

Framework for multi-fidelity simulations of flow interaction and noise of an open rotor

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Flow-induced noise from open rotor aircraft has received immense research interests as the flow interactions of the components of open rotors lead to significant non-linear features and the flow-induced noise is complicated. Numerical approaches for predicting open rotor flow interactions and the induced noise are in demand without compromising computational accuracy and reducing cost. In this paper, an existing multi-fidelity framework for propeller noise modelling is extended to open rotor configuration. A generic contra-rotating open rotor (CROR) configuration is developed to assess the capability of this multi-fidelity framework. The flow and noise of this configuration are modelled separately in hybrid manner. The flow solution is computed using two methods, which employ unsteady Reynolds average Navier-Stokes (URANS) equations and lattice-vortex method (VLM) at respectively higher- and lower-fidelity levels. Then, the acoustic solution is computed based on the flow solution using Gutin's method. Results show that transonic features over the rotor blades and significant tip vortices in the wake characterise the CROR flow. Multi-rotor interactions are observed. The aerodynamic loadings are investigated in terms of their mean and fluctuating components. In addition, the far-field noise from the two rotors are compared. The present multi-fidelity framework will be used in future aircraft design which involves open rotor engines. This work is being administered 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
τ	=	propeller torque
θ	=	direction angle of acoustic far-field
y^+	=	dimensionless wall unit
ESDU	=	Engineering Sciences Data Unit
NRBC	=	Non-reflective boundary condition
BPF	=	Blade passing frequency
SPL	=	Sound pressure level
OASPL	=	Overall sound pressure level
PSD	=	Power spectral density

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I. Introduction

ONE of the requirements for today's aeronautical society is to advance the technologies and aircraft configurations that could 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 [1]. 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 [2]. 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 [3]. 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 [4]. Therefore, it is essential to develop advanced open-rotor noise prediction technologies for aircraft design as well as environmental noise management. This forms the aim of the present paper.

Noise sources of rotating blade machinery can be described by a combination of tonal (discrete) noise and broadband noise [5]. The tonal noise is mainly related to blade rotating motions. Rotating blades produce fluid volumetric fluctuations which generates monopole sources known as thickness noise. Deterministic loading on blade surfaces produces periodic pressure fluctuations which generate steady loading noise. On the contrary, the broadband noise is caused by non-deterministic sources of loading noise such as turbulence ingestion noise, rotor self-noise (trailing-edge noise) and quadrupole noise. The quadrupole noise becomes important at high Mach numbers [6]. In addition, one significant noise source, which is unique to the contra-rotating open rotor, is wake-interaction noise [7]. The viscous wake of the front row interacts with the rear row. The induced sound is radiated from the rear row in both discrete and broadband features. The discrete part is caused by the concentrated tip vortex of the front rotor and the broadband part results from the small-scale vortices of the wake [8].

Most of conventional models are applied with deterministic noise sources [9], where the aerodynamics of propellers needs to be known in advance. An semi-empirical model developed by Gutin [10] offers a simplified approach for estimating propeller noise based on its thrust, power consumption, diameter, number of blades and tip Mach number. Gutin's method focuses on the sound pressure generated by the propeller as from a single source at the propeller hub, and calculates noise attenuation at higher harmonics and using Bassel functions [10]. Good accuracy of Gutin's method was reported at the first harmonic level for helicopters and propeller driven aircraft in static or low forward speed (below 40 knots) conditions [11]. However, broadband noise is considered to be insignificant and neglected in this model. Because broadband noise induced by fluctuating pressure is not significant for propeller blades at low angles of attack of and quadruple noise is weak at low helical tip Mach numbers as well ($M < 0.9$) [12]. Based on the same assumptions, Hanson proposed a model which focused on the lift, drag, and volume displacement of each blade element, and incorporates key parameters from Gutin's work [13]. Hanson's method computes sound pressure in the frequency domain through integration along the propeller radius using far-field equations, with considering the Doppler effect, geometry effects (e.g. sweep and lean) and the aeroacoustic non-compactness noise sources [14]. Good accuracy of Hanson's method was reported within 0.2 dB for the near and the far-field of a 6-bladed propeller at a flight Mach number of 0.46 and a propeller tip rotational Mach number of 0.677 [15]. With advances in computational aeroacoustics (CAA), higher-fidelity modelling for the three-dimensional flow and the noise generation of propellers with complicate geometries has been enabled [16]. Most CAA methods are performed in a hybrid way where the propeller flow field is first solved, often by computational fluid dynamics (CFD), and then the acoustic field is computed by the methods of acoustic analogy, e.g. Ffowcs-Williams and Hawkings (FWH) method [17]. Huang et al. performed Large Eddy Simulations (LES) and FWH method to predict the far-field noise including the broadband noise of a propeller-wing configuration and achieved a good agreement within 1.42 dB [18]. In addition, the acoustic solution of flow passing propellers can be obtained simultaneously with the flow solution using direct aeroacoustic simulations, which solve the governing equations of compressible flow using high-accuracy algorithms [19, 20]. For aircraft design, models at different fidelity levels are required [2]. For example, lower-fidelity and fast-predictive models are demanded for conceptional design. In contrast, higher-fidelity models are demanded for detailed design. Recently, we developed a multi-fidelity framework for modelling aircraft noise. Successful implementations were demonstrated of modelling low Reynolds number propeller noise [21]. And it is required to extend the implementations to practical open rotor configurations.

