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A LIGHT-WEIGHT ACOUSTIC SILENCER DESIGN FOR A MULTI-ROTOR MAV

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Multi-rotor Micro Air Vehicles (MAVs) have been the subject of increased attention in the past decade because of their unique military and civilian potential applications, but in propeller-based propulsion systems, the noise generated from the propeller can be significant and thus affect MAVs detection in surveillance and military applications. In the present paper, shrouded ducts with various structure and wall materials are explored for seeking the optimized duct designs.

Keywords: Micro Air Vehicles (MAVs), propeller noise, silencer, shrouded duct, 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 maneuverability 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 relative 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 proved 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) Seeking the optimized duct structures which does not have strong flow-induced vibrations and noise when being installed around a rotating propeller; 2) Experimentally study on the aero-acoustic performance of the various duct wall materials.

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, 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.

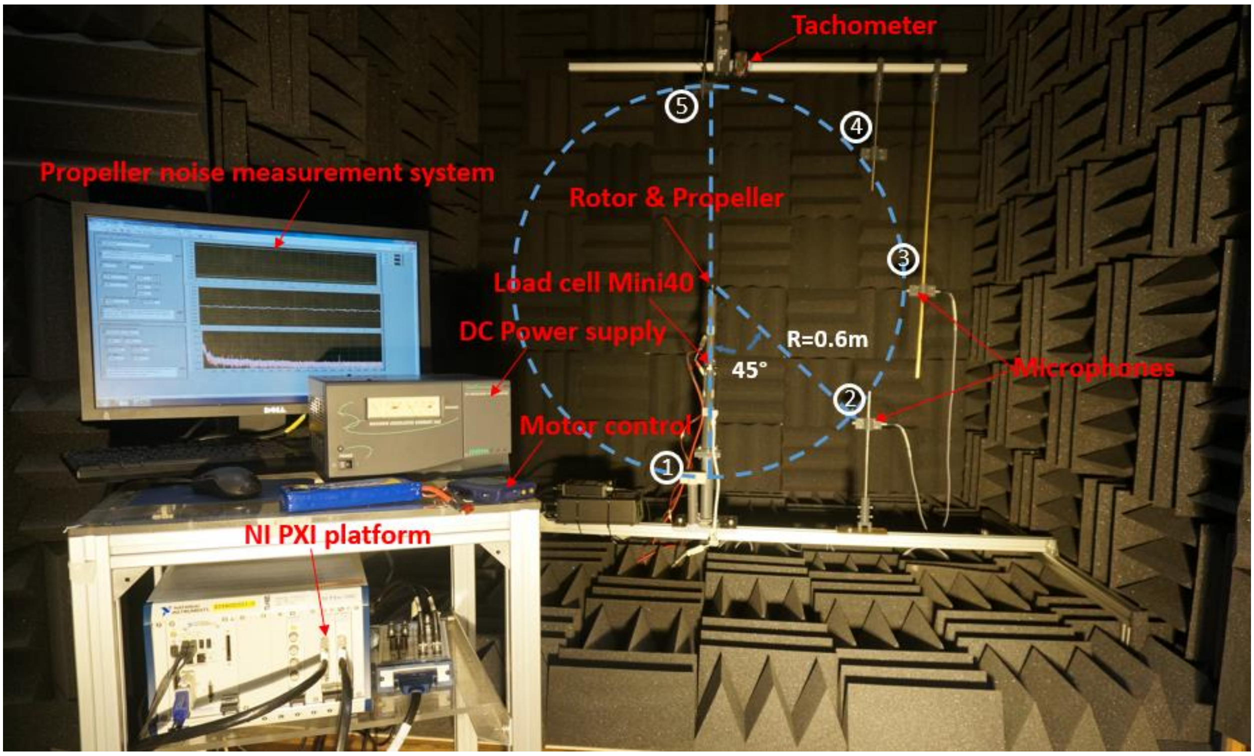


Figure 1: Schematic of the installation inside the anechoic chamber.

The noise was recorded with two 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 kHz by a fast analog-to-digital board (National Instruments PXI 6621). Each recording consists of 10^6 samples. The microphones were installed on a support frame that allows positioning it around the MAV along a circle of radius R = 600 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'/p_{ref}, where p' is the fluctuating acoustic pressure and p_{ref} = 20 μPa 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:

$$\mathrm{OASPL} = 10log_{10}\int_0^{f_{\mathrm{upper}}} 10^{0.1SPL(f)}df \tag{1}$$

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

The thrust generated by the multi-rotor MAV 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 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 Hz and then the mean value of the filtered data is calculated as the thrust of the present propeller system.

