Acoustic emissions from a high-speed propeller

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Abstract. This paper investigates the far-field noise signature of propellers rotating at a speed range of 2500-6000 rpm. The experiment is conducted on a two-bladed propeller with a tip to tip diameter of 25.4 cm and a pitch of 17.8 cm. The propeller is connected to a brushless DC stepper motor of 900 rpm/V capacity that helps in achieving the above-mentioned propeller speed. The experiments are conducted inside the anechoic chamber to simulate the free-field environment. The acoustic spectra showed that the propeller noise at higher rpm consists of both tonal and broadband frequency components. The tonal noise and its harmonics were found to be lower than Blade Passing Frequency. The tonal peaks are more pronounced in higher rpm when compared to the lower rpm. Acoustic measurements also revealed the distinct variations in the noise levels with rpm. The Overall Sound Pressure Level tends to increase as the speed of the propeller increases. The rate of increase in noise levels is dominant at higher rpm compared to that at lower rpm. The propeller noise is 7 dB higher than the brushless motor noise at higher speeds. The obtained results are compared with previous research papers.

1. Introduction

Propellers are one of the crucial components of propulsion of unmanned aerial vehicles (UAV). Propeller is one of the cheapest parts of UAV, but it has a significant contribution to its efficiency and its noise. The aviation industry is mainly focusing on designing a more quieter propeller without affecting much of the propeller efficiency. Now, most of the UAVs use electric motors, which produce less noise than conventional engines. UAVs with reduced noise more suitable for the working environment. There are more UAVs and drones used in military applications. In such a case, when the propeller noise is less, it becomes difficult to trace the detect the UAV and the survivability increases. In civil applications, the propeller noise has to be low for the reduction of noise pollution and passenger comfortability. Maintaining an appropriate noise level is vital in airports. Propeller noise reduction is an essential aspect of propeller design. The propeller noise depends on various parameters like diameter, chord length, pitch, aerofoil type, speed, and the number of blades. Ffowcs-Williams and Hawking [1] in their work have analytically predicted the noise produced by the arbitrarily moving surface using the Acoustic analogy proposed by Lighthill [2,3]. They have derived the density field for turbulence for moving objects due to the arbitrarily moving multipole sources. They have derived equations to represent the surface distribution of surface sources in arbitrary motion. They have also made further deductions on high speed moving surfaces. Farassat et al. [4 - 6], based on the Ffowcs-Williams-Hawking equation solutions, has derived the formulas for the noise of the rotating blade. Yang et al. [7] have numerically studied the effect of geometric parameters of the propeller, such as diameter, chord width, and pitch angle on the acoustic and aerodynamic performance. They have concluded that the diameter has a significant effect on the aerodynamic properties, especially in the propeller blade tip. When the diameter or the pitch is varied, the SPL reduces by almost 0.6 dB. However, the pitch angle does not affect SPL when it is above 71 degrees. Further, the chord length has its impact on noise when only it decreases. Pagano et al. [8] have carried out an optimization of a propeller in pusher configuration without much reduction in the propeller

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efficiency. During optimization, they have considered tonal noise due to the blade tip thickness, and the broadband noise due to leading-edge and trailing edge. They have found that the tonal noise is due to the flow past the blade tip and the interaction of blade exhaust with the inner part of the blade. Marino [9] has carried out both numerical and experimental investigations on the acoustic emissions in propellers with varying advance ratios. On varying the microphone along axial positions, they found that the acoustic pressure was maximum near the tip region where the trailing vortex was higher. Chirico et al. [10] conducted a computational study using Computational Fluid Dynamics (CFD) solver to acoustically analyze various propeller designs. They used a validated CFD method for tonal noise estimations. Unequally spaced hub design appeared to be noisier than the baseline design. While operating at low speeds, offloaded tip design was producing less noise compared to the baseline design. This paper presents an experimental investigation of aeroacoustic properties of small diameter propeller. The noise study is mainly concerned about the acoustic characteristics of the propeller at different speeds from 2500 to 6000 rpm. The various acoustic spectra of the propeller with the motor are studied. An attempt is carried out to explore the various components of propeller noise at different speeds. The tonal and broadband characteristics of the propeller motor system are studied. OASPL of the propeller rotating at different rotational speeds is compared.

2. Experimental Setup
Experiments are carried out in an anechoic chamber of dimensions 2.6 m x 2.6 m x 3 m for a free-field environment. The chamber is soundproofed with polyurethane wedges. The cut-off frequency of the anechoic chamber is 300 Hz. The experiment is conducted on a two-bladed propeller with a tip to tip diameter of 25.4 cm and a pitch of 17.8 cm. The propeller is connected to a brushless DC stepper motor of 900 rpm/V capacity that helps in achieving the required speed. The speed of the motor is controlled by 40 amps Electronic Speed Controller (ESC). The motor is powered by a 3S LiPo battery of 11.1V capacity. An IR Sensor module is used to measure the instantaneous speed of the rotating propeller. The acoustic data are recorded using a quarter-inch free-field condenser microphone (PCB make, Model number 378C01). The sensitivity of the microphone is 2mV/Pa. The experimental setup and the schematic diagram are shown in Figure 1.

