On the development of noise measurement guidelines for RPAS lighter than 150 kg

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On the development of Noise Measurement Guidelines for RPAS Lighter than 150 kg

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1 INTRODUCTION

1.1 Motivation

The use of Remotely Piloted Aircraft Systems (RPAS) has experienced a significant increase in recent years. These systems are now being utilized for new purposes, such as package delivery, medical supply transportation, and urban videography. This has resulted in an uptick in their use, particularly in densely populated urban areas. However, for the use of RPAS to be sustainable, it is essential to maintain sound levels that are in line with or below the usual background levels of the region. It is worth noting that these levels can differ significantly between large city centers, suburbs, and rural areas. Studies funded by Transport Canada [1] have revealed that noise pollution generated by RPAS may impede public acceptance, indicating that future noise regulations may need to consider social acceptability, taking into account not only safe noise levels, but also the annoyance and perception of noise by humans

1.2 Objectives

At present, there is uncertainty regarding the level of noise regulation necessary for RPAS, given their varied noise source characteristics resulting from differences in fuselage designs, propulsion configurations, weight, and flight modes. Establishing a standardized approach for characterizing their noise presents a challenge, but it is vital for ensuring sustainable operation. The objective of this report is to offer a summary of the available literature on RPAS noise that is relevant to the development of noise standards for lightweight and small (Mass < 150 kg) multi-rotor RPAS. Furthermore, the report highlights the inadequacies of current noise standards and provides recommendations for future standards, with particular emphasis on the perception of noise by humans, sound annoyance, and societal acceptance.

1.3 Current Transport Canada Regulation

In Canada, Transport Canada is responsible for overseeing all aspects of aviation. To address the growing use of Remotely Piloted Aircraft Systems (RPAS), Part 9 of the Canadian Aviation Regulations (CARs) was introduced in 2019. This section outlines the specific rules and guidelines that operators must follow to ensure the safe and legal operation of their RPAS.

Part 9 of the CARs requires RPAS operators to act responsibly when operating their aircraft. This responsibility is outlined in subsection 900.06, which states that “No person shall operate a remotely piloted aircraft system in such a reckless or negligent manner as to endanger or be likely to endanger aviation safety or the safety of any person”. However, there are no specific noise limitations.

2 PUBLIC PERCEPTION OF RPAS NOISE

2.1 Overall Perception

Remotely Piloted Aircraft Systems (RPAS), have been used for various purposes, such as aerial photography, surveillance, and delivery services. However, their increasing popularity has brought concerns regarding their noise levels, which can potentially disturb the peace and privacy of residents near drone activity areas. The public perception of RPAS noise is mixed, with some considering it a nuisance, while others are indifferent or supportive of their use.

2.2 Key Factors

Aside from the objective factors of sound levels, sound frequency, and sound source distance, the perception of RPAS noise by the public can be very subjective. There are several key factors that can influence the public perception:

Usage: the perception of RPAS noise can be influenced by the purpose of their use. For example, RPAS used for military or surveillance purposes can be seen as intrusive and cause discomfort to those who feel their privacy is being invaded. On the other hand, drones used for search and rescue or environmental monitoring can be seen as necessary and even life-saving, leading to a more positive perception of their noise.

Frequency and Duration: public perception of RPAS noise can also depend on the frequency and duration of drone activity. If drones are flown regularly and for extended periods, it can become a source of frustration for residents, and they may demand measures to reduce noise levels or limit their use. However, occasional use of drones for short periods may not cause significant disruption and may be viewed more positively.

Education and Awareness: Another factor that can impact public perception of RPAS noise is the level of awareness and education regarding RPAS technology. Many people may not have a clear understanding of how RPAS operate, leading to misconceptions about their noise levels and potential dangers. For instance, some people may believe that the RPAS is being used for spying on them or that they can cause physical harm. As a result, they may have a negative perception of RPAS noise, even when it is not a significant issue.

Media Portrayal: Lastly, public perception of RPAS noise can also be influenced by the media's portrayal of RPAS. Media reports on RPAS often focus on their negative impact on privacy, safety, and the environment, which can create a biased view of their use. As a result, people may perceive RPAS noise negatively.

