DOI: 10.61782/fa.2025.0299

FORUM ACUSTICUM EURONOISE 2025

DIFFERENCES IN SOUND EMISSION LEVEL OF MULTI-ROTOR UAS DURING HOVER AND CRUISE

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ABSTRACT

UAS noise is an increasing concern in today's society, necessitating effective control and monitoring. One approach to address this issue is the development of reliable UAS noise models. In some studies, the sound emission of multi-rotor UAS was characterized using hover measurements in an anechoic room; however, comparisons with forward-flight measurements revealed discrepancies for certain UAS. To investigate these differences, we conducted measurements during transitions from hover to cruise using an on-board measurement system mounted on the UAS. In addition to recording the emitted sound, the system acquires relevant flight data and the precise UAS position. In this paper, we present initial measurement results comparing the overall emitted sound pressure level (OSPL) at hover and across various flight speeds for two propeller types. For one propeller, the OSPL increases abruptly by 2 dB at low speeds, while a near-linear trend is observed for the other. The constant rotor speed during these changes suggests that aerodynamic factors are likely responsible. Although further analysis is needed, these findings emphasize the importance of assessing different flight conditions when modeling sound emission of UAS.

Keywords: *UAS noise, drone noise, noise measurements, sound emission, onboard measurement*

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1. INTRODUCTION

Noise is an increasing concern in today's society and requires careful monitoring and control [1,2]. Depending on the field of investigation, different noise prediction models are necessary, ranging from those that generate overall sound pressure level (OSPL) at receiver positions to auralizations and annoyance models [3–6]. Most of today's existing unmanned aerial systems (UAS) noise models rely on lab measurements in hover mode or stationary ground microphone recordings during cruise.

Wunderli et al. [7] proposed a modeling approach to simulate third-octave band noise emission levels for various types of UAS, derived from lab recordings in hover. For each third octave band, a multi-regression model was developed using (1) rotor rotational speed and (2) emission angle as variables. During a validation study where these models were used to calculate noise levels in cruise flight sections, discrepancies of up to 10 dB were observed compared to models based on lab measurements, independent of rotor rotational speed or cruise speed. To account for this difference, a level correction term for cruise was applied to the OASPL, improving model performance with a maximum standard deviation of 1.8 dB between measurements and simulations. However, the physical cause of this level correction and the flight speed at which it should be applied remained unclear.

We hypothesize that noise emissions in hover and cruise phases may differ significantly, with strong dependence on the UAS and propeller type, and that a measurable transition phase exists where this change occurs. Demonstrating this effect would have important implications for UAS noise measurements and modeling. To investigate this, we measured sound emissions during the transition between hover and cruise for a multi-rotor UAS equipped with two different propeller types. Using an onboard measurement system, we identified significant acoustic differences between these two flight states. In this paper, we present preliminary results from these measurements.

2. METHODS

Since the flight design consists of dynamic maneuvers, the use of stationary microphones would have been challenging. During cruise, the distance between the UAS and the microphone gets large quickly, leading to poor signal-to-noise ratio. Backpropagation of the signal to a fixed distance from the UAS is challenging due to the dynamic changes in geometry. In consequence, we used an onboard measuring system, keeping the distance between microphone and UAS short and constant. In this section, we describe the sound emission measurements with our developed onboard measurement system.

2.1 Experimental Setup

As UAS type, we selected the DJI Matrice 300 RTK [8], recently used in UAS noise studies (e.g. [4, 9]) and a common choice for inspection and mapping tasks. For each measurement, we equipped the UAS with two different commercially available propeller types: the standard R2110, referred to as "Propeller 1," and the R2195, referred to as "Propeller 2." The latter is designed for high-altitude operations, generating more lift per rotation than the standard model. These propellers have distinct shapes (especially the blade tips), as shown in Figure 1.

Table 1. Propeller types installed on the UAS during measurements.

Propeller 1	Propeller 2
	

To measure the emitted sound, the rotational speed of each rotor and the position/velocity of the UAS simultaneously, we used an onboard measurement system called "backpack", developed at the authors' institution (Empa). It has already been successfully used in a recent project, to record UAS sounds for auralization tasks [4] and is described in more detail in [10]. It consists of different parts, described in the following Table 2.

Table 2. Onboard measurement system ("backpack") and its components.

