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Aeroacoustic Performance of Propellers in Turbulent Flow

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The aerodynamic noise characteristics of propellers in turbulent flow have been investigated experimentally. In this work, the effect of turbulence interactions on the noise signatures and aerodynamic loading of propellers were investigated using a turbulence-generating passive grid with a solidity ratio of 0.35 and a 3D printed NACA 0012 airfoil wing wake. These turbulence generating methods aim to simulate the fluctuating gusty wind in flight and airframe installation effect, respectively. The experiments were conducted at forwarding flight configuration with freestream inflow velocity ranging from 8 m/s to 24 m/s. Six-axis aerodynamic load measurements and far-field acoustic pressure measurements were performed simultaneously. The results show an increasing trend of thrust energy spectra for propeller operating with turbulence interactions in relative to clean laminar inflow. The acoustic spectrum of the propeller is rich in discrete tones and broadband noise. The results indicate that at a frequency band above 1000 Hz, an increase of noise spectra by about 2 dB/Hz for grid turbulence and around 5 dB/Hz to 15 dB/Hz for wing wake cases were recorded. The overall sound pressure level directivity appears to be less affected by the turbulence ingestion at a low rotational speed. However, at higher RPM, the results demonstrate enhanced radiation downstream.

I. Nomenclature

n	=	propeller rotation speed in [rev/s]
N	=	propeller rotation speed in [rev/min]
Ω	=	propeller rotation speed in [rad/s]
ρ	=	air density [kg/m^3]
D	=	propeller diameter [m]
T	=	thrust in the z direction [N]
Q	=	torque along the z direction [Nm]
P	=	power [W]
C_T	=	coefficient of thrust
C_Q	=	coefficient of torque
C_P	=	coefficient of power
BPF	=	blade passing frequency [Hz]
$OASPL$	=	Overall sound pressure level [dB]
θ	=	azimuthal angle between microphone and plane of propeller rotation [$^\circ$]

II. Introduction

TURBULENCE interaction noise is omnipresent in many device and application, including in automotive, marine and aerospace industries, where this phenomenon can be seen from the incoming turbulence from the upstream bodies interacting with the propeller. It is also the ubiquitous factor that drives towards a more sophisticated and sustainable design of rotary-wing propulsion system such as the Urban Air Mobility (UAM). UAM is a robust air transport system developed to efficiently connect people in an urban landscape. Propeller is a common element incorporated to power UAM, and it is well known that a propeller-driven system exhibits a relatively complex sound generating mechanisms.

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Understanding propeller noise mechanisms is intricate due to the complications introduced by geometric and flow operating conditions, as well as the frequency and directivity of far-field noise radiation. The interpretation of measurement data and development of theory would be difficult due to the coexistence of different mechanisms at various strengths.

The literature study shows that the ingestion of turbulence as an inflow to the rotating blades is a crucial source of blade passage frequencies and broadband noise. Grid generated turbulence interaction with propeller blade has been experimentally studied by Sevik [1], where a comparison of propeller noise under different turbulence ingestion were reported. The physical phenomena of the far-field noise radiation of propeller is also mathematically described by Wojno et al. using the acoustic propagation law [2]. In which the amplitude of sound pressure at any point in the far-field was mathematically modelled as a function of the amplitude of the unsteady thrust spectrum. As a blade passes through tip vortex or unsteady wake generated by the preceding blades or turbulent inflow, the blade vortex interaction (BVI) occurs. This result in an acoustic signature that consists of high amplitude tonal noise that repeated at the harmonics of the blade passing frequency [3]. Furthermore, the noise spectrum of propellers generated under vortex shedding and inflow turbulence also consists of broadband components that exist in the form of dipole sound, with its axis aligned to the propeller rotational axis [4, 5]. Turbulence ingested by propeller can be characterised by its length scale, time scale, intensities and spectral content. Among these parameters, the impact of increasing turbulence intensity has been found to increase in the broadband noise levels [6].

