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NOISE EMISSIONS AND NOISE ANNOYANCE OF A SINGLE-PROPELLER ELECTRIC AIRCRAFT DURING FLYOVER

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In recent years, the search for more sustainable propulsion systems for aviation has led to an increased interest in electric propulsion aircraft. These aircraft are often claimed to be more silent due to the lack of an internal combustion engine which eliminates the combustion and exhaust noise. However, the dominant noise source for single-propeller aircraft, independent of the propulsion method, is often the propeller itself. Additionally, lower noise levels simply assessed with conventional sound metrics like the sound pressure levels might not necessarily correspond to lower noise annoyance. Therefore, this research investigates the noise levels and expected psychoacoustic annoyance of the electric aircraft Pipistrel Velis in comparison to its fuel-burning counterpart, the Pipistrel Virus. The Velis can serve as a direct replacement for the Virus as they have the same number of seats and the same take-off weight, raising the question of what the effect of this replacement is on community noise annoyance. The research is based on experimental measurements during flyovers of both aircraft. Overall, it was found that the Velis is found to have lower noise emissions and lower psychoacoustic annoyance according to its sound quality metrics. This is reflected in the loudness, tonality, and impulsiveness, likely due to the presence of fewer tones below 500 Hz.

Keywords: Electric aircraft, Propeller noise, Psychoacoustic annoyance, Sound quality metrics

1. Introduction

The aviation sector contributes significantly to greenhouse gas emissions by burning fossil fuels in jet engines. While engines are becoming more fuel efficient, the increase in number of flights worldwide partially counteracts the reduction in emissions affecting the climate [1]. Therefore, the aviation industry is looking for alternative propulsion systems besides the ever-continuing quest of increasing engine efficiency.

Alternative propulsion systems include, but are not limited to, hydrogen fuel cells, hydrogen combustion, and electric motors drawing from batteries. Many concepts that use one of these systems employ propellers due to their higher efficiency compared to turbofan engines at low-speed conditions [2]. Additionally, the propeller can be connected to any type of motor, hence providing the possibility to research different propulsion systems.

While some studies suggest that the electric motor hardly contributes to the total noise level, this does not guarantee that electric aircraft will be perceived as less annoying [3, 4]. This would be an analogy to electric cars, that are more silent than cars with combustion engines [5]. Yet, this claim omits the influence of the propeller itself which might be dominant over the combustion engine. In addition, conventional sound metrics often fall short of explaining human auditory perception [6]. Sound perception is an important contributor to the societal acceptance of these new aircraft types as communities are fighting for stricter noise regulations.

Therefore, the research presented in this paper focuses on noise emissions and annoyance of an electric propeller-driven aircraft in comparison to a combustion engine counterpart. In essence, it aims to answer the question "If an electric aircraft performs the same flight manoeuvre as its non-electric counterpart, would there be a noticeable difference in noise annoyance?" The aircraft investigated here are the two-seater Pipistrel Virus (referred to as Virus) and its direct (electrical) replacement Pipistrel Velis Electro (referred to as Velis), which is the first-certified fully electric aircraft. The experimental data considered was obtained during acoustic flyover measurements. They are compared through spectral analysis, conventional sound metrics, and sound quality metrics. In the near future, the outcome of the sound quality metrics will be validated against responses of a large-scale listening experiment. These steps contribute to the ultimate goal of assessing the community impact of replacing combustion engine aircraft with electric aircraft in terms of noise.

2. Experimental setup

2.1 Characteristics of Pipistrel Velis and Virus

The research objects for this study are two propeller-driven aircraft manufactured by Pipistrel. The combustion engine aircraft is the Pipistrel Virus SW121 and the electrical version is the Pipistrel Velis Electro SW128 as seen in Figures 1(a) and 1(b) respectively.

(a) Pipistrel Virus (Virus) (b) Pipistrel Virus (Velis Electro)

Figure 1: Photos of the exact aircraft used in the current study. Photo courtesy: E-flight Academy.

Table 1 presents the from the Type Certificate Data Sheet (TCDS) from EASA. Both aircraft fall under the same TCDS category, as Pipistrel launched the Velis and Virus as sub-models within aircraft type SW 121. Both aircraft have nearly identical airframes as can be derived from the dimensions, in combination with the photos. The Maximum Take-Off Weight (MTOW) is identical too. The weight differences from the motor, propeller, and fuel/battery are compensated in the maximum payload weight which is lower for the Velis than the Virus. Another airframe component, the landing gear, is registered as a fixed tricycle for both types, however, the photos of the aircraft types show that the Virus has fixed covers around the landing gear. While these covers add weight to the plane, they also provide drag reduction during flight.