3. SHROUDING DUCT AND MICRO-PERFORATED PLATE DESIGNS

Three shrouding ducts with different wall materials have been designed and fabricated, the duct frame is shown in Fig. 2(a). The structure of both ducts was fabricated with a 3D printing machine (Stratasys Fortus 250mc) using Acrylonitrile-Butadiene-Styrene (ABS), the properties of the duct wall materials are given in Tab. 1. Typically, the carbon fiber has the largest density and youngs' modulus, while the foam has the smallest density.

Table 1 - Properties of different materials for the fabrication of shrouding ducts.

Material	Young's modulus (GPa)	Density (g/cm^3)
ABS plastic	2	1.04
Carbon fiber	70	1.59
Depron foam	-	0.033

The internal wall of the duct is cylindrical and has inlet profile consisting of 1/4 circle and outlet profile of a Clark-Y airfoil to provide an aerodynamically clean flow. For the same reason the horizontal rods supporting the duct from the motor housing have the shape of a NACA 0015 airfoil. The smaller the gap between the propeller tip and the duct internal wall, the better the aerodynamic performance of the whole system, however, for the present light weight duct structure, it will vibrate at the high rotation speed, thus the gap between the propeller tip and the duct wall should not be too small. Therefore, the internal radius of the duct is 76.15 mm which is 0.3 mm (or 0.39%) larger than the radius of the propeller (75.85 mm). The total weight of duct frame without back cavity is 17.46g, and the ducts with various duct wall materials ABS plastic, Carbon fiber and Depron foam are 27.76g, 26.45g and 22.00g respectively. Back cavity was designed (Shown in Fig. 2(b)). Also, in order to maintain sufficient strength of the back-cavity wall, its thickness is 1 mm. Nevertheless, these additional components significantly increase the weight of duct which is 49.40g.

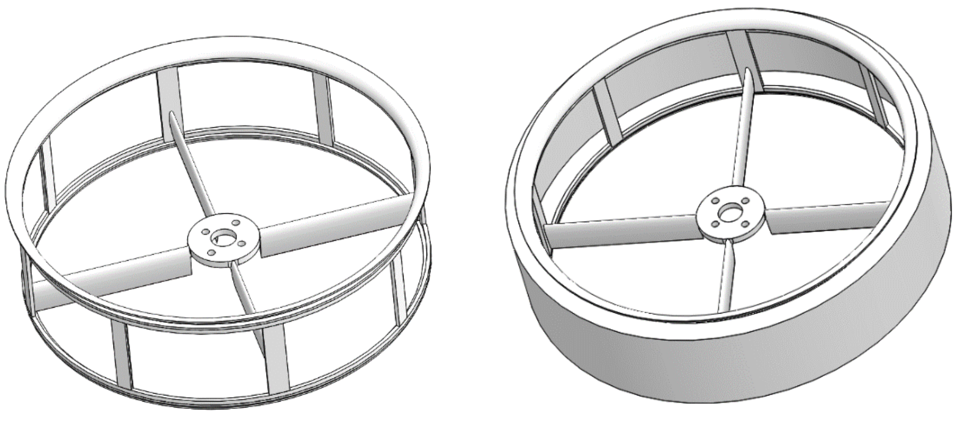


Figure 2: Shrouding duct designs: (a) Duct frame; (b) Duct frame with back cavity.

The design parameters of the micro perforated panel (MPP) are investigated using the Maa's equation. [28] A good MPP design could target the absorption of noise at frequencies lower than 1000 Hz while having an absorption band as wide as possible. The theoretical absorption coefficient of this MPP used in conjunction with both10 mm-depth and 20mm-depth back cavity is plotted in Fig. 3. It is observed that such combination for the 1.5mm Depron has a wide absorption band from 1260 Hz to 3409 Hz and 740Hz to 2758Hz indicating it should absorb the main propeller noise. The micro-perforated holes are on the plate using a CNC milling machine (Woosung M300S CE with cutting resolution of 0.01 mm).

