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EFFECT OF UNMANNED AERIAL VEHICLE CONFIGURATIONS ON THE ACOUSTIC AND PSYCHOACOUSTIC SIGNATURES

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Authorities are starting to pay attention not only to the noise levels of Unmanned Aerial Vehicles (UAVs) but also to their quality for acceptance. This manuscript presents a study of four types of propeller-driven UAVs (single-propeller quadcopter, coaxial-propeller quadcopter, quadplane eVTOL (electric vertical take off and landing) and tailsitter eVTOL) to assess their acoustic and psychoacoustic signatures. Experimental outdoor recordings are conducted under realistic flyover conditions. An acoustic analysis showed that quadcopters present higher noise levels compared to the eVTOLs, where the coaxial-propeller configuration revealed to be the noisiest and the quadplane the quietest. A psychoacoustic analysis demonstrated that the coaxial-propeller quadcopter was roughly three times more annoying than its single-propeller counterpart, whereas the quadplane and tailsitter eVTOLs showed similarly lower annoyance values. Additionally, the coaxial-propeller quadcopter exhibited the highest levels of loudness and impulsiveness, while the tailsitter had the lowest. Conversely, the tailsitter exhibited contrasting behavior in terms of sharpness. Regarding tonality, the quadplane was the most tonal, and the tailsitter eVTOL the least. In terms of modulation frequency characteristics, the single-propeller UAV emitted the harshest and most pulsating sound, while the tailsitter had lower values.

Keywords: Acoustics, Psychoacoustics, Unmanned aerial vehicles

1. Introduction

Unmanned Aerial Vehicles (UAVs) have attracted the attention of commercial and recreational sectors due to their operational advantages in tasks, such as point-to-point delivery, photography, and diverse monitoring activities. These vehicles can be categorized based on their lift generation configuration, such as fixed-wing, rotary-wing, and hybrid UAVs [1]. Fixed-wing UAVs are characterized by their aerodynamic efficiency, typically resulting in extended flight endurance, whereas the main advantage of rotary-wing UAVs is their flexibility to take-off and land at designated points and hover, adopting rotating propellers for lift generation. On the other hand, hybrid UAVs represent an intermediate configuration between fixed-wing and rotary-wing UAVs and are commonly referred to as electrical vertical take-off and landing (eVTOL) vehicles. Despite their inherent benefits, the noise signatures of these devices and their effect on the subjective response of people are important factors to be considered to ensure their public acceptance [2, 3].

Studies of UAV noise revealed that it normally comprises higher high-frequency content compared to traditional aircraft operating at similar overall sound pressure levels [4, 5]. Despite UAV noise being primarily influenced by rotor noise, specific geometrical configurations can significantly alter the noise profile resulting in acoustic installation effects [6]. These new acoustic sources are generated due to the scattering of the sound radiated by the propellers and the fuselage. Jiang et al. [7] analysed the noise scattering of a UAV fuselage and indicated that acoustic reflections can induce substantial amplifications or shielding effects that change the directivity of the UAV's overall noise radiation. Zarri et al. [8] found that the installation noise effects of a UAV resulted in noise amplifications of at least 5 dB in almost all directions and reaching maximum levels of 30 dB in specific directions. Zawodny and Boyd [9] assessed the effect of the fuselage on small-scaled rotor noise and reported that the fuselage had a large impact on tonal noise, but it did not change high-frequency broadband noise significantly. These changes in the noise signature due to installation effects can significantly change the degree of perceived annoyance. In fact, Gwak et al. [4] associated the annoyance from UAV noise with the presence of tones and high-frequency components.

The literature illustrates that installation effects result in additional noise. However, there is a lack of studies regarding the effect on sound quality and noise annoyance. These installation effects can be found in different configurations of UAVs, resulting in distinct broadband or tonal noise signatures, thereby influencing sound perception. Additionally, authorities are starting to pay attention not only to the noise levels of UAVs but also to their sound quality for societal acceptance in urban environments. Therefore, this manuscript presents a study of four different types of UAVs to assess their acoustic and psychoacoustic signatures. Experimental outdoor recordings are conducted under realistic flyover operational conditions. The acoustic analysis involves examining the noise in both the time and frequency domains, whereas the psychoacoustic assessment compares traditional noise metrics with annoyance levels. Additionally, an examination of the sound attributes contributing to noise annoyance is conducted.