In this paper, the capacity of this multi-fidelity framework for modelling the flow interactions and noise of a generic counter-rotating open rotor (CROR) configuration is demonstrated. Section II presents the multi-fidelity framework, followed by describing flow and noise models employed in this paper. As followed, a benchmarking CROR configuration is presented in Section III, together with its computational setups. In Section IV, flow and noise results of multi-fidelity modelling are presented and discussed. Finally, Section V concludes the remarks of this work and gives ideas of future works.

II. Numerical Methods

The generation of aerodynamic noise from open rotors has been well described by compressible Navier-Stokes equations together with the state equation of an ideal gas [22]. The governing equations can be written in Cartesian coordinates using a strong conversational form,

$$\begin{aligned}\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{U}) &= S_m, \\ \frac{\partial (\rho u_{x_i})}{\partial t} + \nabla \cdot (\rho u_{x_i} \mathbf{U}) &= \frac{\partial p}{\partial x_i} + \nabla \cdot \tau_{x_i} + F_{x_i}, \\ \frac{\partial (\rho E)}{\partial t} + \nabla \cdot (\rho E \mathbf{U}) &= q - \nabla \cdot \rho \mathbf{U} + \nabla \cdot (\tau \mathbf{U}) + S_Q\end{aligned}\quad (1)$$

where ρ , p , E , and q denote repetitively the density, pressure, total energy, and heat flux of the flow. $\mathbf{U}$ is velocity vector, consisting of components u_i where i refers to the i -th dimension of Cartesian spatial coordinates. S_m and S_Q are associated respectively with the source terms of mass and heat. And F_x , F_y , and F_z represent the source terms of body forces aligned with coordinate directions.

For engineering applications, the calculations of flow and acoustic field are often separated for saving computational costs[17]. Namely, the hydrodynamic and acoustic components of aeroacoustics are decoupled. The hydrodynamic part is obtained by flow modelling, and then the acoustic part is calculated by noise models based on the flow results.

A. Multi-Fidelity Framework

A multi-fidelity framework of flow and acoustic models has been developed for modelling aircraft noise [21]. As shown in Figure 1, the framework employs flow and acoustic solvers at different fidelity levels. In previous research [21], the capability of the framework was demonstrated by modelling the aeroacoustics of a low Reynolds number propeller configuration using one flow model of coarse-grid large eddy simulation and three acoustic models of Ffowcs Williams-Hawkins analogy, Hanson's method, and Gutin's method.

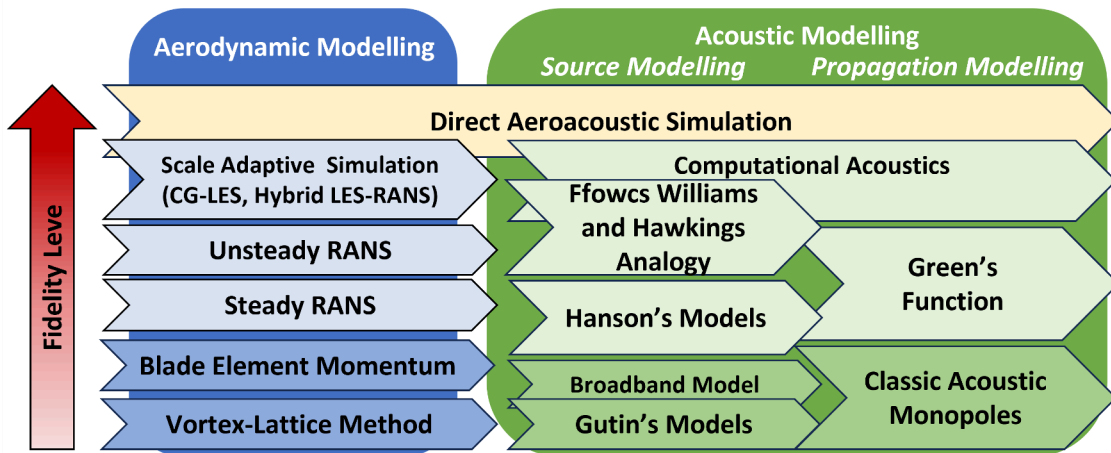


Fig. 1 Demonstration of aerodynamic and acoustic models in the multi-fidelity framework.

