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Aeroacoustic Performance of Rotors in Tandem Configuration

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This experimental study presented in this paper aims at understanding the complex aeroacoustics relationship between small-scale rotors in tandem configurations. The effect of the upstream rotor on the aeroacoustics of the multi-rotor system in a counter-rotating configuration was studied. Two rotors in tandem alignment were tested for varying separation distances, free-stream velocities, and tilt angles for the upstream rotor. The results are presented in terms of power spectral density of the acoustic pressures and the directivity of the overall sound pressure levels. The results show that the presence and position of an upstream rotor significantly affect the rotor system's noise signature. The tip-to-tip separation distance affects the magnitude of the radiated noise at the first blade passing frequency. Additionally, an increase in the free-stream velocity increases the radiated broadband noise. The OASPL directivity patterns show a minimal sensitivity to the free-stream velocity except for a few exceptional cases. Finally, the tilt angle of the upstream rotor has a significant effect on the OASPL directivity at higher tilt angles.

I. Nomenclature

N	=	rotor rotational speed in [rev/min]
D	=	rotor diameter [m]
R	=	rotor radius [m]
S	=	tip-to-tip separation distance [m]
β	=	blade pitch angle [°]
α	=	test rig tilting angle [°]
BPF	=	blade passing frequency [Hz]
PSD	=	power spectral density [dB/Hz]
OASPL	=	overall sound pressure level [dB]
U	=	free-stream velocity [m/s]
p_{ref}	=	reference pressure, 2×10^{-5} [Pa]
ϕ_{pp}	=	Power spectral density of the pressure fluctuations [dB/Hz]

II. Introduction

THE growing interest on the propeller based unmanned and manned air vehicles draws continuing investment in vertical take-off and landing aircrafts. The tantalizing concept of Urban Air Mobility (UAM), which pledges effective and green transport systems, introduces the third dimension for transportation planning for cities of future. However, the increase in UAM and already ubiquitous presence of propeller based air traffic challenges the scientific community with the accompanying aerodynamic and aeroacoustic problems.

Aerodynamics and aeroacoustics of propellers and rotors have been under investigation for decades. However, the size and power limitations for future urban air mobility (UAM) devices compels the limits of knowledge in the field. The aerodynamic and aeroacoustic characteristic of these designs will differ from conventional helicopters and turboprop aircraft due to the different design characteristics and operational requirements of the employed rotors and propellers, and because of adoption of electric propulsion. The reduction of radiated noise from propellers requires extensive

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research due to its complexity and intertwined nature with the generation of the aerodynamic forces. There have been numerous studies on the aerodynamics and aeroacoustics of propellers operating at high Reynolds numbers [1, 2], yet studies on propellers at low Reynolds numbers have been rather limited. The literature shows that propeller size has a pronounced effect on propeller efficiency [3] and the geometrical properties such as chord twist and blade taper ratio [4] significantly affect the aerodynamic and aeroacoustic characteristics of the propellers. To face the challenges imposed by the recent surge of propeller driven systems, a detailed understanding of the aerodynamic and aeroacoustic characteristics is required. Moreover, any attempt to decrease the noise emission may lead to a degraded performance of the propellers.

The broad range of requirements of the multi-rotor systems designed for the urban air mobility vehicles is accompanied by a flexible and broad range of the design of the vehicles. The variety of the designs lead additional complications in flow field due to the vertical take-off, landing, cruise, as well as the non-axial inflows experienced in real life. Moreover, the parameters of having ducted or non-ducted propellers, distance between propellers, number of blade in propellers are subject to change in designs, which requires very detailed analysis for aerodynamic and aeroacoustics performance for each case. This requirement led an acceleration and increase in the research activities. Figure 1 presents some VTOL concepts which are already been in the market. The lack of knowledge in the understanding of aerodynamics and aeroacoustics of small scale propellers amplitudes with the existence of multiple propellers with a highly flexible design space[5]. Recent studies [6–11] span topics of aerodynamic characterization and noise attenuation for small scale isolated propellers and rotors.