2. Methodology

2.1 Experimental Setup

The measurements used for this work were conducted in the context of a broader experimental campaign performed at an airfield in Valkenburg, Zuid-Holland, the Netherlands. This airfield is actively used by different UAV companies as a testing area for their systems, and it serves as a hub for drone-based technologies. The measurements were performed using an acoustic array consisting of 64 microphones and a diameter of 4 m. The data was recorded with a sampling frequency of 50 kHz. The airfield is located in a quiet environment, away from loud infrastructure or cities. For this research, four flyovers performed with UAVs of different configurations were selected: a single-propeller quadcopter, a coaxial-propeller quadcopter, a quadplane eVTOL and a tailsitter eVTOL, as seen in Figure 1. The UAV flights analysed in this work correspond to a straight flight path over or close to the acoustic array (located at $(x, y, z) = (0, 0, 0)$ m), as displayed in Figure 2. Additionally, the main UAV characteristics used in this work are presented in Table 1.

Table 1: Main characteristics of the UAVs considered.

UAV number	UAV name	UAV model	Propellers	Weight [kg]	MTOW [kg]
1	DJI M300	Quadcopter - Single propeller	4	6.3	9
2	Dronevolt H20[1]	Quadcopter - Coaxial propeller	8	34	34
3	Avy Aera 3	eVTOL - Quadplane	5	-	19.5
4	Atmos Marlyn	eVTOL - Tailsitter	4	5.7	6.7

[1] The UAV Dronevolt H20 includes a payload and has eight single propellers arranged in four pairs.

Figure 1: UAVs adopted for the study [10, 11, 12, 13].

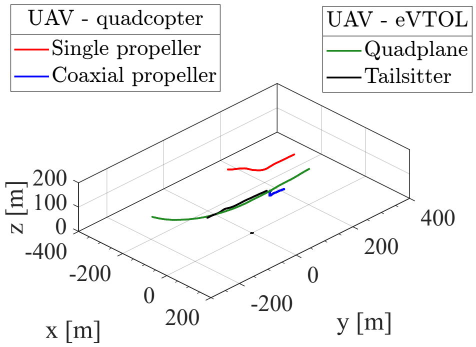


Figure 2: 3D trajectory of each UAV.

2.2 Traditional and Psychoacoustic Metrics

Conventional sound metrics, such as the equivalent sound pressure level L_{eq} or its A-weighted version $L_{\mathrm{A,eq}}$, as well as the sound exposure level (SEL), are typically employed for noise assessment. The effective perceived noise level (EPNL) metric is generally used for noise certification of commercial aircraft. However, there has been a growing concern regarding the use of these sound metrics to evaluate noise annoyance, as they neglect important characteristics of human hearing. Unlike most conventional sound metrics, which quantify the purely physical magnitude of sound based on the pressure, Sound Quality Metrics (SQMs) describe the subjective perception of sound by human hearing. Hence, SQMs are expected to better capture the auditory behavior of the human ear compared to conventional sound metrics typically employed in noise assessments. The five most commonly-used SQMs [14] are:

- Loudness (N): Perception of sound magnitude corresponding to the overall sound intensity.
- Tonality (K): Perceived strength of unmasked tonal energy within a complex sound.
- Sharpness (S): High-frequency sound content.
- Roughness (R): Hearing sensation caused by modulation frequencies between 15 Hz and 300 Hz.
- Fluctuation strength (FS): Assessment of slow fluctuations in loudness with modulation frequencies up to 20 Hz, with maximum sensitivity for modulation frequencies around 4 Hz.

