Acoustic Analysis of Uneven Blade Spacing and Toroidal Geometry for Reducing Propeller Annoyance

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***Abstract*—Unmanned aerial vehicles (UAVs) are becoming more commonly used in populated areas, raising concerns about noise pollution generated from their propellers. This study investigates the acoustic performance of unconventional propeller designs, specifically toroidal and uneven-blade spaced propellers, for their potential in reducing psychoacoustic annoyance. Our experimental results show that these designs noticeably reduced acoustic characteristics associated with noise annoyance.**

***Index Terms*—Broadband noise, tonal noise, vortices, noise pollution, airfoil, CFD simulation, power spectral density (PSD), uneven blade spacing, toroidal propeller.**

I. Introduction

The recent boom in drone usage allows such technology to be used in a variety of consumer and industrial applications, including surveillance, delivery, agriculture, filmmaking, rescue, and further applications for land-based and aquatic drones [1]-[2]. As multirotor drones and unmanned aerial vehicles (UAVs) become more common within populous areas, the environmental problems resulting from the use of such vehicles become apparent, especially noise pollution. Research by Schäffer et al. found the psychoacoustic annoyance of drones to even exceed that of airplanes or automotives at similar sound pressure levels. This, combined with the fact that the public is still forming opinions on the acceptability of larger-scale UAV usage in their communities, makes the development of high efficiency, low-annoyance propellers necessary for the future of civil UAV applications [4].

Propeller noise can be separated into two main categories: tonal and broadband noise. Tonal noise is created by the harmonics of the blade passage frequency (BPF; rotational frequency multiplied by the number of blades), while broadband noise is created by the formation of vortices at the tips and trailing edge of the blade, resulting in excessive turbulence and, consequently, heightened levels of acoustic output [4]. Uneven blade spacing has shown promise in reducing perceived tonal noise by spreading out the frequencies over a wider range, especially in the lower ranges [5].

Such irritation can be attributed to the special acoustic characteristics of propellers, particularly pure tones (sinusoidal waveforms) and high-frequency broadband noise [4]. Pure-tone effects can be more irritating to humans than random noise distributed more equally along different noise frequencies. Kryter and Pearsons illustrate that sound consisting of a pure tone superimposed on background noise can be made to sound less noisy by dispersing the energy of the tone over several discrete frequencies [5]. Low-annoyance propeller design should aim to minimize pure-tone effects as well as reduce the overall broadband noise level in order to be effective.

II. Background

Conventional Propellers: Traditionally, propellers employ linear blades that are spaced at even intervals around the propeller hub to evenly distribute mass. The blades are designed to create an area of high pressure under each blade when spinning, thus generating lift. Varying rotational speeds allows for different amounts of vertical lift to be generated by the propeller, with faster rotation leading to greater lift [4].

Traditional propell2ers, however, emit large amounts of broadband noise, as the vortices formed at the tips of each blade create high turbulence [3].

Toroidal Propellers: The toroidal propeller minimizes this effect with blades whose tips "fold over" into the adjacent blade, thus reducing the impact of vortices [5]. With the effect of vortices minimized, the noise emitted from the propeller at the frequency range to which humans are most perceptive is also minimized, thus decreasing the perceived loudness.

Uneven Blade Spacing: The application of uneven blade spacing in drone design, as used by companies like Zipline, offers a novel solution to mitigate tonal noise. Uneven blade spacing disrupts the alignment of pressure pulses generated by the rotor blades, diffusing the concentrated tonal noise into a broader frequency range, thus also reducing the perceived loudness [1]. While the integration of uneven blade spacing does necessitate careful navigation of associated engineering challenges such as the maintenance of aerodynamic efficiency and flight stability, it is an avenue that holds promising potential for decreasing sound annoyance.

III. Motivations & Proposal

To collect rigorous, useful experimental data for the different propeller designs, they must adhere to similar constraints involving properties including size, design methodology, and material. They must also be evaluated for both noise and thrust performance.

Materials & Fabrication: Additive manufacturing, commonly implemented through 3D printing, allows for the rapid and effective development of drone propellers [7]. Due to the relatively low cost and fast production speed of 3D printing compared to traditional propeller manufacturing methods such as injection molding and metal machining, prototypes can be produced efficiently. While 3D printed propellers generally tend to have less desirable performance than commercially manufactured parts [8], such limitations are negligible for the purposes of this paper as all propellers are fabricated using the same method.

