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# Psychoacoustic Characterisation of a Small Fixed-pitch Quadcopter

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## ABSTRACT

**In this study, a series of acoustic measurements were taken on a small fixed-pitch quadcopter, both in a controlled indoor acoustic environment and while flying outdoors. At controlled indoor conditions, audio signatures were recorded with the quadcopter fixed to a horizontal stand, with 1, 2 and 4 rotor blades operating, and only with the electric motors working. At field conditions, audio signatures were recorded on the ground, varying the relative (lateral) distance and altitude between the quadcopter flight track and the microphone, and the quadcopter payload. Frequency spectra, in the form of narrowband sound-levels, and a series of sound quality metrics (loudness, sharpness, roughness, fluctuation strength and tonality) were calculated from the recorded audio signatures to investigate the specific psychoacoustic characteristics of the small quadcopter under the whole set of experimental conditions tested. On the other hand, at a first step to anticipate potential noise issues of quadcopters operating in urban environments, an objective comparison on the basis of frequency characteristics and sound quality metrics is performed between the small quadcopter and a number of road vehicles and aircraft.**

**Keywords:** Quadcopter, Sound Quality Metrics, Psychoacoustics
**I-INCE Classification of Subject Number:** 79

## 1. INTRODUCTION

The significant progress on electrical power, high-energy density batteries, and robotics and autonomous system technologies is allowing the advancement of Unmanned Aerial Vehicles (UAVs), commonly referred to as ‘drones’ [1]. UAVs have significant potential for a number of applications such as inspection, monitoring, surveying, surveillance and delivery of goods. Yoo et al. [2] suggest parcel delivery by UAVs, as a more efficient way to deliver products than traditional delivery by truck. A carefully deployed drone-based delivery could reduce greenhouse gas emissions and other environmental impacts compared to traditional freight sector [3-5].

Despite all the benefits enabled by these technologies, the operation of UAVs in urban areas can lead to important noise concerns. Noise is considered as probably the

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largest limiting factor for the public acceptability of UAV operations in urban areas [6]. Compared to current aerial vehicles, small UAVs using all-electric propulsion are expected to be quieter. However, with the expectation of a potentially significant number of UAVs, operating much closer to the public than current aerial vehicles, noise annoyance will be a factor. There is an important uncertainty in the prediction of the resultant annoyance due to UAV noise exposure. One of the main reasons is that the noise of UAVs does not resemble the noise of contemporary aircraft [7].

This paper presents the results of an ongoing research for the acoustic characterisation of small UAVs. Frequency spectrum patterns of a small quadcopter was examined for a number of conditions tested both at a controlled indoor acoustic environment and outdoors under realistic flight settings. On the basis of narrowband frequency spectra and sound quality metrics (i.e. loudness, sharpness, roughness, fluctuation strength and Aures/Terhardt tonality), an objective comparison was carried out between a small quadcopter and a number of road vehicles and aircraft. Several Psychoacoustic Annoyance models were implemented for anticipating potential noise issues associated with small UAVs operating in urban areas.

## 2. MATERIAL AND METHODS

### 2.1 Experimental data

The database of audio files used in this paper was gathered during four different measurement campaigns. For collecting road vehicle audios, a series of individual vehicle pass-by events were recorded with a microphone placed at 3.5 m from the edge of the roadway. Audio samples of two types of vehicles were selected: cars and motorbikes. Moreover, audio files of aircraft take-offs were recorded with a microphone placed at approximately 900 m from the end of the sound runway of Heathrow airport. The height of the aircraft passing over the measurement point was approximately 435 m. Audio samples of two aircraft types were selected: A320 (engine CFM56-5) and the modern variant A320neo (engine PW1127G).

Audio recordings of a series of straight-and-level flyovers (FO) of a small quadcopter were made in an open field, with minimal interference of extraneous sounds and low background noise level. The DJI Phantom 3 Standard quadcopter was the vehicle tested. Two altitudes above ground level (A = 1 and 2 m), two lateral distances between the microphone and the flight track (L = 0 and 5 m) and three extra-payload conditions (P = 0, 434 and 656 g) were tested. Table 1 shows the list of audio files analysed.