An additional SQM included in this study is impulsiveness (I), which has been observed to influence annoyance responses in outdoor conditions [15] and is potentially related to blade vortex interaction noise [16]. Unlike the approach of Green et al. [15], which uses a hearing model to compute impulsiveness, this study employs a loudness-based metric that considers the summation of impulse-induced peaks in the loudness time history of a sound [17]. The five SQMs aforementioned were calculated for each sound wave considered and combined into a single global psychoacoustic annoyance (PA) metric following the model outlined by Di et al. [18]. Henceforth the top 5% percentiles of these metrics values are reported (and hence the subindex 5). All the conventional sound metrics, the SQMs (except for impulsiveness), and the PA metric were computed using the open-source MATLAB toolbox SQAT (Sound Quality Analysis Toolbox) v1.1 [19].

3. Results and Discussion

3.1 Acoustic Analysis

3.1.1 UAV Trajectories and Signal-to-Noise-Ratio

The distance between each UAV and the microphone as well as the (x, y, z) components of the adjusted trajectories of each UAV are shown in Figure 3. This adjustment is made to the UAV altitudes to maintain the same minimum distance to the center of the acoustic array among all UAVs. Consequently, a correction to the measured audio waves is applied to account for the varying effect of sound spreading with distance, using Equation 1. The parameters z_{old} and z_{new} represent the original and corrected altitudes, respectively. Note that ΔL_{p} is negative for $z_{\text{old}} < z_{\text{new}}$ and positive vice versa. Hence, the effect of having different measuring distances is at least partially accounted for. A correction of 3.27 dB is obtained for the quadcopter equipped with single propellers, while -4.85 dB and -4.62 dB are obtained for the quadplane and tailsitter eVTOLs, respectively. The audio wave of the coaxial propeller quadcopter was not altered.

$$\Delta L_{\text{p}} = 20 \log_{10} \left(\frac{z_{\text{old}}}{z_{\text{new}}} \right), \tag{1}$$

Figure 4 depicts the A-weighted signal-to-noise ratio (SNR) corresponding to each UAV. This parameter is computed by subtracting the overall A-weighted sound pressure level of a background noise measurement from each UAV noise measurement. This allows to quantitatively verify whether the sound produced by each UAV, after applying the spreading sound-based correction, remains noticeable. It is shown that the quadcopter equipped with coaxial propellers presents the highest SNR values of approximately 36 dBA. Following this, the quadcopter with single propellers, quadplane, and tailsitter eVTOLs exhibit peak SNR values of around 28 dBA, 9 dBA, and 2 dBA, respectively.

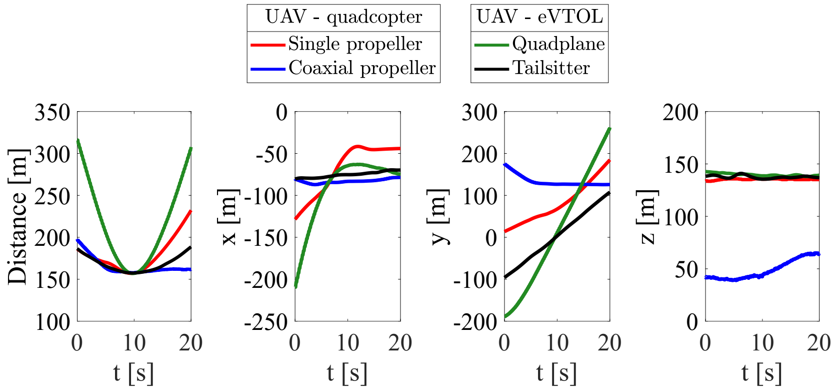


Figure 3: Absolute distance and (x, y, z) coordinates for each UAV flight path.