3 PHYSICS OF RPAS NOISE

3.1 Source Noise

Multi-Rotor RPAS are the most prevalent type of RPAS in operation today. Their noise differs from conventional helicopters and tiltrotors. Unlike conventional rotors, the rotors on multi-rotor RPAS may operate with variable rotational speed, and have lower tip Mach numbers. This distinguishes their noise signature in terms of frequency and tempo significantly from conventional rotor craft. In addition, interactions between the rotors and the airframe are very different, with multi-rotor RPAS dominated by blade-wake interaction and blade-airframe interactions, resulting in very different flow fields around the aircraft [2]. These inherent characteristics of multi-rotor RPAS result in a noise signature that is highly three dimensional as illustrated in the figure below [3].

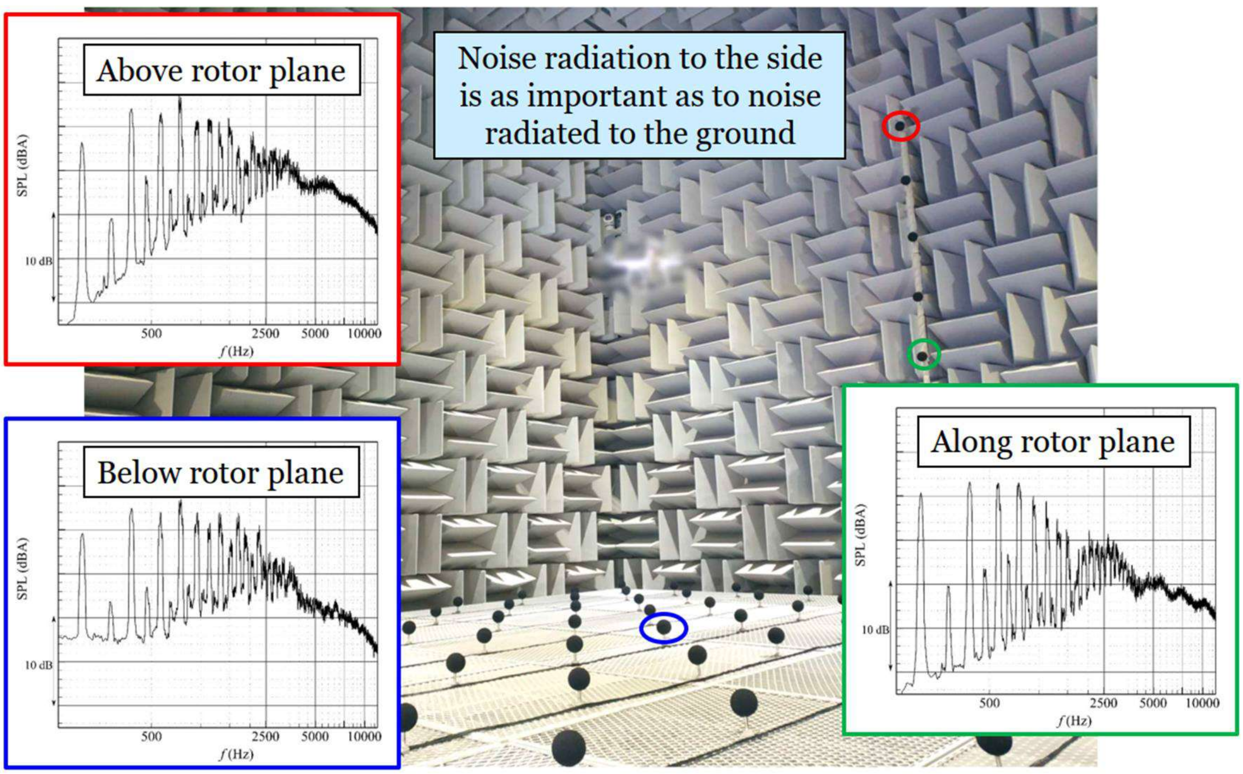

Figure 1: Sound pressure levels for a typical quadrotor RPAS at hover at three different locations in an anechoic chamber - above rotor plane, below rotor plane, and along rotor plane (*adapted from [3]*).