*Table 1. List of audio files used in this paper.*

| Type of vehicle | Description |
|---|---|
| Aircraft | A320 with engine CFM56-5 (x4) |
| Aircraft | A320neo with engine PW1127G (x4) |
| Quadcopter | FO-A1-L5-P0 (x2) |
| Quadcopter | FO-A1-L5-P434 (x2) |
| Quadcopter | FO-A2-L0-P0 (x2) |
| Quadcopter | FO-A2-L0-P434 (x2) |
| Quadcopter | FO-A2-L0-P656 (x2) |
| Quadcopter | FO-A2-L5-P0 (x2) |
| Quadcopter | FO-A2-L5-P434 (x2) |
| Quadcopter | FO-A2-L5-P656 (x2) |
| Road vehicle | Car (x4) |
| Road vehicle | Motorbike (x4) |

An audio file of the quadcopter hovering at an altitude of 1 m, 2 m of lateral distance from the microphone and with no extra payload was recorded for comparison with the measurements carried out at the aeroacoustics lab. A set of measurements was also conducted in an aeroacoustics lab. The quadcopter was fixed to a stand at a distance of 1.8 m above the ground such that only the four rotor blades could move. Three microphones were positioned at 0.96 m, 1.93 m and 2.93 m away from and below the quadcopter, at azimuthal angles 53.9, 70.0 and 76.6 degrees (from the vertical), respectively, and were pointed directly at the quadcopter (i.e. at zero degrees incidence). The quadcopter was operated at full power with and without each of its rotor blades to assess the contribution of each component of the quadcopter to the total noise signature.

### 2.2 Data processing and analysis

Four-second clips were extracted from each audio file selected. These 4 s clips contained a complete pass-by of the road and quadcopter vehicles. For the case of the aircraft, these 4 s clips contained the most prominent audio character (i.e. just before the aircraft was overhead). For the sake of comparison, all audio samples were normalised to an overall $L_{Aeq}$ of 65 dB(A), so differences are attributable to spectral and/or temporal patterns. This normalisation also minimises the effect of variations in recorded levels consequence of the distance between source and microphone.

The Head Acoustics ArtemiS Classic software was used to calculate the psychoacoustic metrics, loudness, sharpness, roughness, fluctuation strength and tonality. Time-varying loudness ($N$) calculations were based on the DIN standard 45631/A1. The method employed to calculate sharpness ($S$) was based on the DIN standard 45692. There are no standard methods for calculating roughness ($R$) and fluctuation strength ($F$). In this paper, roughness and fluctuation strength calculations were based on a modulation analysis proposed by Aures. Tonality ($T$) was calculated using an algorithm based on publications by Terhardt [8] and Aures [9].

## 3. RESULTS

### 3.1 Measurements at aeroacoustics lab

Fig. 1 shows the frequency spectrum of the quadcopter tested in an anechoic aeroacoustics laboratory, for 4 conditions: only the electric motor working, and the electric motor with 1, 2 and 4 propellers operating. For the electric motor only condition, a significant content in high frequency is observed. High frequency tones are located between 2.4 kHz and 6 kHz. For the 1, 2 and 4 propeller conditions, the sound levels of the harmonics of the Blade Passing Frequency (BPF) at the low-to-mid frequency region are very close. At the higher harmonics of the BPF, the 2 propeller condition shows slightly higher sound levels, and the 4 propeller condition shows significantly higher sound levels (compared to the single propeller condition). The adding of +3 dB for every time the sound intensity is doubled (i.e. from 1 to 2 and to 4 propellers) is not enough for explaining the increase in sound levels shown in Fig. 1. The high sound levels at the higher harmonics might be explained by unsteady sources occurring at periodic basis, such as the interaction noise from disturbed inflow due to other rotor blades or the fuselage [10-11].

### 3.2 Field measurements

Fig. 2 shows the spectrograms of the quadcopter measured in the aeroacoustics lab and the quadcopter hover measured in an open field. In the aeroacoustics lab, the measurements were conducted with the quadcopter placed on a stand and working at full power. For this condition, a steady frequency behaviour with time is observed.