This paper focuses on this method and emphasises the modelling of the hydrodynamic part. In this paper, URANS and vortex lattice method are used for flow modelling, and Gutin's method is used for acoustic modelling.

B. Flow Modelling

1. Higher-fidelity flow solver based on URANS

This method solves unsteady Reynolds Average Navier-Stokes (URANS) equations to capture the evolutions of flow structures and the transmission of turbulent kinetic energy, while use less cell count to save computational costs [23]. This method has shown good capability for modelling propeller aeroacoustics [24, 25]. A general purpose CFD code, ANSYS Fluent (v231), is called by the framework to perform the URANS computations. The rotating motion of rotors is mimicked by sliding-mesh method. The Spalart-Allmaras model is employed for turbulence modelling. Pressure-based scheme is applied to the solver as that this method is capable for maintaining good robust.

2. Lower-fidelity flow solver based on VLM

For Vortex Lattice Method (VLM), flow is assumed to be inviscid and incompressible. Lattice of vortex elements is used to approximate flow over the lifting surfaces of rotor blades [26]. The induced lift and drag are calculated by assuming an infinitely thin sheet with discrete vortices and solving for the circulation which satisfies the Kutta condition at all control points. An open-source code, OpenVSP, is called by this framework to conduct VLM. It is capable of modelling three-dimensional unsteady flow fields considering multi-component interactions.

C. Acoustic Modelling Using Gutin's Method

Gutin's method attributes noise directly to the steady and fluctuating lift and drag forces on the propeller [10]. The method assumes that the aerodynamic loading on blades are concentrated at a single point on the blade, that gives a straight method of estimating the peak harmonic sound pressure levels from isolated rotors and propellers. The sound pressure level of the first harmonic of the blade passage frequency is estimated as follows,

$$\text{SPL}_{\text{BPF}} = I_1 + I_2 + I_3 + I_4 + I_5 \quad (2)$$

where I_1 to I_5 are five components of the first harmonic sound pressure level in terms of non-dimensional parameters. The values of these components are referred to a data set which was obtained from previous static measurements, mostly from rigs, where the effect of ground reflection has been removed. Arithmetic summation of these components gives an estimate of the first harmonic sound pressure level. Similarly, higher harmonic sound pressure levels $\text{SPL}_{m\text{BPF}}$ ($m = 2, 3, \dots$) are estimated using the following relationship,

$$\text{SPL}_{m\text{BPF}} = I_1 + I_6 + I_7 \quad (3)$$

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. 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. In this paper, Gutin's method is performed using the ESDU code of Gutin's method [11]. The calculation uses propeller steady thrust $\bar{T}$ and power $\bar{P}$. $\bar{P}$ is calculated using the torque results $\bar{\tau}$ from the flow modelling, as $\bar{P} = n\bar{\tau}$.

III. A Generic Contra-Rotating Open Rotor Configuration

This multi-fidelity framework is assessed by application to a benchmark configuration of contra-rotating open rotors. In this section, the design of this open-rotor configuration is described first, followed by the computational setups of multi-fidelity solvers.

A. Configuration Design

The present open rotor engine is aimed for a transport aircraft family with a single-aisle cabin. The thrust requirement of the aircraft's propulsion system is set as $F_x = 176$ kN at a sea-level static condition and $F_x = 38$ kN at a cruise condition [24]. The principal characteristics of this open rotor are, thus, prescribed to meet these performance criteria. A contra-rotating pusher configuration is selected, referring to available reference information in literature, as well as considering cabin noise and certification issues relating to blade loss scenarios [24]. An open-rotor configuration, as shown in Fig. 2, is, then constructed to demonstrate the capability of the present multi-fidelity framework.

The open rotor configuration consists of 8×8 -bladed rotors installed on a generic nacelle. The front and aft rows, rotating in counter-clockwise and clockwise direction respectively, have a diameter of $D = 4.2672$ m and a rotor-to-rotor

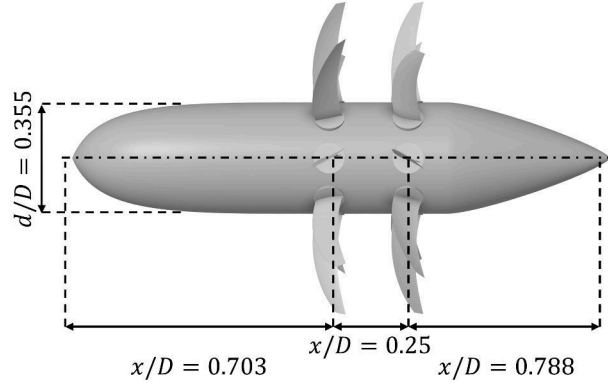


Fig. 2 Illustration of the benchmarking CROR configuration.

distance of $x/D = 0.25$. The same open-rotor layout and dimensions have been used in previous numerical works by DLR [24]. The nacelle presents a streamlined profile with a diameter of $d/D = 0.355$ and a length of $L/D = 1.741$. The relative position of the rotors to the nacelle is demonstrated in Fig. 2.