The understanding of noise generating mechanisms are paramount during forward flight. Propellers are expected to experience stronger blade vortex interactions during cruising as compared to hovering [7, 8]. While numerous works have been performed on small-scale propeller noise, such as found in [9–17], most of them involved only single and isolated configuration systems. However, investigations of propeller flow interactions, in particular, have been mostly conducted on marine propellers. Whereas, studies on UAV propeller application is found to be scarce. Although the prediction model and method found in the literature provided theoretical insights, an extensive selection of data for realistic prediction for propeller-flow interaction is limited.

This paper presents the preliminary experimental results on the aerodynamic noise characteristics in a turbulent flow. The measurements are performed under various inflow conditions to address the effect of the ingestion nature. Additionally, the effects of the freestream velocity and rotational speed are also addressed. This paper is organized as follows: Sec. III explains the aeroacoustic facility, experimental rig and the techniques used; Sec. IV provides the results of the experiments in two main parts, i.e., aerodynamic performance and aeroacoustic performance. Finally, Sec. V reports the conclusion of this manuscript.

III. Experimental Methodology

A. Experimental Facility

The experiments were performed in the aeroacoustics facility at The University of Bristol, which is an open jet, close-circuit anechoic wind tunnel. The nozzle used in present studies has a dimension of 0.5 m width and 0.775 m height which allows a steady operation from 5 m/s to 40 m/s with a normal turbulence intensity level of less than 0.2%. The anechoic chamber has a dimension of 7.9 m long, 5.0 m wide and 4.6 m high, with acoustically treated interiors that achieves approximately 250 Hz cut-off frequency. For a more detailed description of the facility, the interested reader is referred to Mayer et al. [18]. The facility is equipped with a 23-element polar array of ¼ inch diameter GRAS model 40PL microphones, which have an upper limit of 142 dB and covers a frequency range between 10 Hz to 20 kHz. These microphones are installed on a far-field polar arch, allowing noise measurement between 40° to 150° at a distance of 1.75 m from the centre of propeller rotating disc. The propeller is positioned in the middle of the open jet nozzle and fixed at approximately 600 mm in front of the nozzle.

B. Test Rig and Setup

A 10-inch two-bladed diameter propeller with fixed pitch was used in this study. The geometrical pitch of the propeller was 10 inch and it is driven by a 40 A speed-controlled brushless motor. The setup was powered by a DC bench power supply, regulated up to a maximum of 25 V. Electrical current was measured at the power supply as the

throttle setting of ESC was varied to change the speed of the motor. Propeller rotation speed was found by measuring the electrical pulse signal from one of the three wires of the BLDC motor, considering the 24 poles of the motor. Figure 1 shows the test rig set up used in the present work.

Fig. 1 Picture of isolated propeller test rig in forward flight: (A) propeller test rig, (B) wind tunnel nozzle, (C) far-field microphone array, and (D) jet collector.

In this study, the aeroacoustic and aerodynamic characterization of the propeller was performed for two types of turbulence ingestion. Firstly, the effect of homogeneous turbulence was studied through grid generated turbulence. This grid is capable of generating an artificial turbulent flow of turbulence intensity (TI) of 4.9% and integral length scale (λ) of 6.1 mm. The geometrical details of the grid are presented in Fig. 3. In the present study, the grid diameter (d) and mesh distance (M), are set as 19 mm and 100 mm, respectively. The breakdown of the information are also tabulated in Fig. 3. The passive grid was previously characterized by Bowen et al. [19] and Celik et al. [20], and was placed in the contraction of the wind tunnel nozzle as shown in Fig. 2(a). Secondly, as shown Fig. 2(b), a rectangular wing with a NACA 0012 airfoil section was used to capture the wing-propeller installation effect phenomena. The NACA 0012 wing with 0.2 m chord and 0.6 m span was designed and manufactured in-house at the University of Bristol using rapid prototyping methods by an Ultimaker S2 3D printer. The wing was tripped at approximately 10 % of the chord by a 6 mm wide and 0.5 mm thick zig-zag turbulator trip tape.