TABLE I. Tested Propellers

Propeller Type	Role in Study	Mass (g)
Type A - 3-blade conventional propeller	Control for 3-blade propellers	6
Type B - 3-loop toroidal propeller	Standard toroidal propeller	11
Type C - 2-loop toroidal propeller with uneven blade spacing and counterweight	Used to see the effect of uneven blade spacing on toroidal propeller	13
Type D - 6-blade conventional propeller	Control for 6-blade propellers	10
Type E - 6-blade propeller with uneven blade spacing	Used to see the effect of uneven blade spacing on 6-blade propeller	10

Design Methodology: Autodesk Fusion 360 was used to design all propellers from the same custom airfoil profile. Each model has a diameter of 6 inches. Five designs were created, as seen in Table I. Two conventional propellers are included, Type A, with three blades, and Type D, with six blades.

Unconventional Propellers: Three unconventional designs were created for testing and comparison to the conventional propellers (types B, C, and E).

Type B, the 3-loop toroidal, utilizes similar airfoil profiles as the conventional propellers, but the tips of each blade are swept into each other, creating three loops.

Type C, the 2-loop toroidal propeller with uneven blade spacing and counterweight, involves two adjacent toroidal "loops" at a 71.6° angle (relevant to a line drawn from the propeller hub through the center of each loop to its outermost edge) with an airfoil opposite to the blades serving as a counterweight.

Type E, the 6-blade with uneven blade spacing, also uses the airfoil profiles of the conventional propellers, but their spacing is offset.

As previously established, a toroidal loop design reduces broadband noise by eliminated tip vortices, while unevenly spaced blades, in conjunction with a counterweight, can reduce tonal noise. In isolation, each design is effective at minimizing a specific type of noise – broadband or tonal – emitted from a propeller, but has little impact on the other, severely impeding the ability of each to minimize noise pollution. We propose that combining these two designs will lead to a greater net decrease in noise output from drone propellers, reducing the auditory burden such propellers inflict on humans.

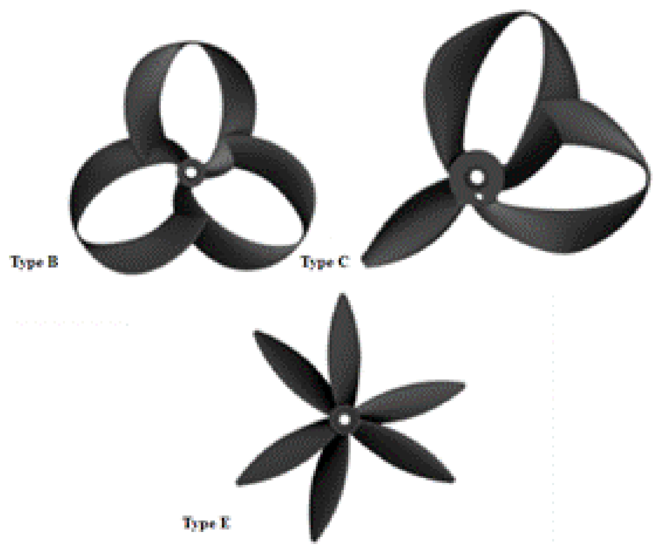

Fig. 1. 3D models of the three unconventional types of propellers used in testing.

IV. Experimental Procedure

Before experimentally testing the designs, basic efficiency tests were simulated in order to determine expected performances for each propeller. Using Ansys Fluent, a computational fluid dynamics (CFD) simulation software, thrust, force, and velocity analyses were run on all propellers to compare their aerodynamic performance. Part of the simulation parameters from [7] were used. Although thrust was tested over a range of angular velocities, a value of 6,000 rotations per minute (RPM) was used for visual CFD analysis (Fig. 2-4).

With CFD analysis, the aerodynamic performance of the propellers can be predicted prior to physical testing. Propellers of types B, D, and E were simulated to generate thrust within 0.01 Newtons of each other (Fig. 4), indicating that unevenly spaced and toroidal designs do not significantly sacrifice performance with respect to conventional designs.

CFD analysis can also suggest why a non-traditional design underperforms. The Type C propeller performed 31% worse than the Type A 3-blade control. This is likely due to the relatively large tip vortex apparent on the counterweight in Fig. 3b.

The testing setup (Figure 5) had two main requirements: the ability to measure frequencies of propeller noise and the

TABLE II. CFD Parameters

Parameter	Value
Angular velocity range	[1, 21] kRPM
Gravity	9.81 m/s^2
Time	Transient
Viscous model	K-epsilon (realizable)
Near wall treatment	Scalable wall function
Inlet air velocity	0 m/s
Iterations per time step	80
Time step size	0.125
Number of time steps	30