The main differences between the aircraft types are the engine and propeller types. The propeller differences could explain differences in the noise profile, as propellers with more blades typically provide more thrust, or for a given thrust there is lower loading per blade. An increased number of blades also increases the Blade Passing Frequency (BPF).

The noise certification value is determined by measurements during take-off according to ICAO Annex 16, Volume I, edition 8, amendment 12, chapter 10.4b [7]. This is the certification standard for propeller-driven vehicles with a MTOW of 8618 kg at most. For this type of aircraft, the measurement is taken under the take-off flight path at 2500 m from the start of take-off roll, while operating at maximum take-off power. While the ICAO noise certification standard can be assumed to provide maximum noise levels, it does not represent a relevant comparison for noise annoyance for two reasons: (1) conventional metrics are not necessarily indicative of annoyance, and (2) communities are not necessarily under the take-off path but could be situated under a cruise path instead.

Table 1: Technical characteristics of the two Pipistrel aircraft under study, obtained from EASA TCDS and Pipistrel manufacturing data [8–10]

Characteristics	**Pipistrel Virus**	**Pipistrel Velis**
Aircraft type	SW 121	SW 121
Aircraft model	SW 121	SW 128
Engine type	Rotax 912 S3	E-811 / 268MVLC
Propeller type	MTV-33-1-A/170-200	Pipistrel P-812 / 164-F3A
MTOW (kg)	600	600
Nr. of seats (-)	2	2
Payload weight (kg)	229	172
Wingspan (m)	10.70	10.71
Length (m)	6.45	6.47
Height (m)	2.06	2.08
Landing gear	fixed tricycle	fixed tricycle
Nr. of propeller blades (-)	2	3
Propeller diameter (m)	1.70 (CW)	1.64 (CW)
Propeller pitch	constant-speed	fixed-pitch
V_{NO} (kts, indicated airspeed)	120	98
Max. continuous power (kW)	69/5500 RPM	49.2/2350 RPM
Certification $L_{A,max}$ (dBA)	70	60

2.2 Flyover acoustic measurements

The flyover acoustic measurements were performed with an acoustic array at Teuge International Airport, the Netherlands. The array was placed at the very end of the overrun area on the airport border, in line with the centre line of the runway. The exact location was dependent on the wind direction, which was different for the Velis and Virus measurements. The setup contained a CAE Bionic M-112 microphone array [11] lying face-up on top of an acoustic absorption foam mat (Flamex Basic 15 mm). For this particular study, only the data of a single microphone close to the centre of the array was analysed to avoid ground reflections from the sides of the array.

For both aircraft, acoustic measurements were conducted during flyovers at consistent flight settings. Due to wind gusts from different directions and tolerances in the controls, the settings were not exactly the same for both aircraft. For each aircraft, a total of 3 flyovers were recorded. The flyovers were performed by approaching, skipping touch-down, and continuing over the length of the runway at an altitude of approximately 10 m. The entire length of the runway was needed to ensure a good line-up and proper settings when passing over the array. Table 2 summarises the flight parameters altitude, velocity, RPM of propeller, and power. The parameters were derived from GoPro recordings of the cockpit display and GPS data as recorded by the aircraft.

As these measurements were used in a concurrent listening experiment, following this research, they were calibrated and scaled according to maximum acceptable levels ($L_{\text{A,max}}$ = 80 dBA). All results presented here, are based on the calibrated and scaled files.

2.3 Sound quality metrics

Unlike the conventional sound pressure metric, which quantifies the purely physical magnitude of sound based on pressure fluctuations, Sound Quality Metrics (SQMs) describe the subjective perception of sound by human hearing. Hence, SQMs are expected to better capture the auditory behaviour of the human ear compared to conventional sound metrics typically employed in noise assessments. The five most commonly-used SQMs [12] 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, with maximum sensitivity for modulation frequencies around 70 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.

Additionally, impulsiveness (I) was calculated based on the model of Willemsen and Rao [13]. This model is loudness-based, thus analysing primarily the presence of sounds with a short duration and high amplitude. This metric was added to analyse whether single propellers suffer from this characteristic, which is commonly known for helicopter noise, as well as multi-propeller systems [14, 15].