Component	Task
MEMS microphones (attached to arms)	Sound emission recording
Optical sensors	Tracking of rotor rotational speeds
GNSS antenna	Tracking of UAS position
Battery	Power supply
Microcontroller	Data acquisition
SD card	Data storage
Housing	Mounting structure for sensors and microcontroller

We used MEMS microphones (SPH0645LM4H, Knowles Electronics, Itasca, IL, USA) for sound recordings due to their lightweight design. Two microphones were mounted on carbon fiber tubes at a distance of 1.1 m from the nearest propeller tips, positioned symmetrically on either side at two different elevation angles relative to the rotor plane. One microphone was aligned with the rotor plane, while the other was angled 30° downward. To minimize wind-induced self-noise, we installed spherical foam windscreens, which also acted as vibration insulators (not measured). The MEMS microphones contain an AD converter and directly provide digital signals. Recordings were made with a sampling rate of 44.1 kHz and with 16 bit resolution. According to the manufacturers specification, the sensitivity of the MEMS microphones has a large range of 6 dB at 1 kHz. We therefore calibrated the MEMS microphones under free-field conditions. These calibration measurements were performed in an anechoic room with a loudspeaker and a free-field measurement microphone as a reference. The calibration measurements revealed an amplification of high frequencies due to pressure buildup at the added MEMS microphone circuit board. To equalize the frequency response of the microphones, we applied a second order high shelf filter.

To measure the rotational speed of each rotor, we placed LEDs alongside photodiodes facing each motor. The LED continuously emitted infrared light, and its reflection was measured by the photodiode at a sampling frequency of 1 kHz. To reduce harmonics, we applied a grayscale strip with sinusoidal intensity around the rotating part of the motor.

For precise UAS position tracking, we used two GNSS receivers: one mounted on top of the backpack and one stationary on the ground. This setup enabled real-time kinematic (RTK) positioning in dual-band mode, achieving centimeter-level accuracy. With this configuration, we obtained position updates at a rate of 15 Hz. The complete setup, including the backpack and sensors, is shown in Figure 1.

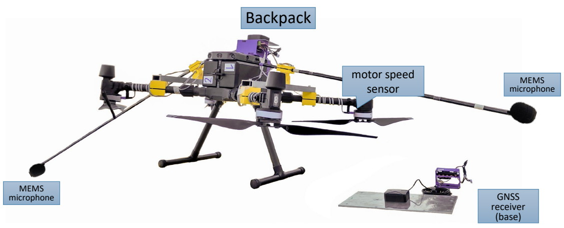

Figure 1. UAS equipped with the backpack and sensors. A second, stationary GNSS receiver (base) enables RTK positioning.

2.2 Flight Test Design

To ensure real-world flight conditions and avoid space limitations, we conducted the measurements outdoors in an open field. The UAS was manually operated, flying extended straight tracks at varying speeds. To minimize ground reflection influences, flights were conducted at an altitude of several 10 meters. The ambient temperature at the measurement site ranged between 5.9°C and 7.1°C, with relative humidity between 56% and 61%, and with low wind conditions (1.4 m/s at the nearest weather station, 10 m above ground).

Since the investigated UAS is designed to carry payloads of up to several kilograms, the attached backpack and sensors had minimal impact on flight performance. The UAS itself weighs 6.3 kg, while the backpack, including all sensors and sensor mounts, adds an additional 1.8 kg.

2.3 Data Processing and Analysis

From the in-flight recordings, time histories of the OSPL were computed, i.e. the unweighted short-term equivalent continuous OSPL with a time window of 1 s ($L_{\mathrm{eq},1s}$). In order to be comparable to the recordings of other UAS types, the obtained levels were scaled to a 1 m reference distance to the UAS's nearest propeller tips, by compensating for geometrical spreading. To obtain a corresponding OSPL assigned to every flight trajectory point, the $L_{\mathrm{eq},1s}$ was interpolated to the sampling rate of the GNSS receivers (15 Hz).

The rotational speed for each rotor was determined by applying Fast Fourier Transform (FFT) to the recorded signals. The rotational speed was then identified using a peak-finding method. For 2-bladed propellers, this corresponds to half the blade passing frequency.

3. RESULTS

This section presents initial measurement results for the UAS at different cruise speeds, equipped with two different propeller types. Figure 2 displays the $L_{\mathrm{eq},1s}$ for both propeller types, covering hover (very low cruise speed) up to cruise at speed of 9 m/s (max. possible speed $>$ 20 m/s). For each 1 m/s flight speed bin, we obtained an average of 75 seconds of flight data for Propeller 1 and 30 seconds for Propeller 2. We fitted the data points with a cubic smoothing spline using a smoothing parameter of 0.1.