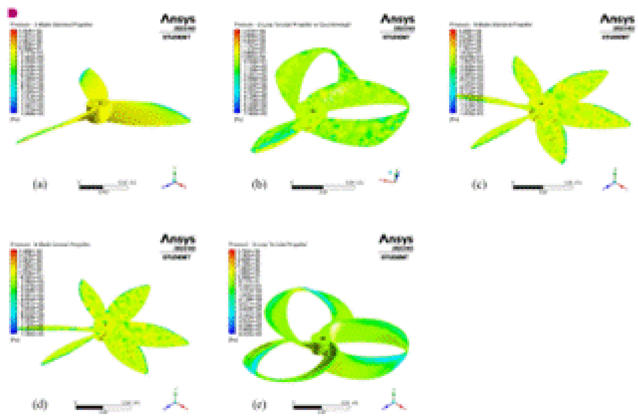

Fig. 2. CFD simulation of surface pressure.

ability to measure the thrust produced by the propellers. To avoid detecting the propeller wash (noise created by airflow), the microphone was stationed on the left side of the propeller. Furthermore, to ensure that background noise and reverberation from the environment were not picked up by the microphone, a sound-dampening chamber was created by lining foam acoustic padding on the walls of a testing box, ensuring that majority of the sound picked up resulted from the propeller directly [9]. To measure thrust, a thrust stand was created by mounting the propeller and motor on a load cell, which converts forces into a measurable electrical signal to quantify thrust. The propellers were tested at both 6,000 and 12,000 RPM to ensure an accurate reading in the differences in frequency and thrust.

Circuit 1: Arduino PWM ESC: To control the motor RPM, an Arduino microcontroller was used to output a 5V PWM signal to the motor ESC, an off-the-shelf component.

Circuit 2: HX711 Load Cell Circuit: To read thrust values, a load cell and HX711 breakout board were used to make the load cell signal readable via Arduino. The data was then sent to a serial data terminal on a computer.

To measure the speed of each propeller, reflective tape was applied to the blades of the propeller for detection by a laser tachometer rated up to 100 kRPM.

All propellers were 3D printed using an AnkerMake M5 printer with white PLA filament, using print settings as detailed

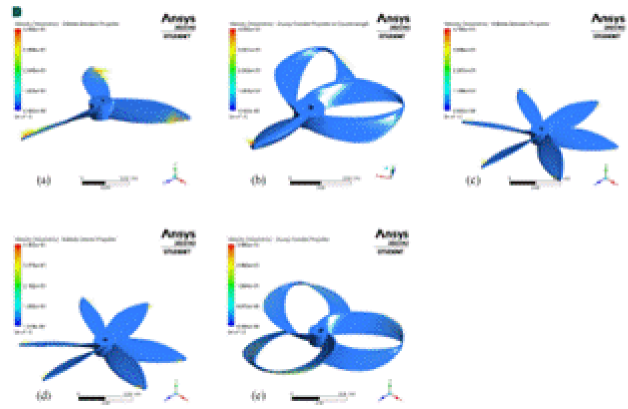

Fig. 3. CFD simulation of air velocity, represented volumetrically. Areas of high velocity at the ends of blades are tip vortices.

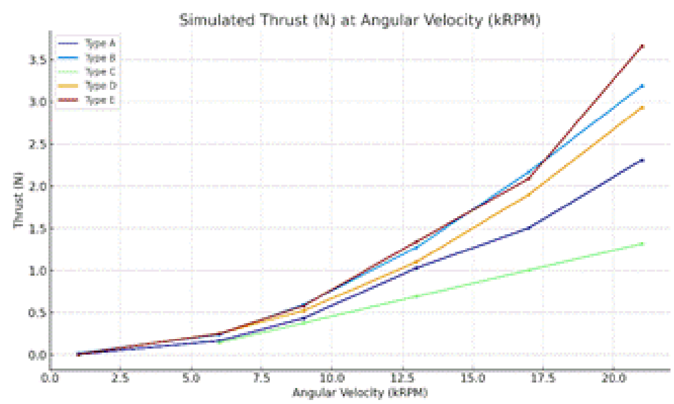

Fig. 4. Simulated thrust values by angular velocity for all propellers.

in Table III.

TABLE III. 3D Printing Settings

Parameter	Value
Print speed	250 mm/s
Infill density	100%
Layer height	0.12 mm
Extruder temperature	205 °C
Bed temperature	55 °C
Support type	Grid

The microphone used was the MEMS (microelectronic-mechanical systems) microphone included in the Samsung S23+. The audio signal from the microphone was recorded using Audacity and decomposed into individual frequencies using the Fast Fourier Transform (FFT) and converted into their sound pressure level (SPL) in decibels (dB) [10]. SPLs are converted into power spectral density to visualize how the signal power is distributed across different frequencies. This method of analysis allows the pinpointing of specific

Fig. 5. Experimental setup.

frequencies where distinct variations in intensity were noticed when comparing the different propellers in terms of tonal and broadband noise produced.

