This paper highlights three on-going projects conducted at HKUST towards the development of a noise assessment platform for multi-rotor flying vehicles. The first project outlines the development of a test rig for assessing the aerodynamic and aeroacoustic performance of small-scale UAV propellers. Generic propellers were developed so that the importance of key design parameters may be determined systematically. Additionally, these generic propellers were made of metal to minimize any aeroelastic effects. The second project focuses on full-scale drone experiments that were conducted within a large anechoic chamber, which overcomes any environmental or meteorological factor that may otherwise be present in outdoor field testing. The experiment consisted of microphone array measurements and simultaneous position tracking, which provided a complete characterization of drone noise under realistic flight conditions. The final project focuses on the development of an acoustic ray tracing code, to predict the noise impact of a hovering drone in complex urban environments. The noise source applied to this code was developed from the anechoic chamber tests.

Keywords: Drones, aeroacoustics, multi-rotor, small-scale UAVs.

1. Introduction

Unmanned electric multi-rotor flying vehicles are a type of unmanned aerial vehicle (UAV) that has become a significant aerospace industry with broad applications such as civil engineering, logistics, and photography. Full-scale outdoor [1] and anechoic chamber [2] tests have determined the propellers and motors as the major noise sources of such vehicles.

Brooks [3] identified the major sources of propeller noise as the tonal self-noise, blade-vortex interaction (BVI), blade-wake interaction (BWI) and broadband-self noise. The relative importance of these noise sources depends on the design of the propellers as well as its operational condition. Small-scale propellers typically used on drones have diameters of 200-300 mm and chord lengths of up to 50 mm. The tip speeds of small-scale UAVs are typically sub-sonic, and the Reynolds numbers are of the order of 10^5. Outdoor field tests have shown that small-scale multi-rotor vehicles generate distinctive tonal noise at the blade passage frequency (BPF) and its harmonics, broadband propeller noise, and high-frequency motor noise [1]. Experiments of clamped multi-rotor systems [2,4], and of single propellers [5,6], have
also highlighted these major acoustic features. The broadband noise of isolated propellers can be reduced by boundary layer trip devices [7] or by the sharper trailing edges [5].

Propeller-propeller and propeller-airframe interaction noise have also been previously investigated. Intaratep et al. measured the changes in the noise levels of a commercial quad-rotor drone with one, two, and four operational motors. This study incorporated both types of propeller interactions mentioned previously. Zawodny and Boyd [8] studied the propeller-airframe interaction noise by placing circular rods at various distances downstream of a small-scale UAV propeller. Periodic interactions induced by the propeller-airframe configuration enhanced the tonal noise levels up to the 7th BPF. The potential flow field of an airframe can also affect the inflow plane of a propeller, thereby affecting the radiated sound levels [8, 9]. Teng and Fattah [6] investigated the tonal noise interactions by two side-by-side co- and counter-rotating propellers at various hub separation distances, rotational speeds, and tilt angles. They showed that hub separation distance does not significantly affect the radiated sound levels. However, the propeller tilt angle and the rotational configuration of motors (co- or counter-rotating) can affect the radiated sound levels by up to 3dB. Additionally, they showed that the tonal noise from two propellers can be controlled by varying the phase angle difference between different propellers such that they induce constructive or destructive interference patterns. Fattah et al. [10] showed that an analytical model could accurately predict this tonal noise interaction.

Although previous works of small-scale UAV propellers and of full-scale drones flights have been conducted, several challenges regarding drone noise research remain. This paper highlights three ongoing projects that aim to address three of these challenges. Firstly, component level tests, such as those of isolated propellers or of simple propeller-airframe interactions, are commonly applied using commercial propellers. Therefore, there is a lack of understanding of which design parameters are key in affecting small-scale UAV propeller aerodynamics and aeroacoustics. Additionally, there are inherent uncertainties and unknowns when working with commercial products that make it challenging to verify numerical simulations with experiments. To resolve this issue a test rig using generic propeller blades was developed. The second challenge relates to outdoor flight testing of small-scale flying drones, which can be easily affected by environmental factors. These factors can be overcome by performing such small-scale flight tests inside large anechoic chambers. Additionally, anechoic chamber tests of fixed drones do not reflect realistic flight conditions. Therefore, full-scale flight tests of free-flying drones were conducted. The final challenge relates to assessing UAV noise in realistic outdoor environments. An acoustic ray tracing code was developed, which uses simplified drone noise models developed using the aforementioned experimental database of full-scale flight tests. The noise propagation code accurately models outdoor noise propagation physics and can handle any urban environment.

2. Test rig for small-scale propellers

Most previous experiments of small-scale UAV propellers [6–8, 10, 11] applied to commercial propellers. A general overview of typical commercial propellers is given in Table 1 which lists the propeller diameter, as well as the approximate Reynolds and Mach numbers based on a rotational speed of 5400 revolutions per minute (RPM). Every blade listed in Table 1 was scanned using an ATOS Core 200 system, which revealed the range of design parameters, such as the pitch angle and blade chord. Based on these result, three generic propellers with a constant 25 mm chord length, 240 mm diameter, and constant pitch angle, were made using Al-6061. The three generic propellers that were developed varied in terms of the NACA profile and the blade pitch angle.