Another consideration is the propulsion system and scale of RPAS. In a typical small multi-rotor RPAS (less than 150 kg), the propulsion system is electric, with the typical distinct acoustic "drone" signature. The dominant source is dominated by the rotating blades at the blade passing frequency; a frequency that is a function of the number of blades and the rotation speed. This dominant source is a tonal noise and is typically associated with the cause for annoyance. Noise from the motor, and turbulences in flow field around the vehicle is less dominant and is broadband in nature [4]. In larger RPAS that make use of a thermal engine, for e.g., a turbojet, the noise from the high jet velocities is dominant.

3.2 Sound Propagation and Measurement

While the physics of sound propagation for noise generated by multi-rotor RPAS vehicles is similar to other noise, there are specific factors that distinguish multi-rotor RPAS noise from other aircraft noise. Typically, these vehicles are expected to operate in unique environments such as urban canyons, and densely populated areas, where local wind and atmospheric conditions can affect both flight performance and sound propagation. Due to these factors, these vehicle operations have more in common with rotorcraft operations than with aircraft operations near airports. Current measurement methods for aircraft noise are well established, but they may not be adequate for the unique challenges posed by multi-rotor RPAS noise in these types of environments [2].

4 PUBLIC HEALTH AND RPAS NOISE

4.1 Aircraft Noise Health Effects

Aircraft noise can have a range of negative effects on individuals and communities living near airports or under flight paths. These effects can include:

- Sleep disturbance: aircraft noise can disrupt sleep patterns, leading to sleep deprivation, fatigue, and reduced quality of life [5].

- Health effects: studies have linked exposure to aircraft noise with a range of health effects, including cardiovascular disease, high blood pressure, and anxiety [6].

- Reduced cognitive performance: aircraft noise can impair cognitive performance, including attention, memory, and reading ability, particularly in children and older adults [7].

- Annoyance and stress: aircraft noise can be a major source of annoyance and stress for individuals living near airports, leading to reduced quality of life and increased levels of frustration and dissatisfaction [8].

4.2 RPAS Specific Noise Health Effects

Studies on the specific health effects of noise from multi-rotor RPAS are limited, as they are a relatively new technology and have not yet been widely adopted for commercial or recreational use. While small multi-rotor RPAS produce lower levels of noise relative to other aircraft, their close proximity to the ground and their potential widespread use in urban and residential areas can make them a significant source of dangerous noise pollution, particularly at the larger scale and denser levels of operations. It is thus reasonable to expect that exposure to high levels of noise from these devices could have similar negative health effects to those associated with other sources of noise pollution, including traditional aircraft noise.

Overall, while more research is needed to fully understand the health effects of drone noise, the available evidence suggests that exposure to high levels of noise from RPAS could have negative impacts on human health and well-being [9].

5 HUMAN PERCEPTION OF SOUND

5.1 Sound Pressure and Sound Intensity

Fundamentally, sound is a vibration that propagates through a transmission medium as a mechanical wave [10]. If this transmission medium is air, these vibrations present themselves as fluctuations in the air pressure. The amplitude of these fluctuations can be measured directly in units of pressure (SI units - Pascals or μPascals), and can then be converted to a logarithmic scale, to give us the commonly used Sound Pressure Level (*SPL* or L_P) in decibels (dB). The relationship between pressure and *SPL* is defined by convention as:

$$SPL = L_P = 10\ log_{10}\left(\frac{P^2}{P_{ref}^2}\right)$$

where *P* is the measured pressure amplitude, and Pref is a reference pressure amplitude. This reference pressure amplitude is chosen with human perception of noise in mind: 2×10^{-5} pascals, the pressure amplitude of the weakest sound that is audible to the average human. Thus, the human perception of noise is built-in to the definition of *SPL*. In addition, because a noise source can fluctuate over time with varying durations, a commonly used metric to assess noise exposure is the Equivalent Continuous Sound Level (L_{eq}), which is simply the sound level in decibels of pressure amplitude integrated over time and divided by the duration time as defined below:

$$L_{eq} = 10\ log_{10}\left[\frac{\int_{T_1}^{T_2} P^2 dt}{P_{ref}^2 (T_2 - T_1)}\right]$$