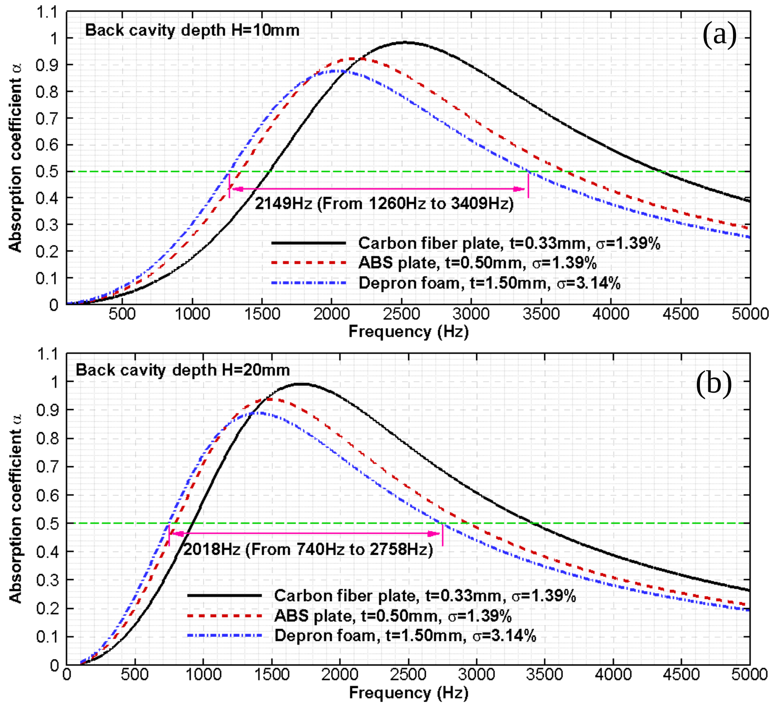


Figure 3: Micro-perforated panel design: (a) Theoretical results for MPP with back cavity of 10 mm depth; (b) Theoretical results for MPP with back cavity of 20 mm depth.

4. Results and discussions

4.1 The effect of the duct structures on the acoustic performance

For the duct design, it has different parts. Thus it should be important to invesigate the effect of these parts on the acoustic performance for the propeller noise. In the present paper, different duct parts are fabricated and tested. And the results are shown in Fig. 4. It is found that the horizontal support with NACA0015 airfoil shape is good design, and it does not generated extra noise when compare with that of the noise generated by the motor and propeller. And the duct frame with 1/4 circular inlet, it is designed for obtaining clean flow for the propeller, but it generates extra noise, thus the main problem for the extra noise generation of such duct design.