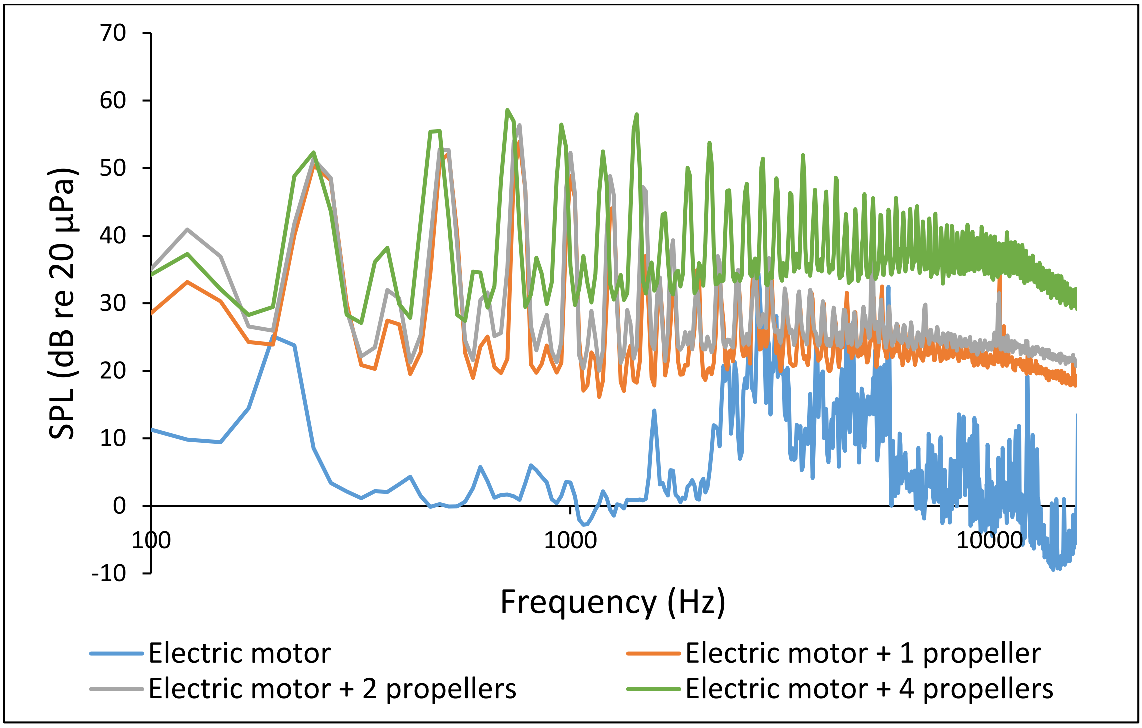

*Figure 1. Frequency spectrum of the quadcopter tested: electric motor only, and electric motor with 1, 2 and 4 propellers.*

For the quadcopter hover measured outdoors, the BPFs of each propeller are near 175 Hz. The BPFs of each propeller are ~250 Hz for the quadcopter measured in the lab. As displayed in Fig. 2 (right), the quadcopter shows an unsteady frequency behaviour with time. Compared with the spectrogram measured in the aeroacoustics lab, the quadcopter hover shows distinct spectral lines at harmonics of the propeller BPFs. Both the frequency variations with time and the distinction of spectral lines are magnified at higher harmonics. Under hover condition outdoors, wind gusts and the flight control system varying rotor rotational speeds to maintain vehicle stability create such an unsteady acoustic signature [10].

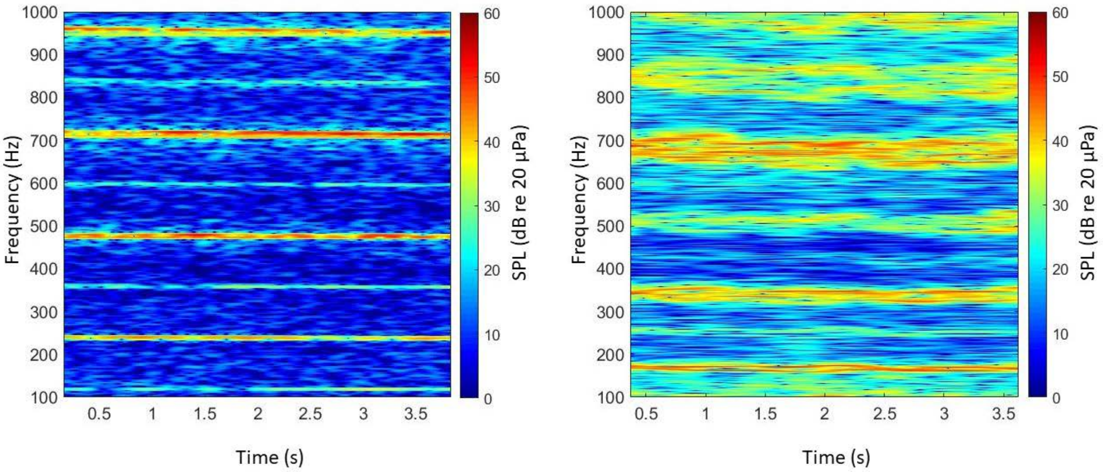

*Figure 2. Spectrogram of the quadcopter measured in the aeroacoustics lab (left) and measured outdoors while hovering (right).*