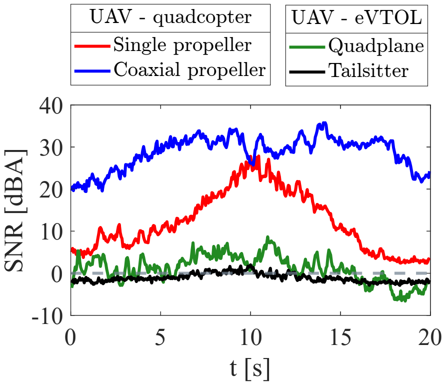
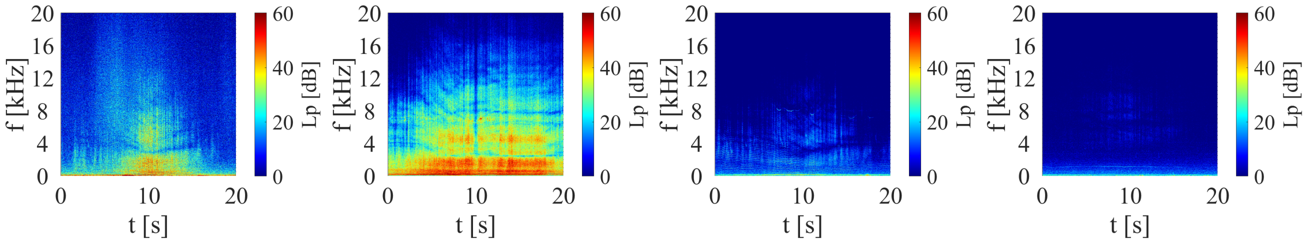


Figure 4: A-weighted signal-to-noise ratio.

3.1.2 *Time-Frequency Characteristics*

The time-frequency characteristics of each UAV are analyzed through their respective spectrograms, as depicted in Figure 5. For each measurement, 20 s of recording time were used. The spectrograms are calculated using 5000 samples per time block with Hanning windowing and a 50% data overlap. With these parameters, the frequency resolution Δf is 10 Hz. The frequency range of interest for this research extends from 0 Hz to 20 kHz. By comparing both quadcopters, the one equipped with coaxial propellers is clearly noisier than the one using single propellers in both low and high frequencies. In contrast, the eVTOL vehicles emit considerably lower noise levels compared to the quadcopters. In controlled stationary conditions, such as hovering in anechoic chambers, tonal components associated with the blade passing frequency (BPF) of the drones can be easily identified. However, in complex situations, such as flyovers in realistic scenarios like in this study, the identification of the tonal behavior can be more difficult [20].



(a) UAV 1. (b) UAV 2. (c) UAV 3. (d) UAV 4.

Figure 5: Spectrograms during the flight missions computed from 0 Hz to 20 kHz.

Figure 6 depicts the time-averaged spectrum of each UAV. Consistent with the observations from the spectrograms, the coaxial-propeller quadcopter exhibits higher noise levels, whereas the tailsitter eVTOL demonstrates a quieter operation. Upon comparing the two quadcopters, the coaxial-propeller-equipped quadcopter shows considerably higher broadband noise compared to its single-propeller counterpart. This finding aligns with previous research by McKay et al. [21]. Additionally, the noise spectrum of the quafcopter with coaxial propellers exhibits more spectral fluctuations across all frequencies, which could be related to the additional tones generated due to propeller interaction [21]. Regarding the eVTOL vehicles, the quadplane registers slightly higher noise levels than the tailsitter, particularly around 100 Hz and 2000 Hz. During flyover missions, the quadplane operates with a single propeller positioned at the tail, whereas the tailsitter employs two single propellers, one per wing. Despite the quadplane's use of only one propeller, it generates higher sound pressure levels than the tailsitter. This discrepancy may be attributed to installation effects, as previously suggested by Zawodny et al. [9] and Zarri et al. [8]. However, the vertical rotors of the quadplane may also be active, potentially due to wind gusts.

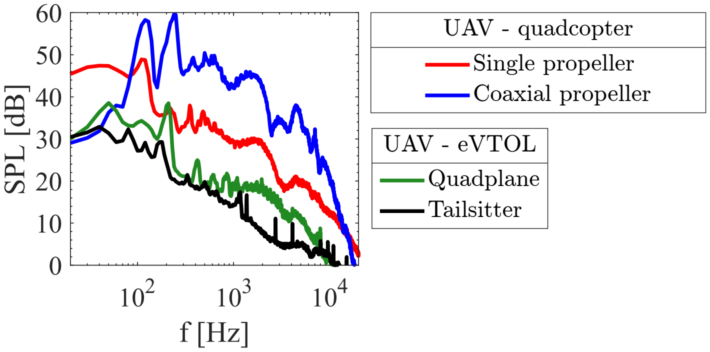


Figure 6: Time-averaged sound pressure level spectrum corresponding to each UAV flyover.

