In propeller-based electrical propulsion systems, the main source of noise is from the propeller. Noise suppression can also be achieved during noise propagation in the surrounding space. In the present paper, a duct with aerodynamic geometry is fabricated using 3D printing technology, and then the aerodynamic performance of such light-weight duct is experimentally evaluated. Furthermore, by combining with micro-perforated holes on the duct wall and a compact back cavity, it acts as a light-weight duct silencer which can be used for reducing propeller noise. Several different configurations are designed and experimentally investigated for seeking the optimized design.

Keywords: Propeller noise, silencer, micro-perforated panel (MPP)

1. Introduction

Micro air vehicles (MAVs) have been the subject of increased attention in the past decade because of their potential unique military and civilian applications, including surveillance, search and rescue and remote detection [1-3]. Among the MAVs, quadcopter (four-rotor MAVs) designs, which have small size and agile manoeuvrability for indoor as well as outdoors operation, have become popular in MAV research [4]. However, one of the most disturbing problems of propeller-driven MAVs is the high-level propeller noise which has a significant effect on their detectability.

In propeller-based electrical propulsion systems, the main source of noise is the propeller. Reducing the propeller noise requires special attention during its design; it can be achieved by a systematic or novel design of the propeller’s geometry and aerodynamic characteristics [5]. Recently a quiet axial fan has been produced that incorporates different noise-reducing features: a structure resembling the serrated feathers used by owls for silent flight, blade-tip winglets, and serrated rotor-blade trailing edges [6]. This allowed noise reduction of up to 12dBA. Few reference papers related to this product can be found due to patent protection. Furthermore, the thrust characteristics of a cooling fan differ
from those required for quadcopter propulsion. Thus, additional systematic research work would be required for developing bio-inspired quiet propellers for MAVs.

Besides reducing the noise level at its sources, noise suppression can also be achieved during noise propagation in the surround space. A common practice for commercial aircraft engines is to shroud their rotors with ducts that both enhance the propulsive characteristics and incorporate acoustic liners consisting of perforated walls with back cavities [7-12]. While such shrouding ducts can improve the rotor’s efficiency [13-14], they can also increase the noise level in the high frequencies range due to rotor-stator interactions and other flow-induced noise [15]. Thus optimized shrouding ducts should be systematically designed. An acoustic liner could be very efficient for reducing the tonal noise generated by the propeller, but conventional acoustic liners require extra weight and installation space which are very critical on a MAV platform. Recently, micro-perforated plate (MPP) [16-19] or micro-perforated membrane (MPM) [20] were proven to be a light-weight, compact and efficient sound absorber for various engineering applications. A light-weight membrane-type acoustic resonator optimized to absorb sound at designated frequencies has a great potential for next generation noise reduction technology [21-22]. Lu et al. had made their original effort on tunable membrane-type acoustic absorbers [23-27]. However, the application of such technologies for suppressing the propeller noise on multi-rotor MAV requires to be explored in more detail.

The objectives of the present paper are 1) Explore the light weight duct structures which can avoid flow-induced vibrations and noise when being installed around a rotating propeller; 2) Experimentally study on the acoustic performance for such kind of designs.

2. Experimental setup

A 6-inch Gemfan Nylon Propeller 6030 driven by 2204-2300kv brushless motors with power supplied by a DC power supply is used for the present experiment. Using the motor control system, the rotation speed of the propellers could be adjusted at the values of 3000, 6000, 7500, 9000, 10500 and 12000 rpm corresponding to a rotation frequency of 50, 100, 125, 150, 175 and 200 Hz, respectively.

Acoustic and thrust measurements of the propeller were performed inside an anechoic chamber as shown in Fig. 1. The inner dimensions of the chamber are 2350×2350×2350 mm and its walls are covered by polyurethane foam acoustic wedges (Illbruck SONEX super) with an absorption coefficient higher than 1.0 for frequencies above 500 Hz. The model was installed at the center of the chamber as shown in Fig. 1 by supporting it about 700 mm above the floor wedges with a pillar firmly fixed for suppressing the influence of any vibration generated by the rotating propeller.

![Figure 1: Schematic of the installation inside the anechoic chamber.](image-url)
The noise was recorded with three Brüel & Kjær Model 4953 1/2 inch condenser microphone with frequency response from 3 to 10,000 Hz (flat from 10 to 3000 Hz) connected to a preamplifier and signal conditioner (Brüel & Kjær Model 2669, and NEXUS 2690-A, respectively). The analog signal of the microphone was sampled at \( f_s = 100 \text{ kHz} \) by a fast analog-to-digital board (National Instruments PXI 6221). Each recording consists of \( 10^6 \) samples. The microphones were installed on a support frame that would allow positioning it around the MAV along a circle of radius \( R = 600 \text{ mm} \). Five equidistant points on the circle were chosen as the measurement points: point 1 is on the vertical below the model, point 3 on the side of the model, point 5 is on the vertical above the model, and points 2 and 4 are at intermediate positions between the ones above. A tachometer was used to measure rotation speed of the propeller.