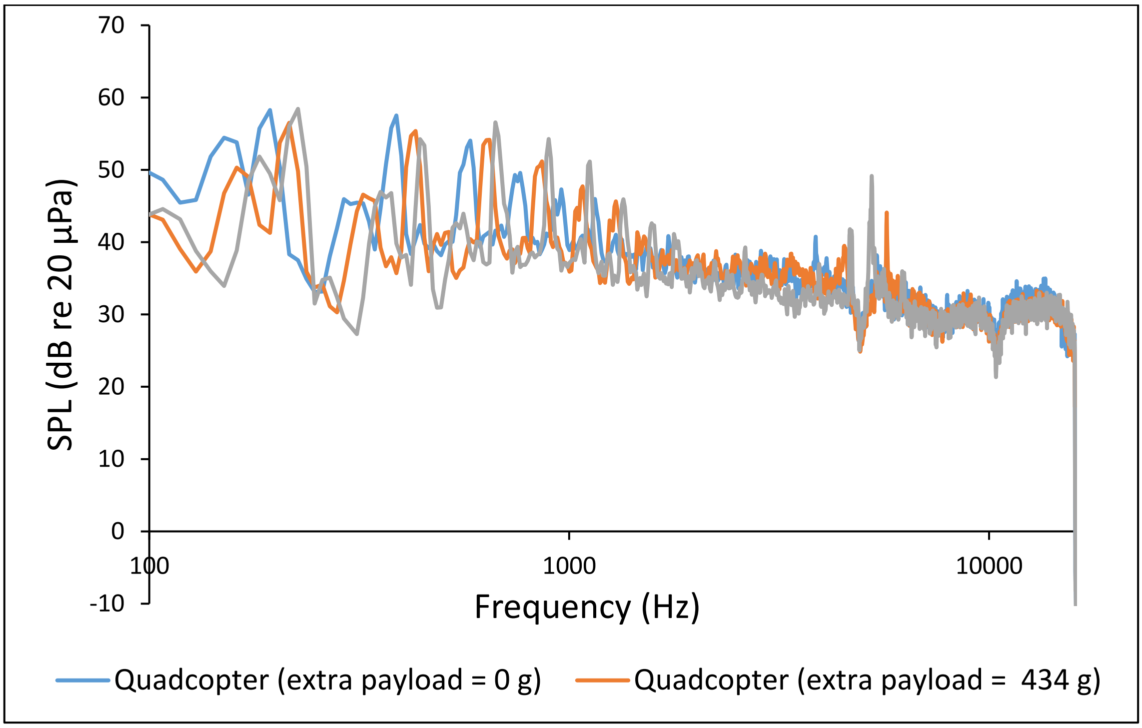

*Figure 3. Frequency spectrum of the quadcopter tested, with extra payload of 0, 434 and 656 g.*

Fig. 3 shows the frequency spectrum of quadcopter flyovers (A = 2 m and L = 0 m) with different extra payload. In the three conditions tested (i.e. 0, 434 and 656 g of extra payload) a similar spectral pattern is observed. There are clearly discernible complex tones up to ~1.6 kHz, and a significant high frequency content between 3.8 kHz and 6 kHz. The increase of the extra payload, and the consequent increase in the quadcopter power, lead to a higher pitch. The rotational speed of the rear propellers was higher than the one of the front propellers to maintain a forward flight [10]. This is observed in Fig. 3 with different BPFs of the rear and front propellers. The rear propeller BPFs the 0 g, 434 g and 656 g of extra payload conditions are ~195 Hz, ~215 Hz and ~225 Hz respectively; the front propeller BPFs are ~150 Hz, ~160 Hz and ~180 Hz respectively. Moreover, with the quadcopter operating at higher power, a substantial increase in the sound level of high frequency tones (generated by electric motors) is observed.

### 3.3 Comparison with aircraft and road vehicle noise

Fig. 4 shows the frequency spectrum of a representative example of the aircraft and quadcopter flyovers, and the road vehicles pass-byes recorded. Compared to road vehicles, the aircraft and quadcopter sounds recorded have a significant content in tonal noise. Fig. 4 displays a typical frequency spectrum of an aircraft flyover, with a BPF at around 1 kHz, several BPF harmonics and a significant decay in high frequency content due to atmospheric absorption. The frequency spectrum of the quadcopter flyover shows a significant content in complex tones between 400 Hz and 2.5 kHz, and high sound levels in the high frequency region generated by the electric motors. Small quadcopters will operate close to the public, reducing the effect of atmospheric absorption in the sound level at the receiver. Therefore, the high frequency noise is likely to be an important part of the annoyance due to the operation of small quadcopters.

Table 2 shows the average value of the 5th percentiles of the loudness, sharpness, fluctuation strength, roughness and tonality metrics for the aircraft, quadcopter and road vehicles tested. With all the sounds normalised to a $L_{Aeq}$ of 65 dB(A), the average loudness of the quadcopter and road vehicles is higher than the average loudness of the aircraft tested. This difference in loudness can be attributed to the significant attenuation in high frequencies due to atmospheric absorption. The average tonality of the aircraft and quadcopter tested is slightly higher than the average tonality of the road vehicles recorded. The average sharpness of the quadcopter is higher than the average sharpness of the road vehicles, and doubles the value of the aircraft recorded.