3.2 Psychoacoustic Analysis

3.2.1 Traditional Sound Metrics and Psychoacoustic Annoyance

All the traditional sound metrics evaluated, illustrated in Figure 7, highlight that the quadcopter with coaxial propellers exhibits the highest noise levels, followed by the single-propeller quadcopter and the quadplane eVTOL, whereas the tailsitter eVTOL shows the lowest. These observations align with the previous findings from time-frequency analysis from the previous section. Figure 8 presents the linear scale annoyance using the model by Di et al. [18] for each UAV. The coaxial propeller-equipped UAV reveals an annoyance prediction of 71.8 units, while the single propeller quadcopter achieves 24.5 units, making the coaxial-propeller-equipped UAV approximately three times more annoying. Comparing eVTOL vehicles, the quadplane is also approximately three times more annoying than the tailsitter, with annoyance values of 9 and 3.2 units, respectively. Nevertheless, the eVTOL vehicles present considerably lower psychoacoustic annoyance values.

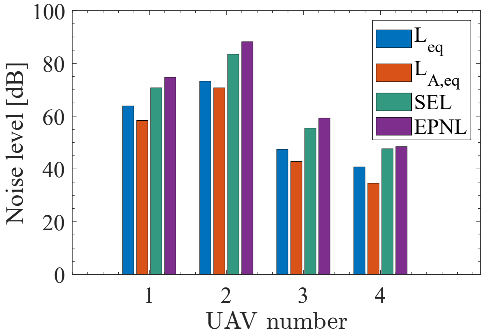


Figure 7: Traditional sound metrics.

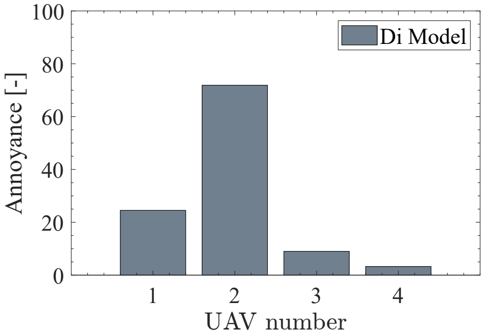


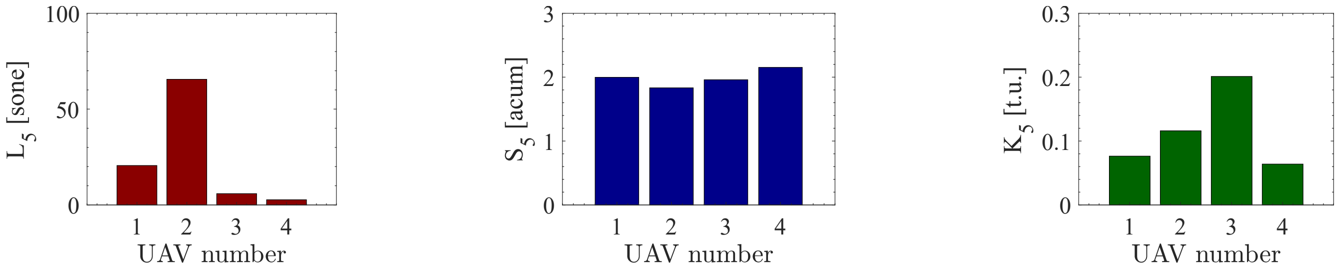
Figure 8: Psychoacoustic annoyance.