These SQMs were calculated for each sound wave and combined into a single global psychoacoustic annoyance (PA) metric following the semi-empirical models by Zwicker (1999) [16], More (2010) [17], Di (2016) [18], and Willemsen (2010) [13]. Henceforth, the top 5% percentiles of these metrics (values exceeded 5% of the time) are reported, and hence the sub-index *5*. The global PA models differ in the SQMs which they take into account. Zwicker's model was the first model, which takes into account N_5, FS_5, R_5, and S_5 through a complex function which contains logistic weighting functions for FS_5, R_5, and S_5. These weighting functions include the effect of N on the other metrics. More and Di expanded this by also including tonality (K_5) in a similar weighting function. Willemsen created a linear regression model which does not include K and FS but includes I.

All the SQMs (except for impulsiveness) and the PA metrics were computed using the open-source MATLAB toolbox SQAT (Sound Quality Analysis Toolbox) v1.1 [19].

3. Analysis of propeller sound

3.1 Conventional sound metrics

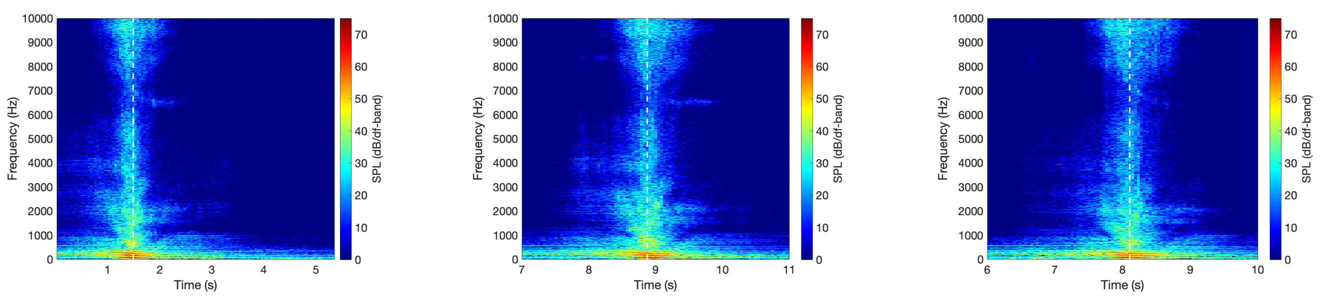
The aircraft were flown in the same manner, yet, not all flight parameters are exactly the same. When assessed in terms of altitude and velocity, Table 2 shows that the Velis 1 and Velis 2 flights are more similar, and that the Virus 1 and Virus 3 flights are more similar. However, the $L_{A,eq}$ shows a difference of 4.5 dBA. Additionally, a large difference in RPM is seen and consequently the Blade Passage Frequency

(BPF) between the aircraft types. This is due to the difference in the number of propeller blades and the RPM necessary for the same thrust with different propeller designs.

Table 2: Flight parameters for each flyover recording according to the data recorded in the cockpit. $L_{A,eq}$ calibrated and scaled to acceptable levels.

Flyover case	Altitude (m)	Velocity (m/s)	RPM (-)	BPF (Hz)	Power (kW)	$L_{A,eq}$ (dBA)
Virus 1	7.6	39.2	2550	85	not recorded	55.9
Virus 2	10.2	41.6	2550	85	not recorded	51.4
Virus 3	6.4	37.8	2550	85	not recorded	51.4
Velis 1	8.9	35.7	2000	100	20	40.9
Velis 2	8.3	35.9	2100	105	25	41.7
Velis 3	12.2	41.7	2560	128	25	47.3

Note that the altitude level has not been corrected for in the audio files, as scaling was already applied on the maximum level. The spectrograms of the Virus and Velis in Figures 2 and 3, respectively, were constructed with a Hanning window of 4096 samples, 50% overlap, and zero-padding of 4096 samples. The spectrograms show three differences: (1) the Velis spectrograms show a tone at 4500 Hz, (2) the Virus spectrograms show a larger contribution of higher frequencies, and (3) the Virus spectrograms show more tones below 500 Hz.