Figure 1 outlines the experimental setup and overall instrumentation of the primary propeller arm, which consisted of the motor, a high-resolution rotary encoder, and a six-axis force transducer. The propeller arm was connected to the rest of the test rig structure and placed within a 3.2 m (L) × 3.1 m
<table>
<thead>
<tr>
<th>Model</th>
<th>$D$ [mm]</th>
<th>$Re_{0.75R}$</th>
<th>$M_{tip}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>GoPro Karma</td>
<td>254</td>
<td>129 000</td>
<td>0.21</td>
</tr>
<tr>
<td>Haoye EP9050</td>
<td>229</td>
<td>59 000</td>
<td>0.18</td>
</tr>
<tr>
<td>Haoye EP1047</td>
<td>256</td>
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<tr>
<td>DJI 8330</td>
<td>217</td>
<td>99 000</td>
<td>0.2</td>
</tr>
<tr>
<td>DJI 9450s</td>
<td>240</td>
<td>69 000</td>
<td>0.2</td>
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<td>DJI 9455s</td>
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<tr>
<td>APC 9x4.7SF</td>
<td>229</td>
<td>88 000</td>
<td>0.19</td>
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<td>APC 9x6SF</td>
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</tr>
<tr>
<td>APC 11x7SF</td>
<td>279</td>
<td>136 000</td>
<td>0.23</td>
</tr>
</tbody>
</table>

Table 1: List of commercial two-bladed propellers.
A (W) × 2 m (H) anechoic chamber at HKUST. This facility was used previously to measure the noise from commercial propellers [6, 10]. The propeller noise was measured under hovering conditions (i.e., \( U_\infty = 0 \)), and the test rig was configured such that the rotor wake would be ejected out from the test chamber via an outlet. A PID feedback system fixed the motor speed and 20 1/4-inch G.R.A.S Type-46BE free-field microphones measured the acoustic field. All microphones were positioned more than 10 propeller diameters away from the propeller hub.

**Figure 2:** Preview of acoustic measurement result acquired by the test rig.

Figure 2 gives a general outline of the results obtained from the test rig. Figure 2(a) shows the changes in the noise directivity of the EP9050 propeller at the BFP, with increasing rotational speed. Figure 2(b) shows the changes in the noise directivity at the BPF from various propellers at a fixed rotational speed of 100 rotations per second (RPS). In summary, the developed test rig can be used to identify the importance and impact of key design parameters. This test rig is being used to establish a wide database of aerodynamic and acoustic measurements of numerous generic metal propellers.

### 3. Full-scale anechoic chamber tests

Experiments were conducted in a 10.5 m × 8.4 m × 7 m large anechoic chamber, which has a cut-off frequency of 100 Hz. A 1.4 kg class quad-rotor with 9.4 inch diameter propellers was tested under various flight conditions. The acoustic field was measured using 80 1/2-inch G.R.A.S. Type-46AE free-field microphones, with attached windscreens. The 8×9 ground array consisted of 72 microphones, and the remaining 8 microphones were arranged along one of the walls. Figure 3 illustrates the outline and setup of this experiment. The drone position was tracked at 20 Hz by an optical positioning system consisting of two 1.4 mega-pixel JAI CV-M4+CL CCD cameras that were equipped with an 8 mm Schneider prime lens, providing an image resolution of 7 mm/pixel.

This setup simultaneously acquired position and acoustic data, which was used to develop accurate maps and characterize the acoustics of flying drones under highly controlled experimental conditions. Unlike outdoor tests, these experiments were not affected by atmospheric or environmental factors. Additionally, free-flying drone experiments provide measurements under realistic flight conditions. Figure 4 shows the acoustic contour fields, generated from the ground array measurements, of a drone flying at approximately 0.5 m/s, across the chamber. Figure 5 shows the differences in the broadband noise levels.
Figure 3: Outline of the anechoic chamber full-scale drone experiments \cite{12}.

between the microphone placed along the rotor plane (Mic 76), and directly below the hovering drone (Mic 42).

Figure 4: Ground map of a quad-rotor cruising across the chamber at time instances of (a) 3.6 s, (b) 5.8 s, and (c) 8.5 s \cite{12}.

In summary, major challenges of outdoor flight testing can be overcome by performing these types of tests in large anechoic chambers. The work outlined in this section, highlights simultaneous noise and position measurements, which developed an extensive database giving a clear and 3-D characterization of drone noise.

4. **Acoustic mapping of flying drones**

The experimental database developed from the single propeller test rig, or from the full-scale flight-tests, provide quantitative characteristics of the noise from single propellers, and from full-scale drone systems. However, these results do not provide any information regarding the acoustic impact of such vehicles operating in complex urban environments, or realistic atmospheric conditions. To this end, an Environmental Acoustic Ray Tracing (EnvARC) code was developed \cite{13}. The code models the major physics of outdoor noise propagation using the method of Gaussian beams, and it specified the drone noise source according to the experimental database developed from a hovering drone (such as the data
Figure 5: Noise characteristics of a hovering quad-rotor measured from (a) mic. 42, (b) mic. 73, and (c) mic. 76 [12].

shown in Figure 5 at a discrete frequency of 375 Hz. This noise source was simulated in a generic urban city model, as shown in Figure 6(a). The city model covered an area of 1,058 square meters and was composed of 170,000 triangular elements outlining buildings, terrain topology, the road network, parks, and waterways. The results of this noise impact simulation is shown in Figure 6(b).

Figure 6: Application of the EnvARC code to a generic urban district.

5. Summary

Three on-going research projects conducted at the Hong Kong University of Science and Technology were outlined in this paper. The test rig for single propellers was developed to establish an aerodynamic and acoustic database of commercial and generic propeller blade profiles, all made of a rigid material to isolate aeroelastic effects. Acoustic and telemetry data was acquired from full-scale drones flying freely in a large anechoic chamber. These experiments provide realistic characterizations of drone noise in a highly controlled environment, and it is not affected by atmospheric or meteorological factors that may otherwise be present in outdoor field-tests. The experimental database of a hovering quad-rotor was used to develop a simplified noise model, which was then applied to an acoustic ray tracing code. Therefore, these three projects outline the noise assessment platform developed at HKUST.
6. Acknowledgments

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