3.2.2 Sound Quality Metrics Breakdown

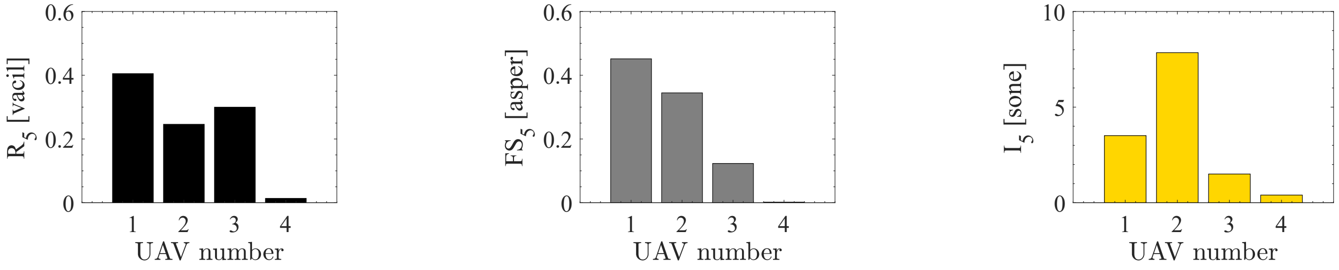
Figure 9 shows the psychoacoustic annoyance breakdown comprised by the five sound quality metrics explained in section 2.2. The impulsiveness metric is also included. The metric values are reported as the top 5% percentiles (values exceeded only the 5% of the time). In terms of loudness, the coaxial propeller quadcopter is perceived as the 'loudest' at 65.5 sone, while the tailsitter eVTOL is the 'quietest' at only 2.7 sone. Regarding sharpness, the tailsitter eVTOL stands out as the 'sharpest' with a value of 2.2 acum due to its higher proportion of high-frequency content. There are small differences in sharpness among UAVs, with a maximum difference of 0.83 acum between the tailsitter and coaxial-propeller UAV. In terms of tonality, the quadplane eVTOL is identified as the 'most tonal', while the tailsitter eVTOL is the 'least tonal', with values of 0.2 and 0.06 t.u., respectively. The perception of tonality depends on factors like bandwidth, center frequency, and level above the threshold. Roughness and fluctuation strength account for the perception caused by amplitude-modulated sounds. The single-propeller quadcopter is evaluated as the 'harshest' and 'most beating' sound, with values of 0.4 vacil and 0.45 asper, respectively. The tailsitter eVTOL, on the other hand, demonstrates the best quality in terms of smoothness and stability with respect to modulation frequencies up to 300 Hz. The 'most impulsive' UAV is the coaxial-propeller quadcopter with a value of 8 sone, whereas the tailsitter eVTOL is the 'least impulsive' at 0.5 sone.

4. Conclusions

This manuscript explored the acoustic and psychoacoustic traits of different UAV configurations under realistic flyover conditions, including quadcopters with both single and coaxial propellers, as well as quadplane and tailsitter eVTOLs. Outdoor acoustic recordings employed a 64-microphone array with a 4 m diameter. The trajectories were adjusted to ensure fair comparison, with corrections made to account for sound spreading effects. Results revealed significant differences in noise levels and frequency characteristics among UAV types. The coaxial-propeller quadcopter exhibited higher noise levels, while the eVTOLs operated quieter. The psychoacoustic analysis showed the coaxial-propeller UAV to be approximately three times more annoying than its single-propeller counterpart, whereas the quadplane and tailsitter eVTOLs presented similarly lower annoyance values. In terms of sound quality metrics, the coaxial-propeller quadcopter was deemed the loudest, while the tailsitter eVTOL was evaluated as the quietest, albeit notably sharp. Tonality perception varied among the UAVs, with the quadplane eVTOL rated as the most tonal and the tailsitter as the least. The single-propeller quadcopter was perceived as emitting the harshest and most beating sound. Regarding impulsiveness, the coaxial-propeller quadcopter was considered as the most impulsive while the tailsitter as the least impulsive. Future work will focus on validating these claims with listening experiments.



(a) Loudness. (b) Sharpness. (c) Tonality.



(d) Roughness. (e) Fluctuation strength. (f) Impulsiveness.

Figure 9: Annoyance breakdown into five sound quality metrics. Impulsiveness metric is also included.