The blade design for this open rotor is conducted in an open-source aircraft design code, OpenVSP, which allows an easy parametric setup for future studies. Blade geometry is kept the same for the front and aft rows. The diameter and hub-to-tip ratio of the rotor are prescribed to be $D = 4.2672$ m and $d/D = 0.355$ respectively. Fig. 3 presents the blade characteristics, showing the distributions of blade chord c , thickness t , twist β , and mean-line sweep ϕ at different blade radial positions r/R . The cross-section profile of the blades is featured by NACA65-series airfoils near the root to $r/R = 0.4$, a transition section from $r/R = 0.4$ to 0.55 , and NACA16-series airfoils from $r/R = 0.55$ to the blade tip.

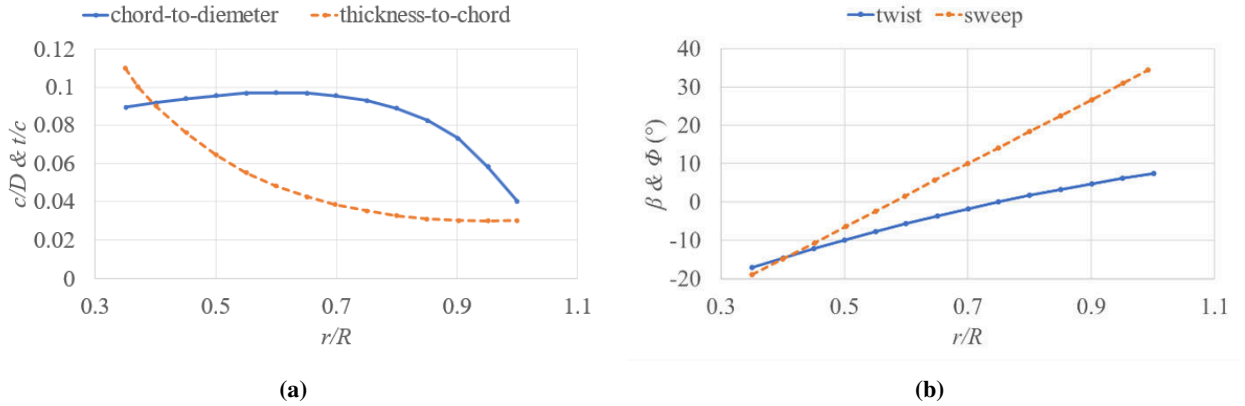


Fig. 3 Distributions of the blade characteristics along radius: (a) chord-to-diameter c/D and thickness-to-chord t/c ratios, and (b) twist β and sweep Φ angles.

The blade pitch of the rotor blades is changeable which depends on the working condition of the open rotor. In this paper, cruising condition is investigated where flight height and Mach number are prescribed as $h=35,000$ ft and $M=0.75$ respectively. The blade pitch of the front and the aft row is prescribed to be $\beta_{75} = 61^\circ$ and 57.9° respectively. The rotating speed of the rotors is set as 895 rev/min, which leads to a helical tip Mach number of $M = 1.0086$.

