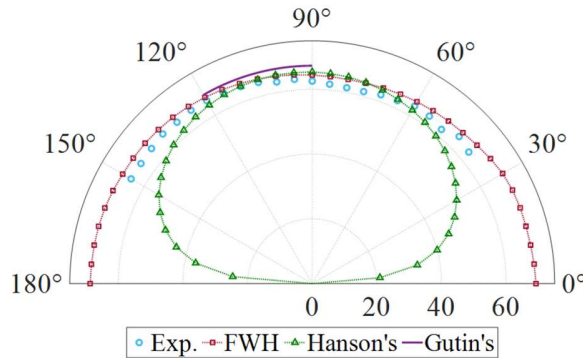


Fig. 11 Directivity of far-field OASPL, compared against experimental measurements [20].

Figure 12 presents the power spectral density (PSD) spectra of sound pressure in two directions from the FWH results. The FWH results are comparable to the experimental measurements, with slight overestimation at high frequency range ($f > 10^3$). It is noted that the BPF magnitude at $\theta = 90^\circ$ are larger comparing to that at $\theta = 120^\circ$, while the high frequency magnitudes at $\theta = 90^\circ$ are relatively lower. It follows that the tonal noise and the broadband noise contribute respective significance in the transverse and streamwise directions. In general, the FWH method well captures the spectra characteristics of the propeller noise. In addition, the broadband noise is significant in the streamwise direction and needs to be considered in the prediction of propeller noise.

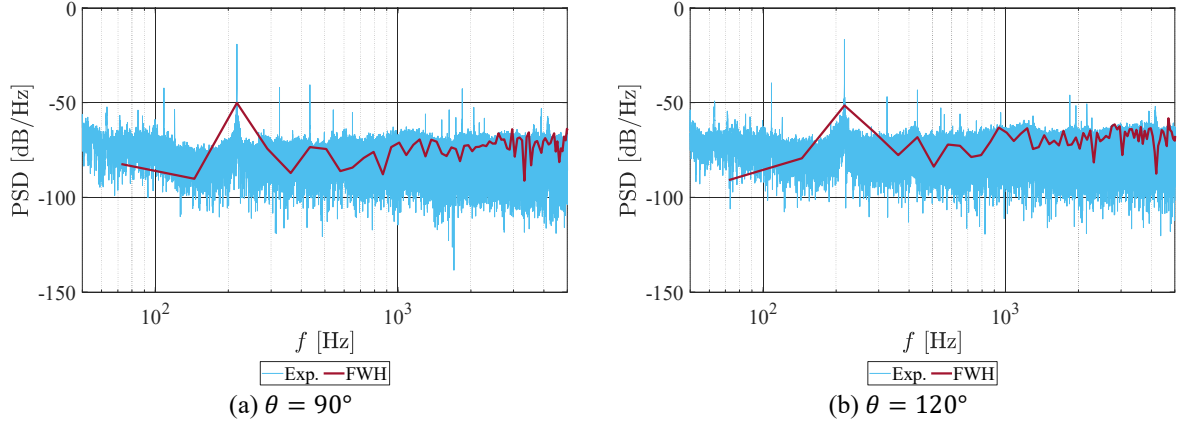


Fig. 12 PSD spectra of sound pressure measured at (a) $\theta = 90^\circ$ and (b) $\theta = 120^\circ$, compared between the FWH and the experimental results [20].

V. Conclusion

In this work, three popular acoustic models for predicting aircraft propeller noise are assessed in a multi-fidelity framework. The three models use FWH analogy, Hanson's method, and Gutin's method at respectively high-, medium-, and low-fidelity levels. The propeller flow data used to inform these three models is the same to ensure a fair comparison of the methods. The propeller flow is characterized by tip vortices and small-scale trailing-edge vortices at $Re_n = 3.7 \times 10^5$ and $Ma_n = 0.231$. Also, the flow-induced noise is featured by blade-passing tones dominating the transverse direction as well as significant broadband noise dominating the streamwise direction.

The capacities of three acoustic models are summarized as shown in Table 2. The FWH method shows good accuracy in predicting the propeller BPF noise and broadband noise. It is the only one of the three methods capable of predicting the broadband noise, which is not negligible for propeller noise prediction. Nonetheless, the FWH method is approximately three orders of magnitudes higher in cost than the other two and is not good at predicting higher harmonics of the tonal noise. On the contrary, Hanson's method presents great efficacy in predicting the tonal noise. Therefore, Hanson's method best suits cases where the tonal noise is of major interest. In addition, the performance of Hanson's method may be improved by taking unsteady aerodynamic loadings into consideration. Finally, Gutin's method shows accuracy mainly in predicting the BPF noise, but it does not compute noise directivity. Nonetheless, Gutin's method requires least flow information (only mean thrust and torque) and is least computationally intensive. Thus, Gutin's method may be ideal for high-level aircraft design and collaboration with low-fidelity flow solvers.

Table 2 Capacity of three acoustic models for modelling the propeller noise.

Acoustic model	Tonal noise		Broadband noise	Noise directivity	Computational time factor
	BPF noise	Higher harmonics			
FWH method	Good	Fair	Good	✓	$\sim 10^4$
Hanson's method	Good	Good	N/A	✓	$\sim 10^1$
Gutin's method	Good	Poor	N/A	✗	1

As future work, models for propeller broadband noise will be investigated to extend the capacity of Hanson's method. In addition, this multi-fidelity framework will be applied to more practical configurations of open rotor

engines. Furthermore, a surrogate model for open rotor aircraft design will be developed based on the multi-fidelity framework database.

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