For comparing different sources that may have different durations, a commonly used metric is Sound Exposure Level (*SEL* or L_E), which is calculated similar to L_{eq}, but is averaged over one second, instead of the duration of the measurement. *SEL* is defined by:

$$SEL = L_E = 10\ log_{10}\left[\frac{\int_{T_1}^{T_2} P^2 dt}{P_{ref}^2 T}\right]$$

where T is equal to 1 second.

A similar approach *SPL* is taken when quantifying the intensity of sound. The intensity of sound is fundamentally the energy transfer rate of the sound wave through a surface, defined in units of energy per time, i.e., power, over area (SI units – W/m^2). Similarly to *SPL*, a logarithmic scale for Sound Intensity Levels (*SIL* or L_I) can be defined:

$$SIL = L_I = 10\ log_{10}\left(\frac{I}{I_{ref}}\right)$$

where I_{ref} is the reference intensity defined as 1×10^{-12} W/m^2, the lowest sound power (per unit area) hearable by an average human under standard quiet room conditions.

SPL and *SIL* are both defined relative to the same reference (the threshold of human hearing), and their logarithmic scaling is defined such that they can be used interchangeably for most applications. It is worth noting here that both *SPL* and *SIL* will vary with distance from the source, and with the surrounding environment of the source (e.g., vicinity of reflecting or absorbing surfaces, temperature, humidity, etc.), thus measurement conditions and locations are very important for repeatable standardized measurements.

5.2 Frequency and Loudness Perception

Human auditory perception is only elicited by sound waves within the frequency range of approximately 20 Hz to 20 kHz; sound on either side of those frequencies is not perceived by the average human. In addition, the sensitivity of the human ear changes depending on the frequency of the sound, being most sensitive to sounds around 2 to 4 kHz, with sensitivity declining to either side of this region. For example, sound at 1kHz and *SPL* of 20 dB is perceived to be just as loud as sound at 20 Hz and an *SPL* of 90 dB. This loudness perception has been recognized, and a commonly used method to account for this is “A-weighting” where a set of corrections are applied to a measured *SPL* depending on the frequency of the sound (a type of frequency weighting). In essence, A-weighting is applied to approximate the loudness perception of the human ear. Measured quantities where A-weighting is applied are typically written with an “A” subscript. For example, an A-weighted Equivalent Continuous Sound Level (L_{eq}) would be written as L_{Aeq}.

5.3 Noise and Psychoacoustics

When it comes to human perception of sound there are objective and subjective considerations. We can objectively define sound as pressure variations that the human ear can detect and account for the loudness perception, but noise which we define as “unwelcome sound” is a subjective quantity. In setting regulations for noise levels, we aim to relate sound levels to hearing safety, health effects (see section 4.1), and annoyance.

To try to quantify these relations we turn to psychoacoustics: the scientific study of the psychological and physiological responses to sound, particularly how the brain processes and perceives sound. By considering psychoacoustics, new metrics can be constructed that can better relate sound levels to annoyance. Psychoacoustic testing typically involves collecting data orally from human participants, and then fitting that data to correlations. The tests are typically conducted in a quiet room, using headphones or speakers to present the sounds to the participant. The participant is then asked to respond to the sounds in various ways, including ranking for annoyance, loudness, or sharpness.

One such widely used metric in aircraft noise regulation is Effective Perceived Noise in Decibels (EPNdB). EPNdB is a measure that evaluates the noise level of a single aircraft pass-by event in comparison to other events. It is classified as an annoyance metric because it is based on annoyance studies conducted in 1959 that aimed to quantify the perceived noisiness of jet aircraft by observers on the ground [11].

More recently, several psychoacoustic noise metrics have been developed [12] and standardized [13]; while not being used in regulations, they have been used by researchers to evaluate the annoyance of RPAS [14, 15], and even optimize their designs [16].