Figure 2 shows that within the studied speed range, Propeller 2 exhibits 1 to 2 dB higher emissions compared to Propeller 1. For Propeller 1, a nearly linear increase in sound emission level with increasing cruise speed is observed. In contrast, Propeller 2 exhibits a sudden, sharp increase in emission level by 2 dB at a cruise speed of 3 to 4 m/s. Apart from this abrupt change, the emission levels remain largely unaffected by variations in cruise speed within the observed range. Additionally, the standard deviation of sound levels for Propeller 2 is noticeably higher at lower speeds, reaching almost 2 dB, but decreases at higher speeds. For Propeller 1, the standard deviation remains between 0.5 and 1 dB across all speeds.

Since the modeling approach in [7] uses rotor rotational speed as an input, we compare the emitted sound to the measured rotational speeds. Figure 3 presents the mean rotational speed across all four rotors as a function of cruise speed, with smoothing applied similarly to Figure 2. Within this speed range, the mean rotor rotational speed appears largely unaffected by increasing

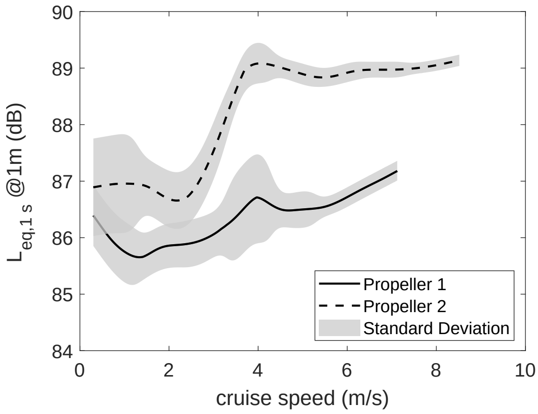

Figure 2. OSPL as a function of cruise speed for two propeller types under an elevation angle of -30° to the rotor plane at a 1 m reference distance to the nearest propeller tips.

cruise speed. As Propeller 2 is designed for higher altitudes, it generates more lift per rotation than Propeller 1, resulting in a noticeably lower rotor rotational speed.

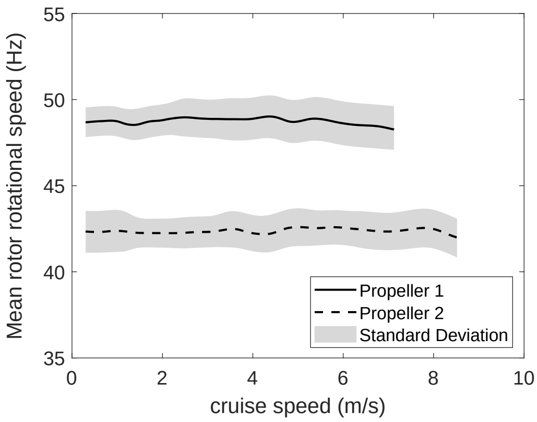

Figure 3. Mean rotational speeds and standard deviation of all four rotors for each measured propeller type as a function of cruise speed.

4. DISCUSSION

Both studied propeller types exhibit distinctly different behavior in terms of sound emission level at different cruise speeds, despite being used on the same UAS type. While the emitted OSPL of Propeller 1 changes only slightly with speed (showing a gradual increase), Propeller 2 displays a pronounced step-like behavior. However, measurements of rotor rotational speeds indicate that this sudden increase in sound level cannot be attributed to changes in rotational speed, as it remains relatively constant within this range. Consequently, we assume that the aerodynamics of the rotors must be influenced by changes in lateral inflow. This is, however, part of future investigations. Additionally the question arises, if a particular shape of the propellers favors this non-linear effect, such as for Propeller 2. Or if for any particular shape, generalizable statements regarding sound emission can be made.

For Propeller 2, applying the modeling approach of [7] would result in a cruise level correction of approximately 2 dB, whereas for the same UAS equipped with Propeller 1, no such correction would be necessary. Additionally, measurements taken within the rotor plane (not presented within this paper) revealed an even higher cruise level correction of 4 dB for Propeller 2. This dependence on the emission angle further indicates that the source directivity of the UAS also differs between hover and cruise.

5. CONCLUSION AND OUTLOOK

In this paper, we measured the emitted sound of a UAS equipped with two different propeller types at various flight speeds to investigate the transition between hover and cruise. Our results show that, depending on the UAS/propeller combination, the sound emission level can increase sharply at relatively low flight speeds, independent of rotor rotational speed. We assume that changes in the aerodynamics are responsible for this phenomena. When developing models for predicting or simulating UAS noise emissions for different flight states, it is therefore essential to measure the emitted sound for each propeller type separately and at both states, hover and cruise at various speeds.

Due to the assumption of aerodynamic changes in cruise flight, not only noise emission levels but also other characteristics of the emitted sound might be affected. Psychoacoustic aspects, as well as measurement data from a smaller UAS equipped with three different propeller types, are currently under investigation and will be presented in a future publication.

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