C. Data Acquisition

A National Instruments PXIe-1082 data acquisition system was used to acquire far-field noise measurement. Matlab R2016a was used to program the interface between the data acquisition system and the microphones. Far-field noise measurements were performed using 23 microphones. The data were collected for 16 seconds with a sampling rate of 2^{16} Hz. The energy content of the far-field pressure fluctuations were derived from power spectrum density are computed with Hanning window type of overlap of 50%, using the time-domain noise data. The energy content is expressed in terms of dB/Hz, and is calculated as $10 \log_{10} \left(\phi_{pp} / p_{ref}^2 \right)$, where ϕ_{pp} is the power spectral density of the measured far-field pressure fluctuations, and $p_{ref} = 20 \mu\text{Pa}$ is the reference sound pressure. Load data were collected by utilising an ATI Mini40E force and torque sensor. The measurements were performed for a duration of 16s and at a sampling rate of 2^{13} Hz. Both noise and loading measurements were collected at varying propeller rotation speeds,

Fig. 2 Pictures of the (a) Turbulence grid set-up. [Annotations as follows: (A) propeller, (B) passive grid and (C) wind tunnel nozzle], and (b) NACA 0012 wing set-up [Annotations as follows: (A) propeller, (B) wing and (C) wind tunnel nozzle] .

Fig. 3 Schematic of turbulence grid mesh and the dimension of the grid[19].

ranging from 4000 rpm to 6500 rpm. The freestream inflow velocity was varied over a broad range, from 8 m/s to 24 m/s.

IV. Results and Discussions

A. Aerodynamic Performance

In present work, the propeller was configured in a purely axial inflow with the mean freestream velocity, U set between 8 m/s to 24 m/s. Figure 4 demonstrates the effect of different inflow conditions on the time-averaged aerodynamic coefficient for propeller operating at 6000 rpm. At a fixed setting of propeller rotation speed of 6000 rpm, the corresponding range of advance ratio between $J = 0.31$ and $J = 0.95$. The time-average aerodynamic performance is evaluated by using the thrust and torque data obtained from the load cell. The data were normalized to the non-dimensional coefficient of thrust (C_T), torque (C_Q) and power (C_P). The mathematical expressions of the propeller's coefficients, power (P), efficiency (η) and advance ratio (J) are given as,

$$C_T = \frac{T}{\rho n^2 D^4}, \quad (1)$$

$$C_Q = \frac{Q}{\rho n^2 D^5}, \quad (2)$$

$$C_P = \frac{P}{\rho n^3 D^5}, \quad (3)$$

$$P = \Omega Q, \quad (4)$$

$$J = \frac{U}{nD}, \quad (5)$$

$$\eta = \frac{C_T J}{C_P}. \quad (6)$$

The results in Fig. 4 show the effect of turbulence ingestion on the thrust and torque producing capability of the propeller. For the lower setting of advance ratio, $0 \leq J \leq 0.6$, the level of thrust coefficient was observed to be at its highest for the case of propellers in wing wake operation. Meanwhile, propellers ingesting grid turbulence shown to produce the highest coefficient of thrust at higher range of advance ratio, $0.6 \leq J \leq 1$. Additionally, the results revealed that the peaks of power coefficient shifted towards higher values of advance ratio for grid- and wing-wake turbulence ingestion cases, relative to propellers in laminar operation.

Fig. 4 Time-averaged coefficient of thrust and torque produced at N=6000 rpm.

Figure 5 shows the comparison of the aerodynamic efficiency for propeller operating at 6000 rpm, under laminar, grid generated turbulence, and wing wake turbulence inflow. The results indicate that propellers under wing wake turbulence operate at the highest efficiency in a broader range of advance ratio. While propellers under laminar and grid turbulence inflow appear to have identical efficiency characteristics.

The propeller loading distribution is also assessed by examining its energy spectrum following power spectral density analysis. Figure 6 shows the comparison of power spectrum of aerodynamic thrust for propeller operating at 6000 rpm under different inflow conditions. It is shown that the thrust energy distribution drops significantly when the freestream velocity increases from 8 m/s to 12 m/s. However, at higher speed settings, the changes appear to be less affected. It is also observed that the thrust energy distribution for propeller ingesting wing wake contains the most peaks at an approximate range of $442 \text{ Hz} \leq N \leq 1300 \text{ Hz}$. Similar trend is also demonstrated in Fig. 7, where the turbulence ingestion is shown to increase the thrust spectra.

Fig. 5 Comparison of propeller efficiency against advance ratio under different inflow conditions.