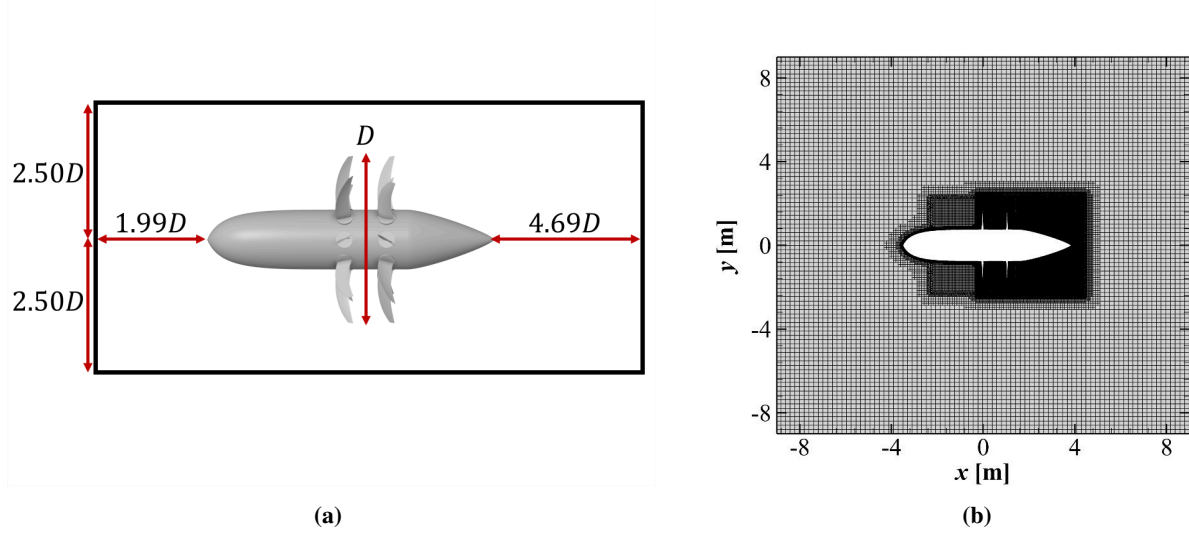


Fig. 4 Demonstration of the numerical setup: (a) a schematics of the computational domain (dimensions not to scale) and (b) the distribution of volume meshes.

B. Computational Setup

1. For the URANS computation

Fig. 4 shows the numerical setup of the URANS calculation. The propeller configuration is placed in a cylindrical computation domain which presents a length of $8.32D$ in the streamwise direction and are a length of $5.00D$ in the spanwise and the transverse directions. Three-dimensional Cartesian coordinates are used to describe the domain space, whose x , y , and z -axes are parallel to the streamwise, spanwise, and transverse directions, respectively. The coordinate origin is placed at the centre of the front row rotor. A pressure far-field boundary condition is applied to the upstream and the side boundaries to generate the free stream at $M_\infty = 0.75$, a non-slip wall boundary condition is applied to the surfaces of the propeller configuration, and a pressure outlet boundary condition is applied to the downstream boundary. To prevent numerical errors due to acoustic reflections, a general non-reflective boundary condition (NRBC) using Riemann's method is applied at the outer boundaries.

The computational domain is meshed using poly-hex cells. As shown in Figure 4b, cells close to the propeller surfaces and in the wake region are refined. The size of surface meshes is set, with referring to previous numerical works using numerical methods [18], as $y^+ = 50$ and $\Delta_{x,z}^+ = 100 - 1000$ in dimensionless wall unit. For time marching, the solution is advanced with a physical time step of 9.31×10^{-5} s, corresponding to 0.5° of the propeller rotating angle. Although the present cell count and the time step are relatively coarser than those for a resolved simulation, it is probably efficient in resolving energy-containing eddies so that most of the turbulent kinetic energy is resolved and the computational cost is reduced.

2. For the VLM computation

In the simulation using VLM, the dimension of the computational domain is described by three-dimensional Cartesian coordinates, with its origin o being placed at the centre of the front row and x , y , and z -axis parallel to the streamwise, spanwise, and transverse directions, respectively. The simulation undergoes 5 rotor revolutions (around 0.335 s) to achieve time-stationary solutions. Three time-step sizes were tested at $\Delta t = 0.0028$ s, 0.0015 s, and 0.001 s, which correspond to rotating angles of $\Delta\theta = 18^\circ$, 8.06° , and 5.37° respectively. The results of first rotor thrust converges with the decrease of the time-step size (as shown in Tab. 1). The differences of mean thrust are in 7.5% between calculations using $\Delta t = 0.0015$ s and 0.001 s. Therefore, a $\Delta t = 0.00093$ s is used as the time-step size for VLM computations.

Table 1 VLM results obtained using different time-step sizes.

Time-step size [s]	$\Delta t = 0.0028$	$\Delta t = 0.0015$	$\Delta t = 0.001$
Mean thrust [kN]	2.575	1.305	1.207
RMS thrust [kN]	0.093	0.188	0.247

IV. Results

A. Flow Features

Figure 5 provides a perspective view of the flow field of the CROR configuration using the URANS results of instantaneous flow distributions of Mach number M and absolute vorticity $|\omega|$ on the mid-plane $z = 0$ m. The CROR flow is characterised by significant transonic features over the front and aft rows, as well as the dominant flow structures of significant tip vortices, which are generated at the blade tips of the aft row. In addition, small-scale vortical structures are observed being formed over the nacelle surfaces and interacting with the tip vortices further downstream.