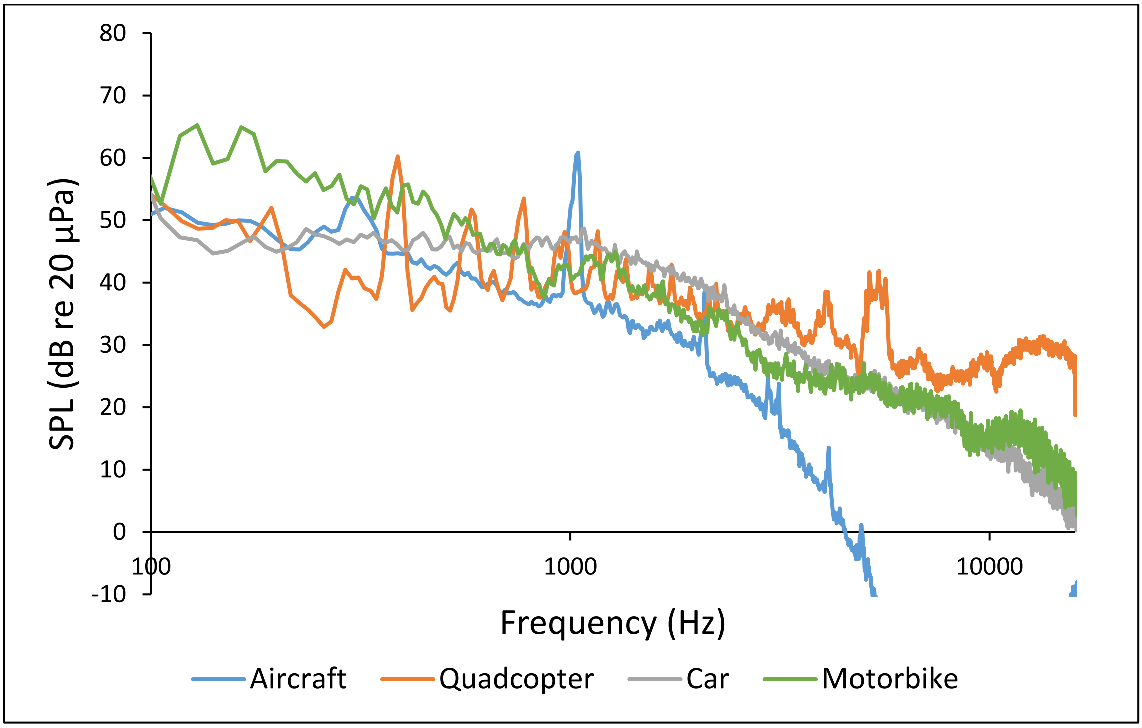

*Figure 4. Frequency spectrum of a representative example of the aircraft, quadcopter and road vehicles tested.*

*Table 2. Sound Quality metrics for the aircraft, quadcopter and road vehicles tested.*

| | Aircraft | Quadcopter | Road Vehicles |
|---|---|---|---|
| Loudness (sone) | 20.05±2.47 | 27.21±3.43 | 26.19±3.12 |
| Sharpness (acum) | 1.69±0.34 | 3.57±0.24 | 2.64±0.39 |
| Roughness (asper) | 2.31±0.39 | 2.19±0.19 | 2.79±0.78 |
| Fluctuation Strength (vacil) | 0.11±0.02 | 0.08±0.01 | 0.09±0.01 |
| Tonality (tu) | 0.32±0.07 | 0.36±0.07 | 0.24±0.15 |

The independent-samples Kruskal-Wallis test was implemented for testing whether there are statistically significant differences between the aircraft, quadcopter and road vehicles recorded, for each sound quality metric calculated. As shown in Table 3, only the differences in sharpness, between the quadcopter and both the aircraft and road vehicles, are statistically significant (at a significance level of 0.05). No statistically significant differences were found for tonality, despite the different tonal content of the aircraft, quadcopter and road vehicles recorded. A possible explanation is that the tonality metric, based on Terhardt [8] and Aures [9] work, was found insufficient to account for a series of complex tones spaced evenly across the frequency spectrum with relatively even sound levels [12].