The complex flow and noise signature due to interactions among propellers in multi-rotor systems has become an important topic of research with the current raise of the urban mobility and green aviation targets. Propellers in multi-rotor systems experience wake-wake interaction, blade-wake interaction, as well as other complexities if the propellers are ducted or in case of presence of gust. Recent studies addressing the noise signature of multi-rotor systems [12–15] and flow characteristics [16–19] have aimed at understanding these complex flow phenomena, and contribute to quieter and more efficient designs. Intaratep et al. [15] has performed an experimental study on the acoustics and performance of quadcopter at static thrust conditions. The study investigated the effect of number of rotors on the aerodynamics and aeroacoustic performance. They have shown that thrust generated by small-scale rotors is sensitive to the blade geometry and rotor configuration, and the aerodynamic performance deteriorates as the number of rotor increases. Moreover, the results showed that 4-rotor interaction radiates significantly higher broadband noise compared to 1-rotor and 2-rotor cases. In their numerical study, Yoon et al. [18] showed that the distance between rotors has a significant effect on the vertical force of a quadrotor. This observation is later supported by Shukla and Komerath [17]. In their experimental work, they have shown that the close proximity deteriorates the rotor performance. Jia and Lee [12] showed that the dominant noise source in a case of quadrotor VTOL is the blade-vortex interaction (BVI).

The investigation presented in this paper aims at understanding the effect of the presence of a second propeller on the aeroacoustic and aerodynamics of the downstream rotor. The preliminary results are presented in this paper to shed light on the effects of several parameters in the design space. The separation distance between the two rotors, the tilt angle of the rotors, and the relative tilt angle difference between the two rotors are studied. 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 four parts. Finally, Sec. V reports the conclusion of this manuscript.

III. Experimental Setup

Experiments were performed in the closed-circuit open-jet anechoic wind tunnel facility at the University of Bristol. The turbulence intensity of the wind tunnel is less than 0.2 % with a flow uniformity over 90 % at the nozzle exit [20]. The chamber is anechoic down to 160 Hz with physical dimensions of 6.7m x 4.0m x 3.3m and the nozzle has an area of 500 mm x 775 mm, which allows a steady operation from 5m/s to 45m/s.

The tests were performed a pair of two-bladed propellers aligned in a tandem configuration. Each propeller had a diameter of 10 inches and a propeller pitch of 5 inches. The setup was powered by a DC bench power supply, regulated up to a maximum of 25V. The propellers were driven by a 40A speed-controlled brushless motor separately using via RCbenchmark software. Current is measured at the power supply as the throttle setting of ESC is varied to change the speed of the motor. Propeller rotational speed was obtained by measuring the electrical pulse signal from one of the three wires of the BLDC motor, considering the 24 poles of the motor. Moreover, a cross-check for the rotational speed measurements was also performed by a digital tachometer. The test rig was positioned at the center of the open jet nozzle, approximately 600 mm away from the nozzle exit, as illustrated in Fig. 2. The distance between the propellers (S) was varied in the range of 0.2R to 1.2R. Additionally, the tilt angle of the upstream rotor was varied for a broad

range of $0^\circ < \alpha < 25^\circ$ for an increment of 5° . The schematic of the test rig is presented in Fig. 2. The measurements were performed with rotor rotating speed of 6000 rpm and at an incoming speed between 0 m/s to 24 m/s.

Far-field noise measurements were obtained using 23 1/4 inch GRAS 40PL microphones, which have a large dynamic range and an upper limit of 142 dB, covering a frequency range between 10 Hz and 20,000 Hz. These microphones are arranged on to a far field array arc allowing measurement between 40° and 150° polar angles at a distance of 1.75 m from center of the propeller system. All microphones were calibrated in both magnitude and phase referenced to a single GRAS 40PL microphone, which was calibrated using a GRAS 42AA pistonphone calibrator. The far-field noise data were acquired using a National Instruments PXIe-1082 data acquisition system. Matlab R2016a was used as the software to interface between the data acquisition system and the microphones to run the data acquisition code. The noise measurements were performed for 16 s at a sampling frequency of 2^{16} Hz.

The noise results are presented in terms of the frequency-dependent energy content of the pressure fluctuations. The energy content is expressed in terms of dB/Hz, and is calculated as $10 \log_{10} (\phi_{pp}/p_{ref}^2)$, 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. The power spectral density of the pressure fluctuations (ϕ_{pp}) was estimated by using the Welch's method [21], where the data from the transducers are segmented for 32 equal lengths with 50% overlap and windowed by the Hamming function, resulting to a frequency resolution of $\Delta f = 2$ Hz. Hereafter, $10 \log_{10} (\phi_{pp}/p_{ref}^2)$ will be referred to as power spectral density (PSD) for brevity. The overall sound pressure level (OASPL) was obtained by integrating the energy spectrum with respect to frequency over 90 Hz to 16 kHz.