Fig. 6 Power spectral density of thrust at N=6000 rpm and U=24 m/s at varying inflow conditions.

B. Aeroacoustics Performance

1. Effect of Turbulence Ingestion to Noise Directivity

The directivity study of far-field propeller noise shows the overall sound pressure level (OASPL) distribution for a wide range of observation angles. Figure 8 shows the OASPL variation of laminar inflow and different turbulence ingestion cases for different incoming flow velocities at 6000 rpm. The maximum noise radiation is observed at

Fig. 7 Power spectral density of thrust at N=6000 rpm at varying inflow velocity under: (a) laminar inflow, (b) grid turbulence, and (c) wing wake.

downstream of the propeller for both with and without turbulence ingestion cases. The amplitude of OASPL is minimum near the plane of rotation. However, an increase in inflow velocities leads to radiating the noise in the upstream direction as well. For the laminar inflow case, the radiated sound pressure decreases with an increase in inflow velocities. The direction of maximum noise radiation remains the same in both upstream and downstream directions. However, further increase in freestream velocity leads to an enhanced sound pressure level in both upstream and downstream directions. Additionally, at higher flow velocities the OASPL hump is generated when compared to the lower inflow velocities. This result is consistent with OASPL variation in the turbulent ingestion cases. Initially, the OASPL decreases with an inflow velocity, however, further increase in the freestream inflow velocity enhances the sound pressure significantly for the grid turbulence ingestion case compared to the laminar one. It should be noted that at higher freestream velocity, both grid turbulence and wing wake interaction significantly enhances the OASPL in the upstream direction.

Fig. 8 Overall Sound Pressure Level (OASPL) characteristics of propeller in forward flight condition at 6000 rpm in (a) laminar inflow, (b) grid turbulence inflow, and (c) wing wake inflow.

The OASPL comparison of different turbulence ingestion with laminar inflow velocity at 16 m/s is presented in Fig. 9. Two different RPM cases, such as 4000 rpm and 6000 rpm, are considered to show the effects of the rotation speed on the sound pressure level during turbulence ingestion. In the present work, the grid with solidity ratio, $\sigma = 0.35$ is placed upstream of the propeller, whereas the wing is placed at $1.0R$ upstream and $0.7R$ radial location. Figure 9 shows the comparison of directivity pattern for propeller at 4000 rpm and 6000 rpm under varying 16 m/s flow ingestion.

Fig. 9 The OASPL variation for propeller under $U=16$ m/s incoming turbulence at rotation speed of: (a) $N=4000$ rpm, (b) $N=6000$ rpm.

The results indicate that turbulence ingestion enhances the OASPL at the downstream angles, however, the direction of maximum noise radiation is unaltered. At the upstream, the directivity slightly altered with different ingestion. Considerable noise increment is observed for the wing wake interaction with propeller blades compared to grid-generated turbulence case. In the case of higher rotation speed (6000 rpm), the grid-generated turbulence does not show significant variation in OASPL. However, the wing wake case shows a significant noise increase in the wide range of emission angles. The maximum noise increment of about 8 dB is observed at the a downstream angle of $\theta = 140^\circ$, also 7 dB noise increment is observed at upstream emission angle (50°).

2. Effect of Propeller Rotation Speed (N) and Freestream Velocity (U) on Noise Spectrum

It is well known that the PSD spectrum of the propeller is rich in discrete tones and broadband noise [16]. The periodic and random pressure fluctuations of the propeller noise lead to generation of discrete tonal noises at the harmonics of blade passing frequency and broadband spectrum for a wide range of frequencies, respectively. The effects of rotation speed and incoming freestream velocity on the propeller noise radiation are investigated in present study. The power spectra are constructed using a time-series signal of propeller noise at the plane of rotation. The PSD spectrum contains intense discrete tones at the blade passage frequency (BPF) and its harmonics at an integer multiple of the first blade passage frequencies. Moreover, a minimum peak at rotational frequency is observed. The high frequency broadband noise is contaminated by the motor mechanical noise. The power spectral peaks of the far-field noise data agree well with power spectra of thrust fluctuation which is discussed in Section IV.B.