*Table 3. Sound Quality metrics with statistically significant differences ($p \leq 0.05$) between the aircraft, quadcopter and road vehicles tested, based on the results of the Independent-samples Kruskal-Wallis test.*

| | Aircraft | Quadcopter | Road Vehicles |
|---|---|---|---|
| Aircraft | - | Loudness (p-value = 0.000),<br>Sharpness (p-value = 0.000),<br>Fluctuation Strength (p-value = 0.000) | Loudness (p-value = 0.005) |
| Quadcopter | | - | Sharpness (p-value = 0.008),<br>Roughness (p-value = 0.018) |
| Road Vehicles | | | - |

### 3.4 Differences in Psychoacoustic Annoyance

The Psychoacoustic Annoyance ($PA$) model, developed by Zwicker and Fastl [13], describes the relation between $PA$ and the hearing sensations loudness, sharpness, fluctuation strength and roughness. The $PA$ model is given by

$$PA = N_5\left(1 + \sqrt{w_S^2 + w_{FR}^2}\right) \tag{1}$$

where

$N_5$ is the 5th percentile of the loudness (in sones)

$$w_S = \begin{cases} (S - 1.75) \cdot 0.25 \log_{10}(N_5 + 10) & S > 1.75 \\ 0 & S \leq 1.75 \end{cases} \tag{2}$$

$$w_{FR} = \frac{2.18}{N_5^{0.4}}(0.4F + 0.6R) \tag{3}$$

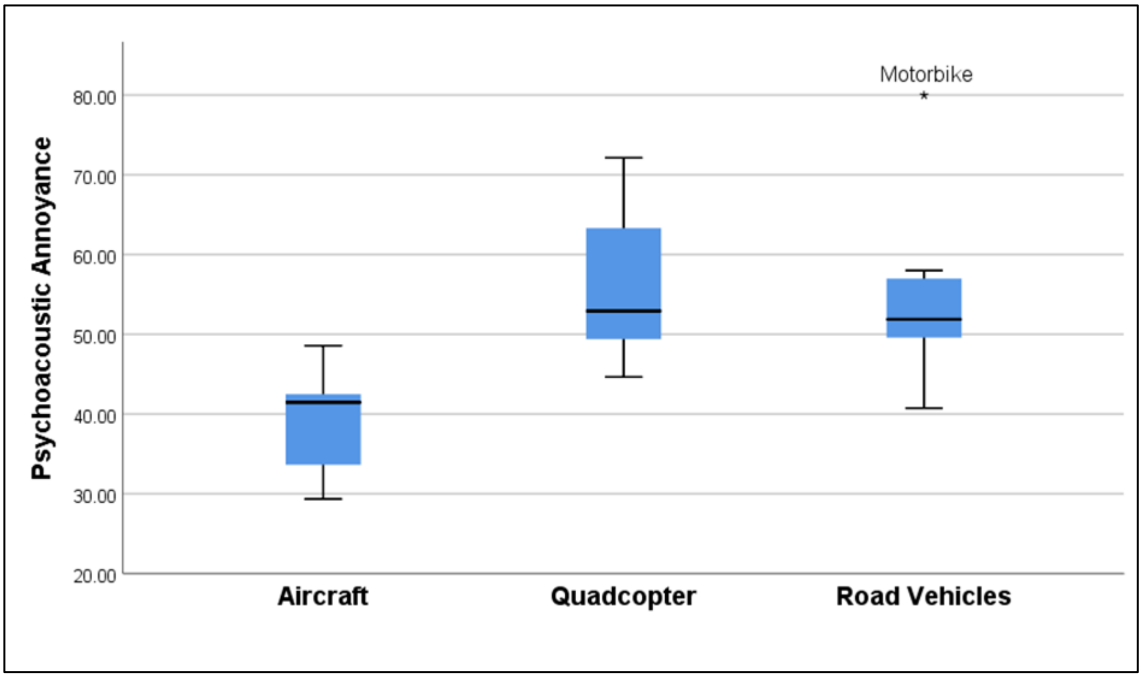

*Figure 5. Psychoacoustic Annoyance for the aircraft, quadcopter and road vehicles tested.*

Although not specified by Zwicker and Fastl in the original form of Eq. 1 (see [13]), the 5th percentiles of the sharpness, fluctuation strength and roughness metrics were used for computing *PA*. As shown in Fig. 5, the average value of *PA* of the quadcopter tested is 56.36±9.13. This value of *PA* is slightly higher than the average *PA* of the road vehicles tested (54.69±11.45), and significantly higher than the average *PA* of the aircraft tested (39.12±6.69).