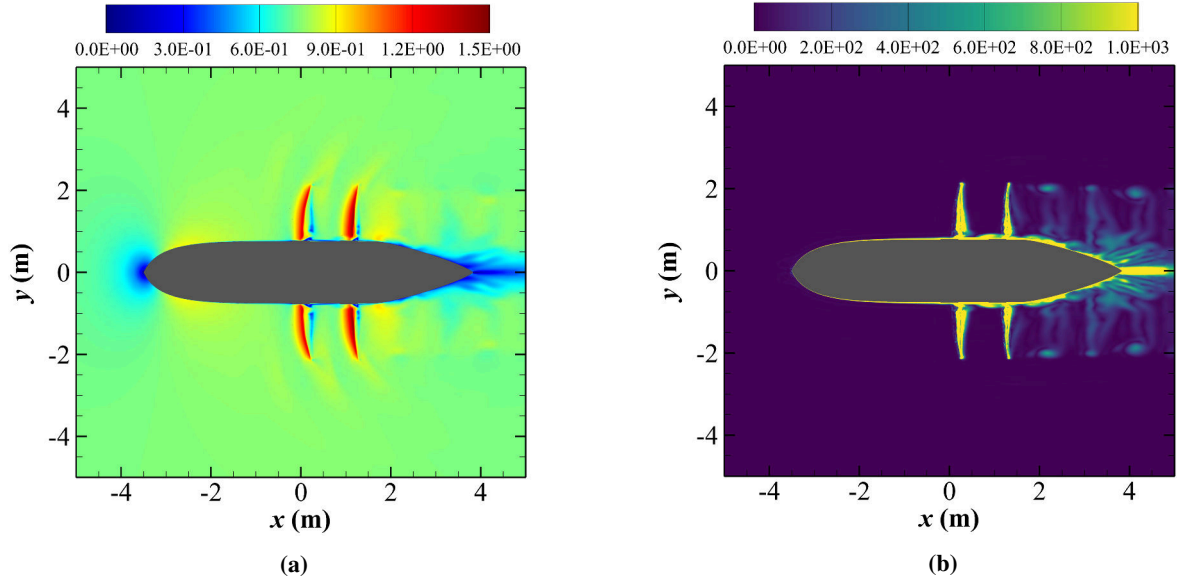


Fig. 5 Distributions of the URANS flow results of (a) Mach number M and (b) absolute vorticity $|\omega|$ on the mid-plane $z = 0$ m.

1. Aerodynamic loadings

Aerodynamic loading on the propeller surfaces is obtained from the URANS and the VLM calculations. The integral of the aerodynamic force in the streamwise direction is regarded as propeller thrust T and the integral of the moment of the force about the x -axis is regarded as propeller torque τ . Fig. 6 presents the time history of instantaneous thrusts and torques of the front rotor and the aft rotor, as well as comparing the results of the two flow models.

Tab. 2 presents the mean thrusts $\bar{T}$ and the standard deviations T' of the front rotor, the aft rotor, and the two rotors as a whole. The averaged values are computed using algebraic averaging with a sampling frequency of 1.07×10^4 Hz and a sampling time corresponding to three revolutions. The differences between the URANS and the VLM results correspond to Fig. 6a, showing that the aft rotor generates greater thrust fluctuating than the front rotor. URANS and VLM get opposite predictions of the greater thrust-producing rotor, which may results from their different predictions of multi-rotor interactions.

Similarly, Tab. 3 presents the mean torques $\bar{\tau}$ and the standard deviations τ' of the front rotor, the aft rotor, and the two rotors as a whole. The averaged values are computed using algebraic averaging with a sampling frequency of

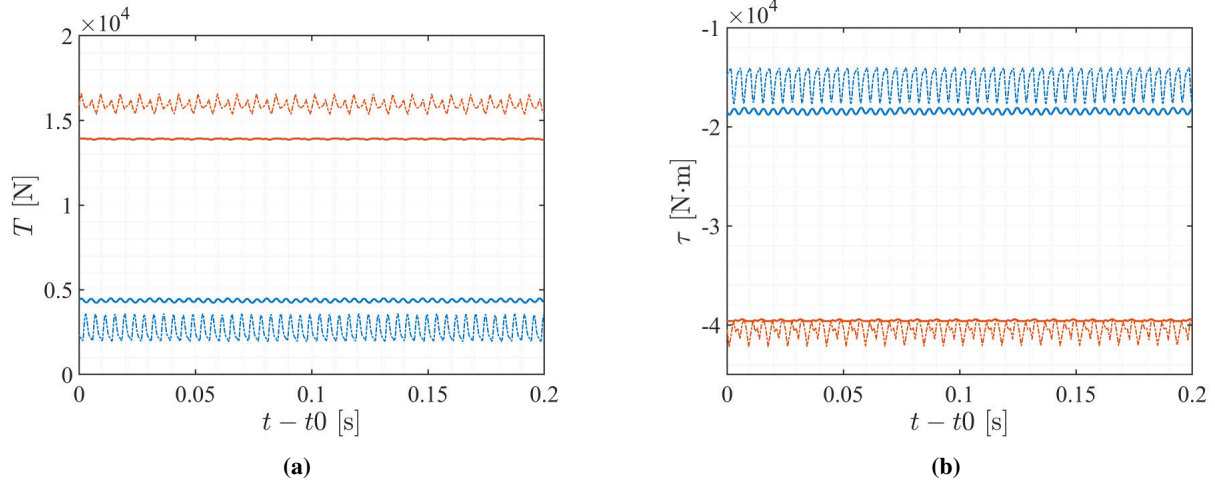


Fig. 6 Time history of (a) thrusts T and (b) torques τ of the front rotor (blue) and the aft rotor (amber), from URANS (straight) and VLM (dashed-dot).