IV. Result and Discussions

In this section the results for aerodynamic and aeroacoustic performance are presented to explore the effect of having a second rotor blade located at the upstream another rotor, which is a widely encountered physical relationship for current rotor-driven UAV systems and UAM vehicles. It is worth noting that the rotors were not phased locked. This leads slight changes in some cases of the different runs of the experiments. However, the results in this section will focus on the possible effects of the tandem configuration, and will try to avoid drawing certain conclusions.

A. Characterization of isolated rotor

This section aims to present the aeroacoustic characterization of a single rotor. In order to better interpret the effect of the tandem configuration, the results of the single case are compared to a selected tandem case under static conditions and under different inflow velocities. Figure 4 presents the power spectral density (PSD) of the pressure fluctuations measured at the microphone polar angle of 90° for single and tandem case, for free-stream velocities of 0 m/s $< U < 24$ m/s. PSD results at the static condition for the isolated rotor case, Fig. 4(a) shows that broadband noise level increases significantly with the presence of free-stream velocity, U . The tonal peaks, which mark the blade passing frequencies (BPF) and their harmonics, are apparent for all cases. The magnitude of the PSD at 1st BPF shows a drastic increase with the introduction of free-stream velocity, increasing from 33 dB/Hz to 70 dB/Hz. Results for a tandem configuration, $S=0.2R$, is also provided in Fig. 4, to discuss the effect of the presence of a second rotor. The results show elevated PSD values for both broadband and tonal peaks for the tandem case compared to the results of the isolated rotor. The PSD at the 1st BPF increases around 3 dB/Hz for tandem configuration for both free-stream velocities of $U = 16$ m/s and 24 m/s. However, the increase in PSD magnitude is markedly higher for $U = 0$ m/s, where more than 13 dB/Hz increase is evident for tandem configuration compared with the results of the isolated case.

Figure 5 is constructed to present a comparison of directivity results for overall sound pressure levels (OASPL) for isolated and tandem configurations. The results indicate that for static condition, $U = 0$ m/s, the OASPL magnitude is significantly lower compared to the cases with free-stream velocity. Considering both configurations, the radiated noise increases in magnitude as the free-stream velocity increase. The results clearly show that having tandem configuration at a spacing distance of $S=0.2R$ increases the radiated noise levels at around 5 dB/Hz.

B. Effect of separation distance (S)

The broad range of the design space for UAMs and UAVs span requires an understanding of the noise signature under different configurations. This section presents the preliminary results enlightening the effect of separation distance on the noise signature for a tandem rotor configuration. The separation distance between rotors varied over the range of $0.2R < S < 1.2R$. Figure 6 presents the PSD results obtained at 90° microphone for free-stream velocities of $U = 0$ m/s, 8

m/s, 16 m/s and 24 m/s from (a) to (d), respectively. A closer look to the results at the 1st BPF are also provided inside each sub-figure to ease the interpretation of the results.

Figure 6(a) presents the PSD results for $U = 0$ m/s. The magnitude of the noise for 1st BPF and its harmonics are similar up to mid-frequencies. The radiated noise level at 1st BPF is higher for all the separation distances than the isolated rotor for all the separation distances. However, as the separation distance increases, for $S > 0.6R$, a slight decrease is evident compared to lower separation distances. Conversely, the broadband noise for $S = 1.2R$ seems to be consistently higher compared to other separation distances. With the presence of the free-stream velocity, Fig. 6(b), the magnitude of the harmonics of the BPF decreases. Moreover, at the 1st BPF, the PSD values for all separation distances are confined within 2 dB/Hz, suggesting that the separation distance does not significantly affect the magnitude of noise at 1st BPF. As the free-stream velocity increases, Figs. 6(c) and (d), the magnitude of the PSD at 1st BPF and broadband noise increases. It is worth noting that at $U = 24$ m/s, the magnitude of the radiated noise at the 1st BPF shows a drastic reduction of around 10 dB/Hz at $S = 0.6R$.

Figure 7 displays the effect of separation distance on the directivity of OASPL (dB) for free-stream velocities of $U = 0$ m/s, 8 m/s, 16 m/s, and 24 m/s. Results are presented with different scales for better visualization and clarity. Considering all the results presented in Figs. 7(a) to (d), the apparent dipolar directivity pattern dominates the results. At static condition, $U = 0$ m/s, the main lobe of the dipolar directivity centers at around 90° . However, the presence of free-stream velocity alters this behavior, and radiated noise becomes more directive towards certain angles. At $U = 8$ m/s, a faster decay of OASPL at angles above 100° is evident. At $U = 16$ m/s, the OASPL patterns for all separation distances become more directive towards the downstream of the flow, where the maximum level of OASPL is centered around the polar angle of 100° . At $U = 24$ m/s, the directivity patterns suggest a similar trend. It is worth noting that at separation distance $S = 0.6R$, there exists a significant reduction at the radiated noise level compared to the results of other separation distances.