![Experimental Setup Image](image_url)

Figure 1: (a) Photograph and (b) Schematic diagram of the experimental setup

3. Experiment Methodology
The motor was mounted on a stand made out of mild steel links. The Infrared (IR) Sensor module was attached to the stand at a distance of 7 cm. The motor is calibrated with the ESC. The IR Sensor was calibrated with a
Digital Optical Tachometer. Both the speed of the motor and IR sensor is controlled by an Arduino Uno. The microphone is placed vertically above the motor at a distance of 120 cm from the tip of the propeller hub. The microphone data was captured at a rate of 150 kSa/s. The data acquisition of the microphone is made by using LabView Software. The Power Spectral Density and Overall Sound Pressure Level (OASPL) calculations were carried out in MATLAB. The uncertainty in the position is 0.1 mm, and the uncertainty in the speed measurements is 50 rpm.

4. Result and Discussions

Figure 2 shows the comparison of the acoustic spectra of the propeller-motor system and only the motor rotating at 6000 rpm. The propeller noise shows larger number of tones with a fundamental tonal frequency at the Blade Passing Frequency (BPF) 146.7 Hz, and the subsequent harmonic tones at higher frequencies. The main reason for tonal noise could be due to the Blade Vortex Interaction [11]. The vortex formed by the fast-moving blade is cut by the rotor blade. This acts as a source for tonal noise generation.

As the frequency increases above 2.5 kHz, tones are not the harmonic. This is due to the contribution of the motor noise [12]. The frequency region in the range of 1.5 – 5.0 kHz shows a broadband noise that might be due to the laminar boundary layer vortex shedding. The Tollmein-Sichlichting waves are amplified by the bubble shear layer. This, when convected along the blade span, leads to the production of a dipole noise. Since there is a variation of velocity along the radius of the propeller, this tonal noise appears as a broadband bump at the higher frequency [13].

| Speed (rpm) | Propeller noise (dB) | Motor noise (dB) |
|-------------|----------------------|-----------------|
| 2580        | 38.91                | 38.35           |
| 3500        | 39.88                | 38.61           |
| 4930        | 45.42                | 38.83           |
| 6000        | 46.89                | 39.46           |

The OASPL values of the propeller noise and the only motor were calculated, and is tabulated in Table 1. The OASPL was calculated for a frequency domain of 300 – 5000 Hz. The OASPL variation of the motor is minimal with speed. The OASPL value of the propeller with motor increases with rpm. The rate of increase in noise levels is dominant at higher rpm compared to that at lower rpm. The propeller noise is around 7 dB higher than the motor noise at higher speeds, whereas at lower speed propeller OASPL is about 1 dB higher.
than the motor noise. There is a significant increase in the OASPL as the speed increases. This might be due to the more contribution of tonal noise on the OASPL.

Figure 3 shows the far-field acoustic spectra of the propeller with the brushless motor at 6000, 4930, 3500, and 2580 rpm by keeping microphone at a constant distance of 120 cm vertically above the propeller. The plot contains both tonal and broadband noise. The fundamental tonal noise and its harmonics are appearing in low frequencies, and the broadband noise is appearing in the high-frequency region. The tonal noise and its harmonics are near the BPF. The number of tonal peaks for 4930 rpm is less than that of 6000 rpm. This is because, as the speed of the propeller decreases, the interaction of the vortex by rotor blade decreases. Hence the number to tones subsequently decreases with a reduction in speed. The tonal noise and broadband noise produced by a propeller at low speeds are significantly less compared to that of high speeds, as the speed of the propeller decreases, the change of velocity along the span of the propeller decreases. This leads to the formation of a less significant dipole. This might be a reason for the appearance of non-distinguishable broadband noise at lower speeds. This also explains the smaller amplitude of broadband noise as the speed decreases.

5. Conclusion
Experiments were carried out in the paper to study the acoustics of propeller noise at different speeds. The speed of the propeller is varied between 2500 to 6000 rpm. The propeller noise consists of both tonal and broadband noise components. The tonal noise appears in the low-frequency region (300 - 1500 Hz). Broadband noise was occurring in the high-frequency region (> 1.5 kHz). The tonal and broadband noise increases with an increase in speed. The OASPL increases with an increase in speed. The tonal noise contributes more to the OASPL. The study also revealed that the propeller noise is 7 dB higher than the brushless motor noise at higher speeds.

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