Table 2 Mean values and standard deviations of thrusts of two rotors.

	$\overline{T_{\text{Frt}}}$ [N]	T_{Frt}' [N]	$\overline{T_{\text{Aft}}}$ [N]	T_{Aft}' [N]	$\overline{T_{\text{All}}}$ [N]	T_{All}' [N]
URANS	4367.339	82.928	2635.758	538.7064	7003.098	465.328
VLM	13906.428	24.578	15914.126	327.971	29820.554	340.389

1.07×10^4 Hz and a sampling time corresponding to three revolutions. The differences between the URANS and the VLM results align with the thrust results, showing that the aft rotor generates greater torque fluctuating than the front rotor. The URANS results suggest the torque fluctuating of the two rotors as a whole is slightly smaller than that of the aft rotor, which is possibly due to the aft and the front rotors are out of phase.

2. Multi-rotor interaction

Figure 7 presents the distributions of instantaneous pressure coefficient on the rotor blade surfaces at three moments from t_0 , $t_0 + 1/(3 \times \text{BPF})$, to $t_0 + 2/(3 \times \text{BPF})$, where $\text{BPF} = 8 \times n$ denotes blade passing frequency. Higher and lower pressure magnitudes are respectively generated on the leading and the trailing edges of the blades, which result in negative rotor torques. Multi-rotor interactions are observed in the VLM results that lower magnitudes of pressure coefficient are generated on the aft rotor blades when the front rotor blades passing through. In addition, differences are observed between the VLM and URANS results. The reason has been yet to clarified. A possible cause can be geometric divergence due to the use of rotatable blades in URANS.

B. Noise Features

Steady loading noise of the front and the aft rotors is calculated by the Gutin's method using the loadings of steady thrust and power. The far-field noise is measured in the plane of the front rotor with $10D$ distant from the rotor centre.

Table 3 Mean values and standard deviations of torques of two rotors.

	$\overline{\tau_{\text{Frt}}}$ [$\text{N}\cdot\text{m}$]	τ_{Frt}' [$\text{N}\cdot\text{m}$]	$\overline{\tau_{\text{Aft}}}$ [$\text{N}\cdot\text{m}$]	τ_{Aft}' [$\text{N}\cdot\text{m}$]	$\overline{\tau_{\text{All}}}$ [$\text{N}\cdot\text{m}$]	τ_{All}' [$\text{N}\cdot\text{m}$]
URANS	-18438.024	223.382	-15500.484	1215.0552	-33938.509	1013.224
VLM	-39544.444	68.653	-40496.396	832.258	-80040.840	857.267