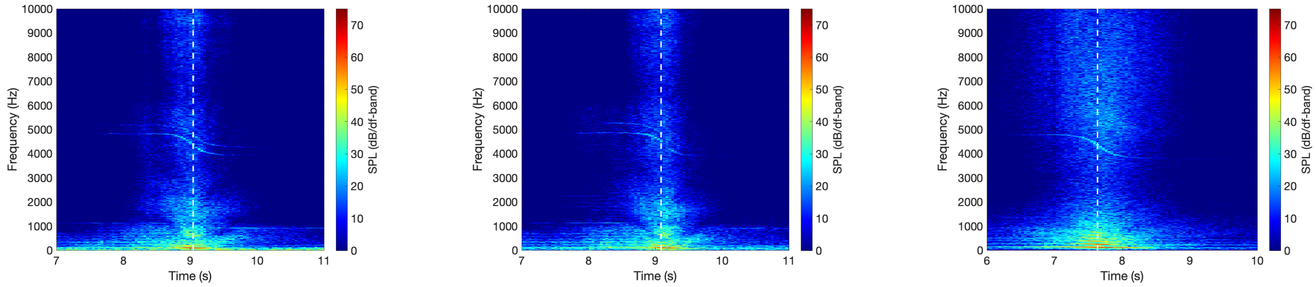
(a) Virus flyover 1 (b) Virus flyover 2 (c) Virus flyover 3

Figure 2: Spectrograms of Pipistrel Virus flyovers with a colour scale of 0 to 75 dB for all spectrograms. The bandwidth in the spectra is 5.85 Hz. The overhead time is indicated with a white dashed line.

As the spectrograms in Figures 2 and 3 do not provide a clear view of the lower frequencies, where propeller noise is dominant, Figure 4 provides the spectrograms and overhead spectra from 0 to 1500 Hz. Clearly, the Pipistrel Virus spectra contain more tones in the lower frequencies which can be attributed to the propeller, the combustion engine, and a modulated combination of the two tones (at 65 Hz and 130 Hz). Interestingly, the Virus spectrogram also shows more broadband acoustic energy which is mostly present at overhead positions. This broadband noise has a limited presence in the forward and aftward flight arc, while the propeller tones are present in the spectrogram for a longer period of time. The combustion engine tone which is present in between the harmonics of the BPF, at roughly 135 Hz and 200 Hz, also has limited presence and is mostly detected around the overhead position. It thus has a strong directionality.

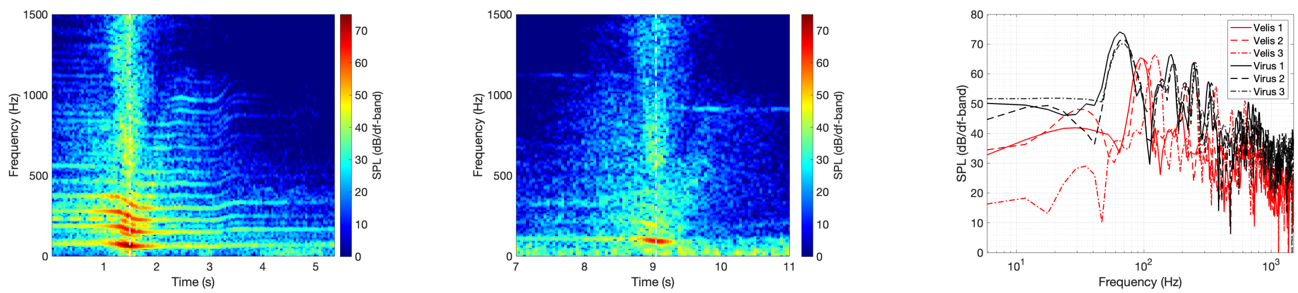
3.2 Sound Quality Metrics

Table 3 shows the sound quality metrics for each sound sample as computed by SQAT. The Virus and Velis are compared based on the Just Noticeable Differences (JND) reported as a percentage change for



(a) Velis flyover 1 (b) Velis flyover 2 (c) Velis flyover 3

Figure 3: Spectrograms of Pipistrel Velis flyovers with a colour scale of 0 to 75 dB for all spectrograms. The bandwidth in the spectra is 5.85 Hz. The overhead time is indicated with a white dashed line.



(a) Virus flyover 1 (b) Velis flyover 1 (c) Spectra at overhead time

Figure 4: Zoom in on spectrograms of Virus and Velis, to see harmonics and engine tones. The colour scale spans 0 to 75 dB for all spectrograms. The bandwidth in the spectra is 5.85 Hz.

each SQM in [12]. Here, the Virus aircraft is taken as the reference situation for the analysis of JNDs.