C. Effect of free-stream velocity (U)

In this section, the effect of free-stream velocity on the radiated noise is addressed. The effect is quantified by the PSD of the pressure signal at microphone location 90° and directivity results (OASPL) for free-stream velocities of $U = 0$ m/s, 8 m/s, 12 m/s, 16 m/s, 20 m/s, and 24 m/s at separation distances of $S = 0.2R, 0.4R, 0.6R$ and $1R$. Figures 8(a) to (d) present the effect of the free-stream velocity for separation distances $S = 0.2R, 0.4R, 0.6R$ and $1R$, respectively. Considering results in Fig. 8(a), $S = 0.2R$, a significant increase of the broadband noise is evident as the U increase. Moreover, at the 1st BPF, the PSD results suggest a significant increase between the static case with $U = 0$ m/s and others. This effect is less evident at higher harmonics of the BPF. Additionally, the levels of PSD, both in 1st BPF and broadband, increases in parallel to velocity increase. For other separation distances, Figs. 8 (b) to (d), the results show a similar broadband nature to the results of $S = 0.2R$. However, there is a significant difference for the narrow-band results at the separation distance of $S = 0.6R$. The PSD results indicate that the increase in the magnitude of the noise does not follow a linear trend, i.e., the PSD does not increase as the free-stream velocity increases. The results show that the noise level reaches to a maximum at $U = 20$ m/s and reduces significantly at $U = 24$ m/s.

Figure 9 displays the effect of separation distance on the directivity of OASPL (dB) for free-stream velocities of $U = 0$ m/s, 8 m/s, 16 m/s, and 24 m/s. Results are presented with different scales for better visualization and clarity. In general, the dipolar directivity pattern is evident at all free-stream velocities and for all separation distances, i.e., $S = 0.2R, 0.4R, 0.6R$ and $1R$, Figs. 9(a) to (d), respectively. The directivity patterns suggest a monotonic increase in the OASPL with an increase in free-stream velocity. It is worth noting a few interesting observations. At separation distance $S = 0.4R$, the directivity pattern slightly shifts at free-stream velocities of $U = 16$ m/s and 20 m/s. Moreover, the results indicate that the noise level is similar at downstream of the rotors ($\theta > 110^\circ$) for these cases. The OASPL directivity patterns at the separation distance of $S = 0.6$ show that the highest noise radiation occurs at the free-stream velocity of $U = 20$ m/s.

D. Effect of tilting angle (α)

This section provides some preliminary results on the effect of tilting of the upstream rotor on the noise signature of the tandem configuration. This configuration is selected due to its relevance with the current design concepts. In order to ease interpretation, the tip-to-tip distance of the rotors was fixed $S = 1R$, independent of the tilting angle. Figures 10(a) and (b) present the PSD results for tilting angles spanning $0^\circ < \alpha < 25^\circ$ for the upstream rotor at a separation distance of $S = 1R$ (tip-to-tip) for free-stream velocities of $U = 0$ m/s and 16 m/s, respectively. A close-up look for the results at 1st BPF is provided to ease the interpretation of the results. Figure 10(a) displays the PSD results for $U = 0$ m/s. The results indicate that the tilting angle of the upstream rotor may affect the radiated noise at the 1st BPF around

10dB/Hz. The highest level of noise is observed at $\alpha = 5^\circ$, and the lowest value is at $\alpha = 20^\circ$. The broadband behavior for all configurations seems to be similar, except $\alpha = 5^\circ$, which consistently exhibits slightly higher values of PSD. The presence of the free-stream velocity, Fig. 10(b), has a marked effect on both the broadband and narrowband characteristics of the noise radiation. The results show an apparent noise reduction in case of all tilt angles, compared to the results of no tilt ($\alpha = 0^\circ$). Additionally, the tilt of the forward rotor reduces the broadband noise levels, as high as 15 dB/Hz for the case with highest tilt angles.