The *PA* model developed by Zwicker and Fastl [13] is based on results of listening experiments with narrow-band and broadband sounds of different spectral distribution. However, the *PA* model does not include a factor for taking into account the tonality of the sounds. Therefore, the *PA* model may underestimate the annoyance response of sounds with strong tonal components [14]. The modified Psychoacoustic Annoyance ($PA'$) model developed by Di et al. [14] (Eq. 4), including a factor for the tonality of sounds, was also calculated for the range of noise samples tested in this research.

$$PA' = N_5\left(1 + \sqrt{w_S^2 + w_{FR}^2 + w_T^2}\right) \tag{4}$$

where

$$w_T = \frac{6.41}{N_5^{0.52}} T \tag{5}$$

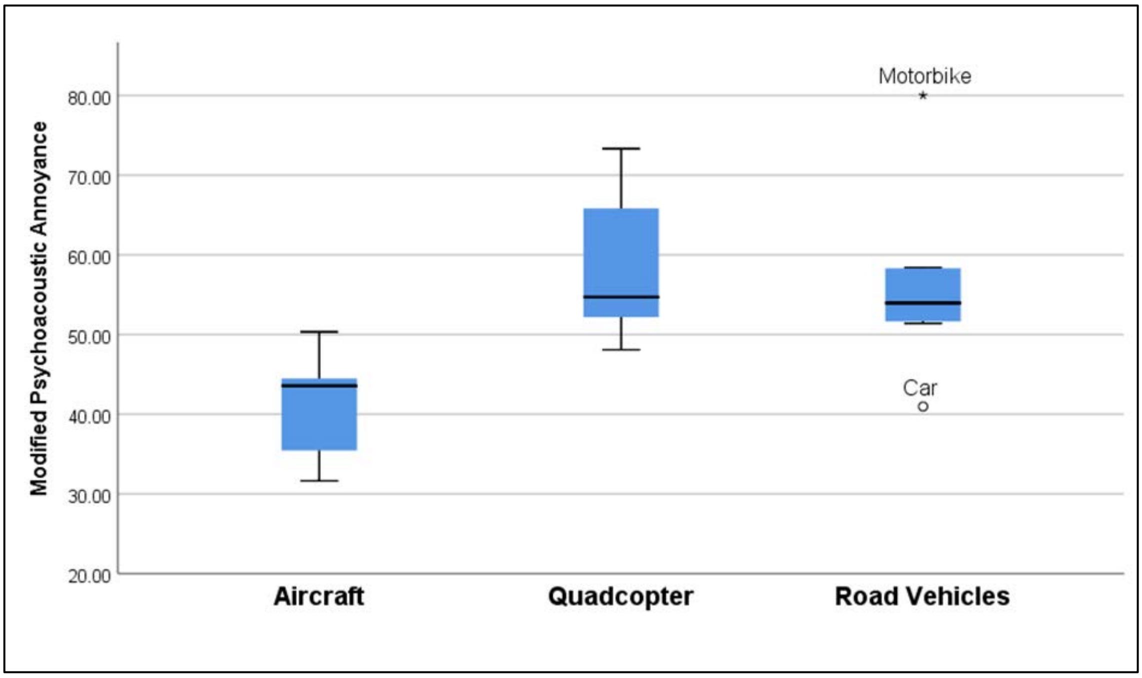

*Figure 6. Modified Psychoacoustic Annoyance (proposed by [14]) for the aircraft, quadcopter and road vehicles tested.*

In Eq. 5, the 5th percentile of the Aures/Terhardt tonality was used for computing $PA'$. As shown in Fig. 6, the addition of this tonality factor, proposed by Di et al. [14], does not lead to significant differences in the average values of $PA'$ of the three noise sources tested (i.e. aircraft, quadcopter and road vehicles), as compared to the average values of the *PA* model. In this case, the average value of the $PA'$ model is 58.53±8.69 for the quadcopter, 56.09±11.10 for the road vehicles, and 41.11±6.53 for the aircraft.

More [15] also developed a modified version of Zwicker and Fastl's *PA* model.

$$PA_{mod} = N_5\left(1 + \sqrt{\gamma_0 + \gamma_1 w_S^2 + \gamma_2 w_{FR}^2 + \gamma_3 w_T^2}\right) \tag{6}$$

where

$$w_T^2 = [(1 - e^{-\gamma_4 N_5})^2 (1 - e^{-\gamma_5 T})^2] \tag{7}$$

On the basis of a series of psychoacoustic tests, More optimised the $PA_{mod}$ model described in Eq. 6 for the specific characteristics of aircraft noise, with special emphasis on tonalness effects (see Table 4).