V. Results

TABLE IV. Thrust (N) by Propeller Design

Propeller Design	6 kRPM	12 kRPM
Type A - 3-blade control	0.63	2.36
Type B - 3-loop toroidal	0.73	2.90
Type C - 2-loop toroidal with uneven blade spacing and counterweight	0.45	2.09
Type D - 6-blade control	0.65	2.71
Type E - 6-blade with uneven blade spacing	0.63	2.45

Although load cell thrust values (Table IV) differ from the simulated values (Fig. 4), relative thrust values are similar for types B, D, and E in both data sets. This shows that there is little to no disadvantage, regarding thrust, for the noise-reducing designs when compared to the conventional designs. In fact, the toroidal propeller (type B) even outperformed the conventional designs.

It was determined that propellers type B, D, and E consistently produced the most thrust, so they were tested for acoustics. Types A and C were not analyzed for acoustics due to their incomparable thrust performance.

The previously outlined acoustic data processing methodology was used on the audio signals, and the PSD for each propeller was weighted using the A-weighting function, to better represent the perceived annoyance by humans. Using the 6-blade conventional propeller, Type D, as a control, the unconventional propellers were compared.

The decomposition of the recordings showed several discrete spikes in SPL at multiples of the BPF used to assess the psychoacoustic properties of the propellers tested.

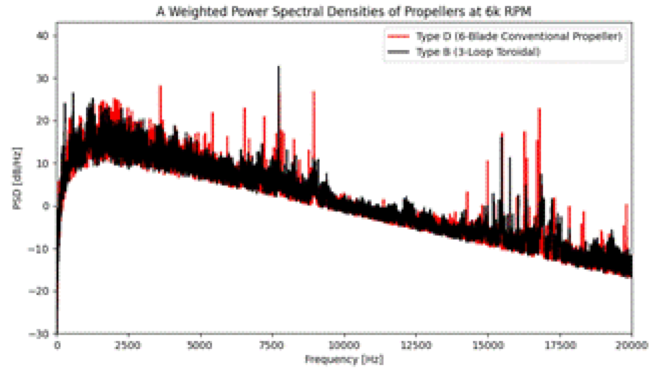

Fig. 6. A-weighted power spectral densities for Types D & B.

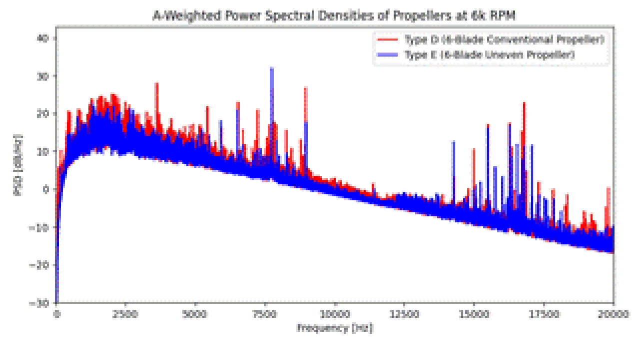

Fig. 7. A-weighted power spectral densities for Types D & E.

With Type D as a control, both propellers type B and E had lowered peaks specifically at higher frequencies. Type B had significantly lower peaks than any other propeller and had the sound profile with the least perceived annoyance overall. Type E also showed decreased peaks at higher frequencies and overall, but the difference was not as pronounced as Type B.

From Fig. 6 and 7 it can be noted that there is an increase in the number of spikes in PSD at multiples of the BPF in the higher frequencies of the uneven spaced propeller compared to the evenly spaced propeller. However, the intensity of these peaks is less pronounced in the uneven spacing, contributing to previous findings mentioned earlier regarding decreased perceived loudness. The overall broadband noise created by the uneven spaced propeller is less than the noise created by the evenly spaced propeller, showing that these changes to propeller design have potential benefits in terms of reducing noise pollution.

VI. Conclusion

It is predicted that the analyses of this investigation will help to accelerate the future of noise pollution-reducing propellers by promoting the exploration of effective designs that still retain thrust with innovative geometries such as the toroidal geometry and uneven spacing of propeller blades. New studies could investigate creating a calculable method to determine a propeller spacing with the least amount of high frequency noise generated, possibly involving the use of both toroidal geometry and uneven blade spacing, as both prove to have significant decreases in perceived loudness within the experimental data.

As drones become more prevalent in society for their wide range of use cases, more attention must be given to their effects upon the environment. The inclusion of techniques to combat noise pollution caused by these drones is important, as this is not currently a major consideration. Technologies which are detrimental to their environments may struggle with wider adoption, therefore minimizing drone noise pollution is a worthy avenue for future research to ensure the feasibility of drone usage in populated environments.

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