6 CURRENT AIRCRAFT NOISE STANDARDS

6.1 Overview

Several aircraft standards exist for the certification of aircraft. ICAO Annex 16 is a document published by the International Civil Aviation Organization (ICAO) that establishes internationally recognized noise standards and recommended practices for aircraft operations. Annex 16 was first introduced in 1971 and has been revised several times since then to keep up with advancements in technology and changes in the aviation industry. These ICAO standards are then enforced by the regulating authorities (e.g., TC in Canada, and FAA in the US) via regulations and certification procedures that adhere to these standards. There are currently no such standards for small RPAS (below 150 kg), but it is important to examine existing aircraft standards as these are the starting points for future RPAS standards that are under development.

6.2 ICAO Annex 16 Volume 1 – Aircraft Noise

International Civil Aviation Organization (ICAO) Annex 16 Volume 1 Part II sets the standards and recommended practices for aircraft noise certification. The document outlines the noise level limits that aircraft should meet, and the testing procedures and methods to be used to measure noise levels during certification. The document establishes noise limits based on the type of aircraft, its maximum takeoff weight, and its propulsion system. The noise limits are expressed in terms of a maximum permissible noise metrics at various distances from the aircraft at various flight conditions.

The latest edition of the ICAO standard (8^{th} Edition July 2017) contains 13 chapters (Chapters 2 to 8, and 10-14) that outline different noise certification standards depending on type of aircraft and the date of application for its Type Certificate. New standards have been added over the years for new application dates, with the most recent standards given in Chapters 8, 10, 11, 13, and 14. The key elements of the standards defined in each of these chapters are summarized in the table below:

Table 1: Summary of ICAO Annex 16 noise standards [16].

Chapter	Aircraft type	Aircraft Mass	Noise Metric	Measurment Points	Maximum Noise Levels
8	Helicopters	above 3,175 kg	EPNdB (Effective perceived noise in decibels)	Takeoff, Overflight, Approach	106, 104, 109 EPNdB
10	Propeller-driven	below 8,618 kg	L_{ASmax} (Maximum A-Weighted Slow Time-weighted sound pressure level)	Takeoff	70-76 dB(A) depending on number of engines and aircraft mass
11	Helicopters	below 3,175 kg	L_{AE} (A-weighted sound exposure level)	Overflight	82 dB(A)
13	Tilt-rotors	not specified	EPNdB (Effective perceived noise in decibels)	Takeoff, Overflight, Approach	109, 108, 110 EPNdB
14	Subsonic Jets Subsonic Jets Propeller-driven	over 55,000 kg below 55,000 kg 8,618 kg - 55,000 kg	EPNdB (Effective perceived noise in decibels)	Lateral, Flyover, Approach	89-109,93-105, 98-105 EPNdB depending on number of engines and aircraft mass

7 DEVELOPMENT OF REGULATIONS FOR RPAS NOISE

7.1 Current Efforts

There are currently no established standards for the measurements of RPAS noise. The European Commission has recently published a Delegated Regulation, EU 2020/1058 [18], which outlines a test code for the noise of RPAS based on ISO 3744:2010 which is a sound power level measurement (*SWL* or L_w) [19]. This regulation pertains to RPAS with a maximum take-off mass (MTOM) of up to 25 kg and specifies that the noise measurement should be conducted on the aircraft as it is maintained above one reflecting (acoustically hard) plane, for both indoors and outdoors. It specifies a maximum A-weighted sound power level (L_{AW}) of about 80 to 85 depending on the RPAS mass. However, the regulation does not provide any specific guidelines for microphone placement to prevent the effects of unsteady aerodynamic flow on acoustic measurement. Additionally, the regulation does not take into account the directional nature of the noise generated by the RPAS.

Also recently, the European Union Aviation Safety Agency (EASA) has recently released guidelines on noise measurements of RPAS up to 600 kg [20]. They propose the use of A-weighted exposure level (L_{AE}) for a reference level flight measurement procedure and the use of A-weighted equivalent continuous sound pressure level (L_{Aeq}) for a reference hover measurement procedure. The level flight and hover reference procedures are shown in Figure 2 below. However, they have not released any maximum noise limits at this time.