*Table 4. Estimates for the modified psychoacoustic annoyance model (Eqs. 6 and 7) [15].*

| | $\widetilde{\gamma_0}$ | $\widetilde{\gamma_1}$ | $\widetilde{\gamma_2}$ | $\widetilde{\gamma_3}$ | $\widetilde{\gamma_4}$ | $\widetilde{\gamma_5}$ |
|---|---|---|---|---|---|---|
| Annoyance Adjustments | -0.16 | 11.48 | 0.84 | 1.25 | 0.29 | 5.49 |

Fig. 7 shows the $PA_{mod}$ model for the aircraft, quadcopter and road vehicles tested. In this case, the average value of the $PA_{mod}$ model, with coefficients optimised for aircraft noise, for the quadcopter (99.06±20.85) is significantly higher that for the road vehicles (68.69±14.17) and aircraft (42.51±7.80).

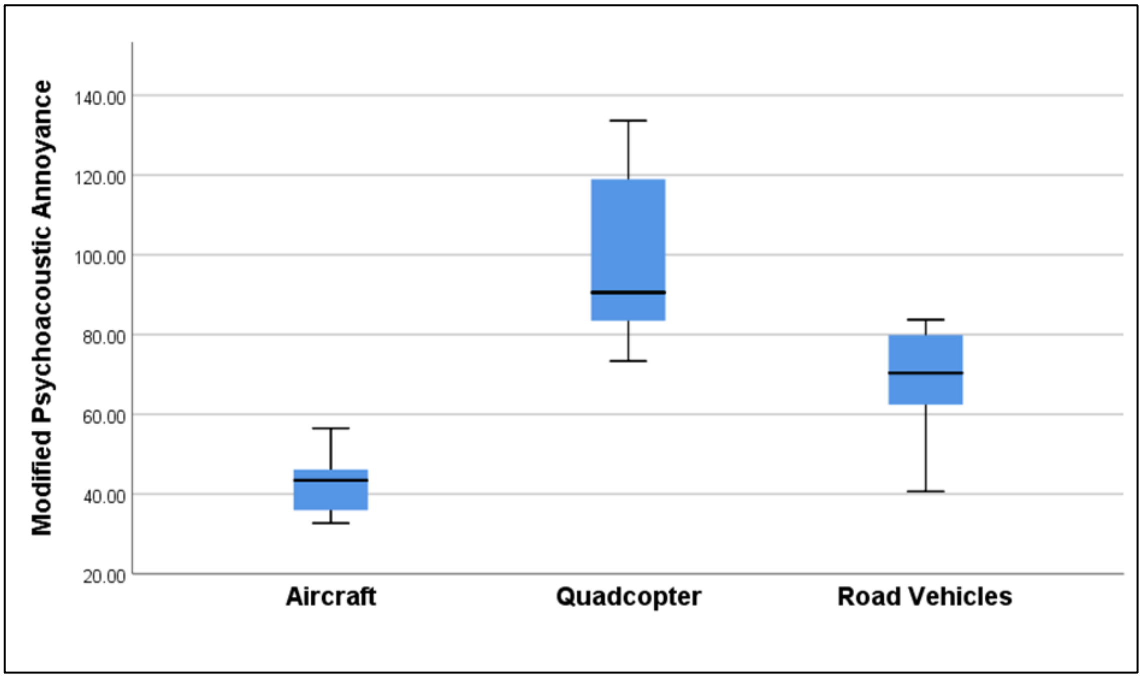

*Figure 7. Modified Psychoacoustic Annoyance (proposed by [15]) for the aircraft, quadcopter and road vehicles tested.*

## 4. CONCLUSIONS

This paper presents the results of a series of acoustic measurements taken on a small fixed-pitch quadcopter. A set of acoustic measurements were conducted in an aeroacoustics lab with the small quadcopter fixed to a horizontal stand and operating at full power. Moreover, acoustic measurements were conducted for a quadcopter hover and a series of quadcopter flyovers. The noise generated by the small quadcopter is characterised by propeller BPFs at around 200 Hz, and a series of harmonics of the BPFs. These are harmonic complex tones spaced evenly across the mid-to-high frequency region with relatively event sound levels. The operation of the electric motors generate an important source of noise in the form of high frequency tones. Because of atmospheric disturbances, e.g. wind gusts, the propellers rotational speed adjustments of the flight control system to maintain vehicle stability create an unsteady acoustic signature, with an increase in the dispersion of spectral lines at higher harmonics of the BPFs. Compared to a number of aircraft and road vehicles tested, the high frequency content in the recorded quadcopter noise is significantly higher. This difference in high frequency content between the vehicles tested is accounted for by the sharpness metric. Due to the higher loudness, sharpness and tonality of the quadcopter, the calculated psychoacoustic annoyance is also higher than for the aircraft and road vehicles tested, especially when the psychoacoustic annoyance is optimised for specific aircraft characteristics.

## 5. ACKNOWLEDGEMENTS

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