Figure 10 shows the power spectra comparison of different rotation speed, N at static condition. The results show that an increase in rotation speed leads to an increase in the amplitude of both narrowband and broadband noise spectrum for propeller in laminar inflow. As expected, the BPF frequency increases with an increase in rotation speed, where the BPF is calculated by multiplying the number of blades and rotation speed. Propeller-associated discrete tones are observed until the frequency of about 10 kHz, furthermore, the broadband components are dominant in the mid and high-frequency ranges.

Figure 11 shows the comparisons of noise spectra of propeller operating at a fixed settings of rotation speed (4000 rpm), under varying freestream laminar inflow velocities. The results demonstrate a significant noise increment at both narrowband and broadband spectrum while increasing the freestream velocities. The PSD amplitude at the first blade pass frequency decreases by about 1 dB/Hz with an increase in inflow velocity from 8 m/s to 16 m/s, with an interval of 4 m/s. However, a further increase in inflow velocity leads to an increase in PSD of about 2 dB/Hz. Meanwhile, the maximum recorded PSD is observed at 24 m/s. A similar phenomenon is observed at its harmonics as well. Low and mid-range broadband noise increases with an increase in inflow velocity, but at a higher frequency, the amplitude is not significantly increased. The minor peak at the shaft rate is visible at lower freestream inflow velocity, however the

Fig. 10 Power spectral density for propeller in forward flight under static condition at different rotation speed.

low-frequency broadband noise masks the shaft rate tones at higher inflow velocities.

Fig. 11 Power spectral density for propeller in forward flight under varying velocities of freestream laminar inflow at N=4000 rpm.

In both of the noise spectra presented, it is notable that the first three harmonics of blade passing frequencies are clearly visible in the low frequency range, whereas the turbulence shedding frequency is dominant at mid and high frequencies. The low frequency tone is called shaft rate and is embedded with the broadband spectrum as a sub-harmonic of the BPF. The frequency of shaft rate can be calculated using rotation speed in terms of revolution per second. The amplitude of the shaft rate tone is non-monotonically changing with rotation speed.

3. Effect of Turbulence Ingestion on Noise Radiation at Different Polar Observation Positions, θ

The PSD comparison at different observation positions is investigated to understand the influence of turbulence ingestion in the narrow- and broadband spectral content when compared to different azimuthal observation positions. The power spectral density comparison at different locations provides a detailed reason for this increase, as presented in Fig 12. As discussed earlier, the grid-generated turbulence does not show significant variations in OASPL and the PSD spectral comparison supports the same observation. Wing-generated turbulence interaction with propeller blades leads

to a significant increase in the mid and high-frequency noise (210 Hz to 10000 Hz). Also, a significant increment in sound pressure is observed at the harmonics of the BPF. The spectral comparison at different emission angles clearly shows higher broadband noise at 50° and 140° when compared to 80° and 90° . The turbulence shedding noise of wing wake interaction with propeller is not effectively radiates near the plane of rotation. These results show the reason for the variations in the OASPL for different ingestion cases.

Fig. 12 PSD comparison of different incoming turbulence at 16 m/s for different observation angles (a) $\theta = 50^\circ$, (b) $\theta = 80^\circ$, (c) $\theta = 90^\circ$, and (e) $\theta = 140^\circ$ at $N=6000$ rpm rotation speed.

V. Conclusion

The noise and loading of propeller in forward flight and how they are affected by the turbulence ingestion have been studied. It was found, as with previous studies, that the power spectral density spectrum of the propeller is rich in discrete tones and broadband noise. It was also found that the turbulence interactions increase the thrust energy spectra, but incur noise penalty by about 2 dB/Hz and 5 dB/Hz to 15 dB/Hz above 1000 Hz for grid turbulence and wing wake cases, respectively. The directivity of overall sound radiation appears to be less affected by the turbulence ingestion at low rotation speed. However, at higher RPM, the OASPL are enhanced at the downstream. Furthermore, a maximum noise increment of about 8 dB and 7 dB at the a downstream angle of $\theta = 140^\circ$ and at upstream emission angle (50°), respectively, are reported. To further assess the characteristics of propellers in turbulence ingestion for aeroacoustic applications, further aerodynamic testing is required for the quantification of the flow field around the propeller blade.

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