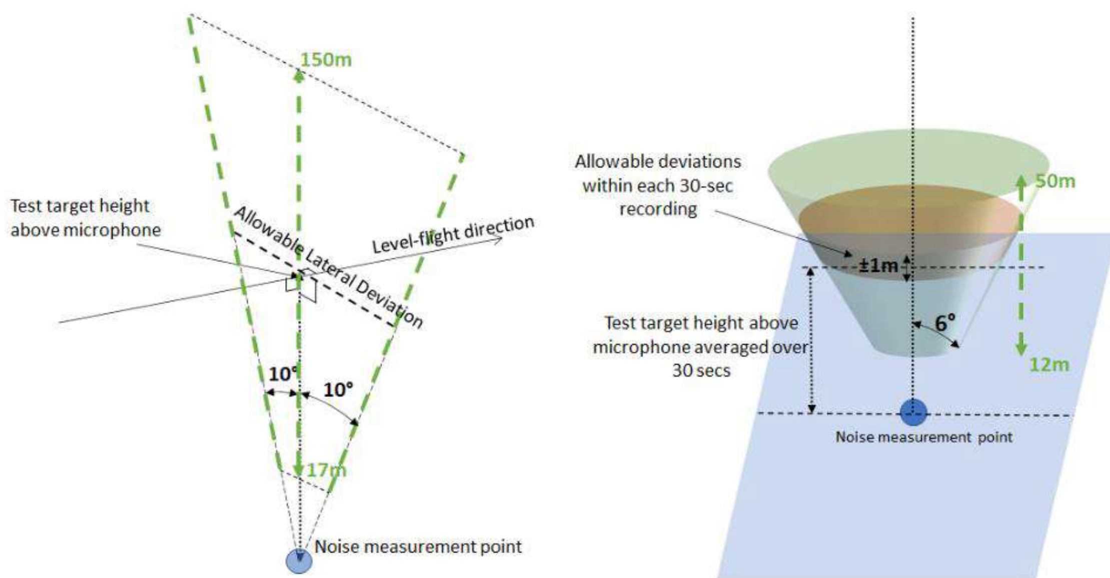

Figure 2: The two reference procedures from the EASA guidelines, level-flight (left), and hover (right), adapted from [20].

7.2 Future Standards

There is currently an international effort by the International Society for Standardization (ISO) to develop a standard for the noise measurements of multirotor powered RPAS with an MTOM of up to 150 kg [21]. This upcoming standard will offer procedures for conducting noise measurements during various RPAS flight phases, such as hover, take-off, landing, and cruise. The standard will also specify microphone configurations to capture RPAS noise from different locations and determine its directivity. Additionally, the standard will outline requirements for conducting measurements to ensure that acoustic far-field conditions are met. The standard is currently in the draft stage.

8 CONCLUSIONS AND RECOMMENDATIONS

The quantification of RPAS noise presents a challenge. A major part of this challenge stems from the annoyance dominant nature of RPAS noise exacerbated by some negative public perceptions that are currently held towards the use of RPAS. Research can continue on better understanding and quantifying the annoyance aspect with the aid of psychoacoustic techniques, in addition the following is recommended:

- Research on health effects of RPAS: there is very limited research available on this, and data is required in a standardized way with special attention paid to vulnerable groups. It is still not clear whether RPAS noise represents or will represent (as operation density increases) a public safety hazard, and will thus warrant federal level regulations in Canada.

- Research on models for noise transmission: RPAS are expected to operate in urban corridors, with potentially close proximity to wall and windows. An understanding of how noise is transmitted and perceived through walls may be crucial for setting noise limits.

- Complaints database: it is recommended that a detailed data base of complaints be collected that captures detailed information about the complaint nature, the RPAS specifications in the complaint, and the complainer's information (age, gender, location). Such a database will be crucial for psychoacoustic research.

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