Table 3: Absolute values of SQM per flight recording.

Flyover case	N_5	K_5	S_5	FS_5	R_5	I [a]	**PA$_{\text{Di}}$**	**PA$_{\text{Willemsen}}$**	**PA$_{\text{More}}$**	**PA$_{\text{Zwicker}}$**
Virus 1	20.95	0.21	1.62	1.92	0.23	2.66	34.57	48.46	38.72	33.24
Virus 2	12.61	0.36	1.54	0.98	0.11	1.12	21.59	33.95	24.08	17.20
Virus 3	13.51	0.41	1.56	0.74	0.14	1.23	23.40	34.64	26.09	17.41
Velis 1	5.97	0.19	1.47	0.86	0.03	0.58	9.63	30.89	9.33	8.30
Velis 2	6.55	0.15	1.50	0.86	0.02	0.64	9.91	31.60	9.72	8.96
Velis 3	9.12	0.24	1.89	0.88	0.03	0.80	14.50	38.74	15.77	12.19

[a] The model by Willemsen et al. computes impulsiveness as a sum of the entire signal

In general, the first flyover with Virus (Virus 1) is fairly different from the second and third flyover (Virus 2 and Virus 3) on all metrics except for sharpness. It is unclear from the flight parameters and the spectrogram why this is exactly the case, although in general, the noise levels of Virus flyover 1 are higher as also seen in Table 2. Higher levels increase the N_5 characteristic. For FS_5 and R_5 the increase might not be explained by level differences.

Table 2 shows that the loudness of the Virus is higher, as could be expected from the higher $L_{A,eq}$ for the Virus aircraft. The JND for loudness is 7%, so the difference is noticeable. Mostly the lower frequencies cause this behaviour, as the equal-loudness contours converge at lower frequencies, meaning that the same ΔSPL can have a larger impact on loudness at low frequencies than at higher frequencies.

Another metric that shows noticeable differences is the tonality, for which the JND is 10%. The Velis has a reduced tonality which might have been expected from the reduced number of tones at frequencies below 500 Hz. However, the tone at 4500 Hz in Figure 3 which is only present for the Velis and not the Virus, seems to make no difference.

The sharpness attribute is similar and relatively low for both aircraft types. As propeller and engine noise show up in the lower frequency range, the airframe is expected to be the main contributor to the higher frequency acoustic content. As the airframe is the same for both aircraft, this difference is expected to be limited which results in the same sharpness value.

For FS, the JND requires a 20% change between the old and new situation, which is not the case if Virus 1 is excluded. The difference in roughness, however small, is noticeable as the change is more than 17%. The difference is possibly due to the change in BPF and level at the tones, which changes the spectral loudness per case on which R is dependent.

There is no JND value for impulsiveness yet, but the difference is roughly 50% which is expected to be noticeable. The impulsiveness for the Velis flyovers is lower, although neither of the spectrograms shows impulsive noise. As the impulsiveness metric by Willemsen et al. is strongly linked to loudness, the difference in loudness could influence the results.

Lastly, all models for PA show a lower annoyance level for the Velis flyovers than for the Virus flyovers. Most PA models predict that the Velis has half the PA of a Virus. However, the annoyance difference for the model of Willemsen between the Virus and Velis is much smaller. This might be due to the reduced correction for the impact of loudness through its linear rather than logistic model. It cannot be attributed to the omission of tonality, as that is also missing in Zwicker's model which represents similar values as Di and More, which do include tonality.

4. Conclusions

The results of this research show that the Pipistrel Velis has lower noise emissions during flyover than the Pipistrel Virus. The Velis especially has less strong tonal noise related to the BPF. The sound quality metrics indicate similar trends, with a noticeable difference in loudness, tonality, and impulsiveness. In general, the Pipistrel aircraft have little roughness and fluctuation strength, and equal levels of sharpness.

Recommendations for future research include identifying the origin of the tone at approximately 4500 Hz for the Velis, to find its source on the aircraft. Furthermore, the perceived annoyance from listening tests should be correlated with the SQM and PA values to find a good method of estimating noise annoyance in an early design stage. The listening test based on the measurements presented here, is currently being conducted at Delft University of Technology.

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