5. Acknowledgments

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REFERENCES

1. Saeed, A. S., Younes, A. B., Cai, C. and Cai, G. A survey of hybrid unmanned aerial vehicles, *Progress in Aerospace Sciences*, **98**, 91–105, (2018).
2. Coleman, C. P. Uk expert report on drones, *Pwc report*, (2018).
3. CAA. Emerging technologies: The effects of evtol aircraft noise on humans, *CAA report*, (2023).
4. Gwak, D. Y., Han, D. and Lee, S. Sound quality factors influencing annoyance from hovering uav, *Journal of Sound and Vibration*, **489**, 115651, (2020).
5. Torija, A. J. and Clark, C. A psychoacoustic approach to building knowledge about human response to noise of unmanned aerial vehicles, *International Journal of Environmental Research and Public Health*, **18** (2), 682, (2021).
6. Roger, M. and Kucukcoskun, K. Near-and-far field modeling of advanced tail-rotor noise using source-mode expansions, *Journal of Sound and Vibration*, **453**, 328–354, (2019).
7. Jiang, H., Zhou, T., Fattah, R. J., Zhang, X. and Huang, X. Multi-rotor noise scattering by a drone fuselage, *25th AIAA/CEAS Aeroacoustics Conference*, p. 2586, (2019).
8. Zarri, A., Dell'Erba, E., Munters, W. and Schram, C. Aeroacoustic installation effects in multi-rotorcraft: Numerical investigations of a small-size drone model, *Aerospace Science and Technology*, **128**, 107762, (2022).

9. Zawodny, N. S. and Boyd, D. D. Investigation of rotor–airframe interaction noise associated with small-scale rotary-wing unmanned aircraft systems, *Journal of the American Helicopter Society*, **65** (1), 1–17, (2020).

10. DJI. *Description of DJI M300*. https://enterprise.dji.com/matrice-300, accessed: 30/03/2024.

11. Dronevolt. *Description of Dronevolt H20*. https://www.dronevolt.com/en/expert-solutions/hercules-20/, accessed: 30/03/2024.

12. Avy. *Description of Avy Aera 3*. https://avy.eu/technologyaera, accessed: 30/03/2024.

13. Atmos. *Description of Atmos marlyn*. https://www.atmosuav.com/product/mapping-drone-marlyn, accessed: 30/03/2024.

14. Greco, G. F., Merino-Martinez, R., Osses, A. and Langer, S. C. SQAT: a MATLAB-based toolbox for quantitative sound quality analysis, 52^{th} *International Congress and Exposition on Noise Control Engineering, August 20 – 23 2023, Chiba, Greater Tokyo, Japan*, International Institute of Noise Control Engineering (I-INCE).

15. Green, N., Torija, A. J. and Ramos-Romero, C. Perception of noise from unmanned aircraft systems: Efficacy of metrics for indoor and outdoor listener positions, *The Journal of the Acoustical Society of America*, **155** (2), 915–929, (2024).

16. Yung, H. Y. Rotor blade–vortex interaction noise, *Progress in Aerospace Sciences*, **36** (2), 97–115, (2000).

17. Willemsen, A. M. and Rao, M. D. Characterization of sound quality of impulsive sounds using loudness based metric, *Proceedings of 20th International Congress on Acoustics, Sydney*, vol. 5, pp. 3397–3404, (2010).

18. Di, G.-Q., Chen, X.-W., Song, K., Zhou, B. and Pei, C.-M. Improvement of zwicker's psychoacoustic annoyance model aiming at tonal noises, *Applied Acoustics*, **105**, 164–170, (2016).

19. Greco, G. F. and Merino-Martinez, R. and Osses, A., (2023), *SQAT: a sound quality analysis toolbox for MATLAB (version v1.0)*. Accessed in May 2023.

20. Alexander, W. N. and Whelchel, J. Flyover noise of multi-rotor suas, *Inter-Noise and Noise-Con Congress and Conference Proceedings*, vol. 259, pp. 2548–2558, Institute of Noise Control Engineering, (2019).

21. McKay, R. S., Kingan, M. J., Go, S. T. and Jung, R. Experimental and analytical investigation of contra-rotating multi-rotor uav propeller noise, *Applied Acoustics*, **177**, 107850, (2021).