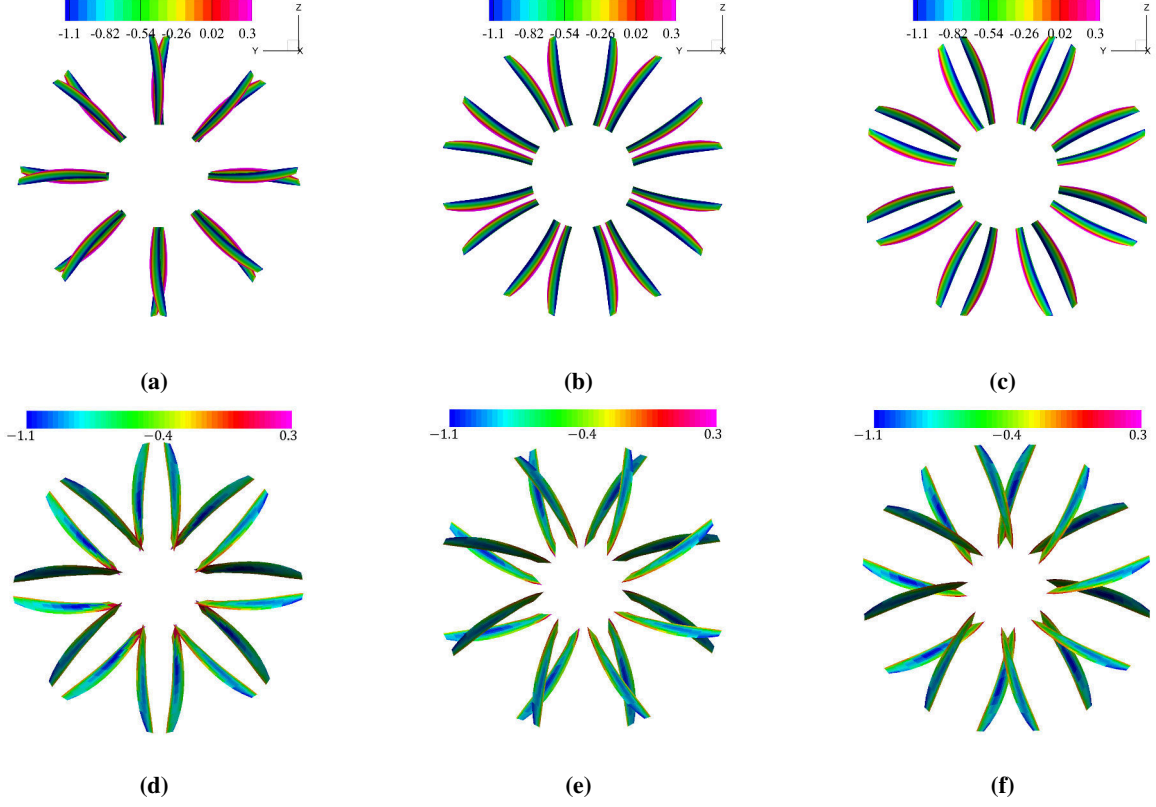


Fig. 7 Distribution of pressure coefficient on the rotor blade surfaces at (a,d) t_0 , (b,e) $t_0 + 1/(3 \times \text{BPF})$, and (c,f) $t_0 + 2/(3 \times \text{BPF})$: (a-c) VLM and (d-f) URANS.

Fig. 8 shows the spectrum of sound pressure level (SPL) at the first 10 BPF harmonics, where SPL is defined as,

$$\text{SPL} = 10 \times \log_{10}(p_a^2/p_0^2) \text{ [dB]} \quad (4)$$

where p_a denotes sound pressure and $p_0 = 2 \times 10^{-5}$ [pa] is the reference sound pressure. The front rotor contributes greater tonal noise than the aft rotor according to the SPL results. However, it is worth noting that the noise contribution can vary with the consideration of unsteady loading noise which is not included by the Gutin's method.

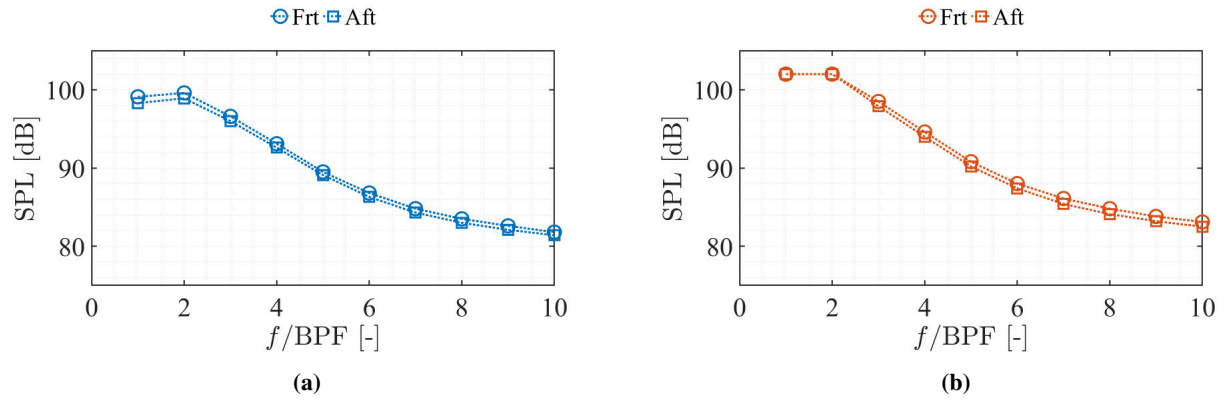


Fig. 8 The SPL spectrum of the first 10 BPF harmonics of far-field noise measured at $10D$, based on the results of (a) URANS and (b) VLM.

V. Conclusion

In this paper, an existing multi-fidelity framework for propeller noise modelling is extended to open rotor configurations. A generic contra-rotating open rotor (CROR) configuration is developed to assess the capability of this multi-fidelity framework. The flow and noise of this configuration are modelled separately in hybrid manner. The flow solution is computed using two methods, which employ unsteady Reynolds average Navier-Stokes (URANS) equations and lattice-vortex method (VLM) at respectively higher- and lower-fidelity levels. Then, the acoustic solution is computed based on the flow solution using Gutin's method. Flow features, including multi-rotor interactions, are investigated. The aerodynamic loadings are considered in terms of their mean and fluctuating components. In addition, the far-field noise from the two rotors are compared. Moreover, difference are observed between results from the URANS and VLM computations. In the future works, the reason will be investigated to improve the accuracy of the modelling.

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