To avoid aliasing, a Butterworth filter was used to low-pass filter the signals at \( f_{LP} = 0.499f_s - 1 \) (49,899 Hz). The corresponding power spectrograms were computed using a Fourier transform providing a spectral resolution of about 0.76 Hz. The microphones were calibrated using the B&K sound calibrator type 4231, and then the voltage power spectrograms were converted to the power spectrograms of \( p' \hat{p}_{\text{ref}} \), where \( p' \) is the fluctuating acoustic pressure and \( p_{\text{ref}} = 20 \mu Pa \) is the commonly used reference pressure. Converted to decibels and time averaged, these become sound pressure level spectra \( SPL(f) \), where \( f \) is the measured frequency. An A-weighting correction was applied to the SPL spectra to account for the relative loudness perceived by the human ear. The corresponding overall sound pressure level (OASPL) is obtained by integrating the SPL spectra:

\[
\text{OASPL} = 10 \log_{10} \int_0^{f_{\text{upper}}} 10^{0.1 \text{SPL}(f)} \, df
\]

(1)

where \( f_{\text{upper}} \) is the highest frequency of interest which in this study is 10 kHz.

The thrust generated by the propeller was measured by an ATI mini40 load cell SI-20-1 whose force range and accuracy in the measured direction (Z direction) are 60 N (≈ 6000 g) and ± 0.01 N (≈ 1 g), respectively. The analog signal of the load cell was sampled at \( f_s = 5 \text{ kHz} \) by a fast analog-to-digital board (National Instruments PXI 6621). Each recording consists of \( 5 \times 10^4 \) samples, the recorded signal is filtered with a low-pass filter at \( f_{LP} = 20 \text{ Hz} \) and then the mean value of the filtered data is calculated as the thrust of the present propeller system.

## 3. SHROUDING DUCT DESIGNS

Three shrouding ducts with better aerodynamic performance were designed and fabricated. The design parameters of the duct is shown in Tab. 1. And the the duct frame is shown in Fig. 2. The structure of both ducts was fabricated with a 3D printing machine (Stratasys Fortus 250mc) using Acrylonitrile-Butadiene-Styrene (ABS). The duct with a back cavity is shown in Fig. 3. As shown in Fig. 2, there are two types of duct: Duct A and Duct B, the difference between these two ducts are the size of the horizontal airfoil support, duct B is larger than that of the duct A to avoid the duct’s vibrations. The design of the back cavity is suitable for testing multi-layer MPP on this back cavity which supposed to further improve the acoustic performance of the duct.

<table>
<thead>
<tr>
<th>Design parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propeller type (6030) diameter, ( D )</td>
<td>152.40mm</td>
</tr>
<tr>
<td>Distance between propeller and duct wall</td>
<td>( \delta_{\text{tip}} = 0.1% \text{ of } D; \delta = 0.15 \text{mm} )</td>
</tr>
<tr>
<td>Inner diameter of the duct ( D_t )</td>
<td>152.70mm</td>
</tr>
<tr>
<td>Length of the diffuser</td>
<td>( L_d = 40% \text{ of } D; L_d = 61.08 \text{mm} )</td>
</tr>
</tbody>
</table>
4. Results and discussions

Various duct designs were designed, fabricated and tested with the results shown in Fig. 4. Duct B design has relative lower OASPL when compare with duct A design. Thus to suppress the vibration of the whole duct can lead the lower OASPL. While for the duct wall design, the hyper elastic membrane on the duct wall can increase the damping of the whole system, thus it can avoid the fluid-structure interaction. So the duct B with elastic membrane wall has the lower OASPL when compared with those of other cases.
Figure 4: Acoustic performance for various duct designs. (a) Measured at point 1; (b) Measured at point 2; (c) Measured at point 3; (d) Measured at point 4; (e) Measured at point 5.

The thrust performance of the duct designs are plotted in Fig. 5. Duct B design with the elastic membrane can increase thrust about 16% which is due to the small gap between the propeller tip and the duct wall. The thrust can be further improve if the gap can be even small which up to 100% as the theoretical prediction.

Figure 5: Thrust performance for various duct designs.

The parameters of the MPP plate is chosen as diameter $d=0.5\text{mm}$, thickness of the carbon plate is $t=0.22\text{mm}$ and the open ratio is about 0.785%. The transmission loss of such silencer design with two kinds of back cavities is shown in Fig. 6. Larger depth of the back cavity can lower the attenuation band of the silencer but it requires more installation space. The double layer MPP can shift the peak of the attenuation band to the low frequency range which can improve the performance of the whole design.
5. Conclusions

A light weight duct silencer design is primarily explored in the present paper. The main conclusions are listed in the following: 1) Duct B with larger airfoil horizontal support part can improve its acoustic performance; 2) The duct wall the hyper elastic membrane do avoid some of the fluid structure interactions, thus it does not increase the noise level; 3) silencer design with suitable parameters are studied. All these designs will be further investigated for installing around the propeller.

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