The effect of the upstream rotor's tilt angle on the directivity pattern of the noise is presented in Figure 11. The OASPL results are presented in different scales for clarity. The results for $U = 0$ m/s show a dipolar pattern, where the main lobe centers at around polar angle of 90° . The presence of the free-stream velocity affects the directivity pattern and the magnitude of the OASPL significantly, as presented in Fig. 11(b). For lower tilting angles, the OASPL curves collapse to a narrow envelope. However, for tilting angles of $\alpha = 20^\circ$ and $\alpha = 25^\circ$, a significant reduction in OASPL is evident. Moreover, at the free-stream velocity of $U = 20$ m/s the OASPL curve is directed to upstream. Conversely, at $U = 25$ m/s the OASPL curve is directed toward downstream, where the maximum of the lobe is around polar angle 110° .

V. Conclusion

This paper aims at presenting some preliminary results toward understanding the complex acoustic signature generated by rotors in tandem configurations. The effect of tip-to-tip separation distance, free-stream velocity, and the tilting angle of the upstream rotor on the radiated noise signature of the configurations was studied. The results were presented in terms of the power spectral density (PSD) of the pressure signal obtained at the polar angle of 90° and the directivity of OASPL.

First, a comparison between the noise signature of a single rotor and tandem configuration is provided. Although the tandem rotors were not phase-locked, the results indicate an increase in the noise radiation levels, as expected. The tip-to-tip separation distance between rotors significantly affects the magnitude of PSD at the 1st BPF and the directivity patterns of the OASPL slightly changes at different separation distances. However, at some cases, the OASPL shows significant reduction. Additionally, the results show that as the free-stream velocity increases, the broadband noise level also increase. Interestingly, at a rotor separation of $0.6R$, the noise levels at the 1st BPF do not follow the general trend. Finally, results on the effect of tilting angle are also presented. The results show that the tilting angle of the upstream rotor has a significant effect on the noise levels at the 1st BPF and OASPL directivity.

The results illustrate the effect of some selected parameters from the design space of future UAM and UAV vehicles on the noise signature of the multi-rotor systems. For future work, a comprehensive aeroacoustic study will be performed to explore more parameters, such as the relative tilting angle between rotors and misalignment of rotors in different planes of motion. Moreover, aerodynamic performance of the rotors should be investigated with an accompanying flow field characterization, including detailed time averaged and frequency-dependent nature of the flow field.

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(a)

(b)

Fig. 1 Examples of current designs for urban mobility vehicles. Photo credits (a) Vertical Aerospace (b) Joby Aviation.

Fig. 2 Schematics of the tandem propeller test test rig. (a) The details of the tandem configuration, nozzle and far-field microphone array (b) The dimensions of the rotor and details of the support system.

Fig. 3 Pictures of the facility (a) The microphone arrays (b) Tandem rotor configuration.

Fig. 4 Comparison of PSD of pressure fluctuations at 90° microphone for single (isolated) and tandem ($S=0.2R$) configurations at free-stream velocities of $0 \text{ m/s} < U < 24 \text{ m/s}$.

Fig. 5 Directivity of the radiated noise (OASPL) for single (isolated) and tandem ($S = 0.2R$) configurations at free-stream velocities of $0 \text{ m/s} < U < 24 \text{ m/s}$.

Fig. 6 Effect of separation distance, S , on the PSD of the far-field pressure fluctuations for $0.2R < S < 1.2R$ for free-stream velocities of (a) $U = 0$ m/s, (b) $U = 8$ m/s, (c) $U = 16$ m/s, and (d) $U = 24$ m/s.

Fig. 7 Effect of separation distance S on the directivity of the overall sound pressure level (OASPL) for $0.2R < S < 1.2R$ for free-stream velocities of (a) $U=0$ m/s, (b) $U=8$ m/s, (c) $U=16$ m/s, and (d) $U=24$ m/s.

Fig. 8 Comparison of PSD levels for different free-stream velocities $0 \text{ m/s} < U < 24 \text{ m/s}$ at separation distances (a) $0.2R$, (b) $0.4R$, (c) $0.6R$, and (d) $1R$.

Fig. 9 Comparison of OASPL directivity for different free-stream velocities $0 \text{ m/s} < U < 24 \text{ m/s}$ at separation distances (a) $0.2R$, (b) $0.4R$, (c) $0.6R$, and (d) $1R$.

Fig. 10 Comparison of PSD level for tilt angles $0^\circ < \alpha < 24^\circ$ at free-stream velocities of (a) $U= 0$ m/s, (b) $U= 16$ m/s.

Fig. 11 Comparison of OASPL directivity for tilt angles $0^\circ < \alpha < 25^\circ$ at free-stream velocities of (a) $U= 0$ m/s, (b) $U= 16$ m/s.