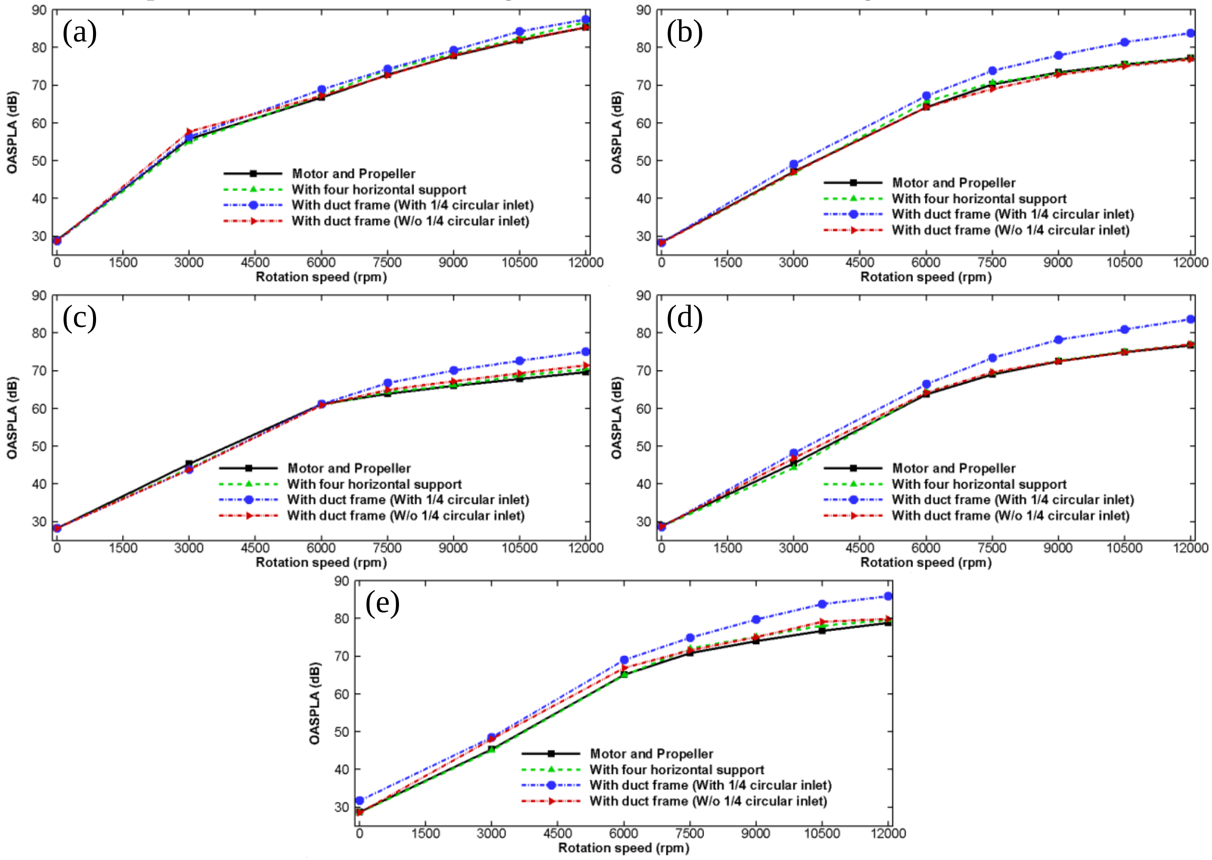
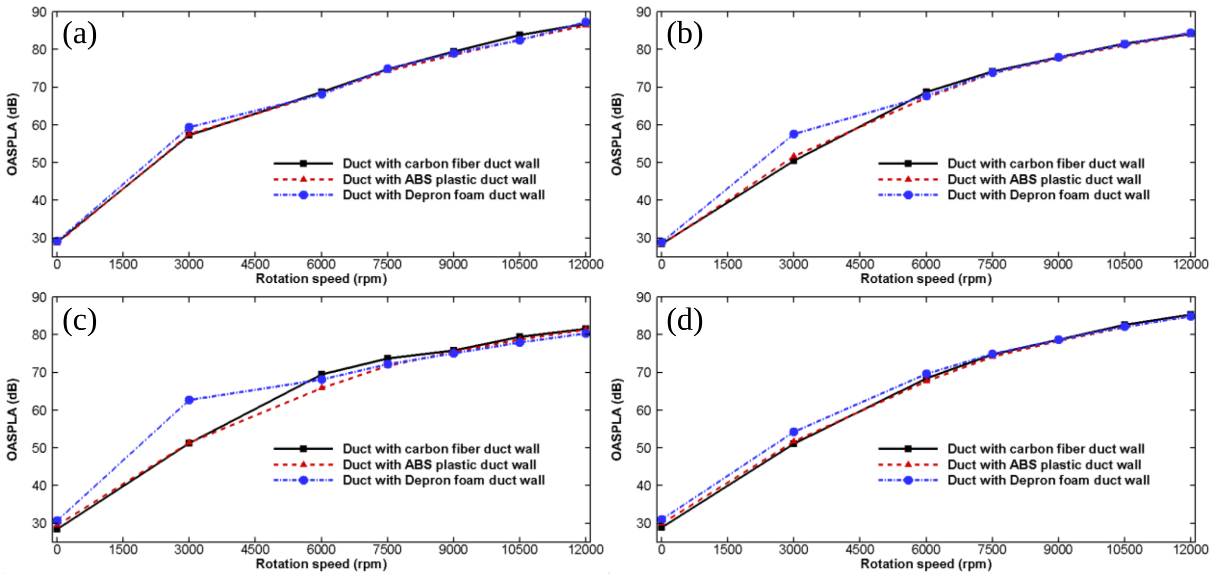


Figure 4: The effect of the duct structures on the acoustic performance. (a) Measured at Point 1; (b) Measured at Point 2; (c) Measured at Point 3; (d) Measured at Point 4; (e) Measured at Point 5

4.2 The effects of the various duct wall materials

It is supposed that different wall materials can have different acoustic performance. While the results shown in Fig. 5 indicate that for all these rigid duct walls, though their Young's modulus and density is different, their acoustic performances are the same. However, if the duct wall material is the hyper elastic materials, the acoustic performance is expected to be different which will be explored in the near future.



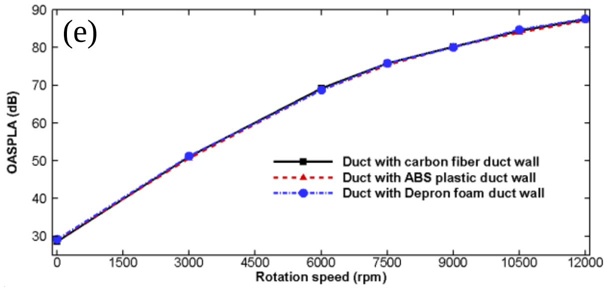


Figure 5: The effect of various duct wall materials. (a) Measured at Point 1; (b) Measured at Point 2; (c) Measured at Point 3; (d) Measured at Point 4; (e) Measured at Point 5

The acoustic performance of a duct with Depron foam duct wall materials. It is found in Fig. 6 that duct wall will generate extra noise. And without the 1/4 circular inlet, the acoustic performance should be better than with 1/4 circular inlet.

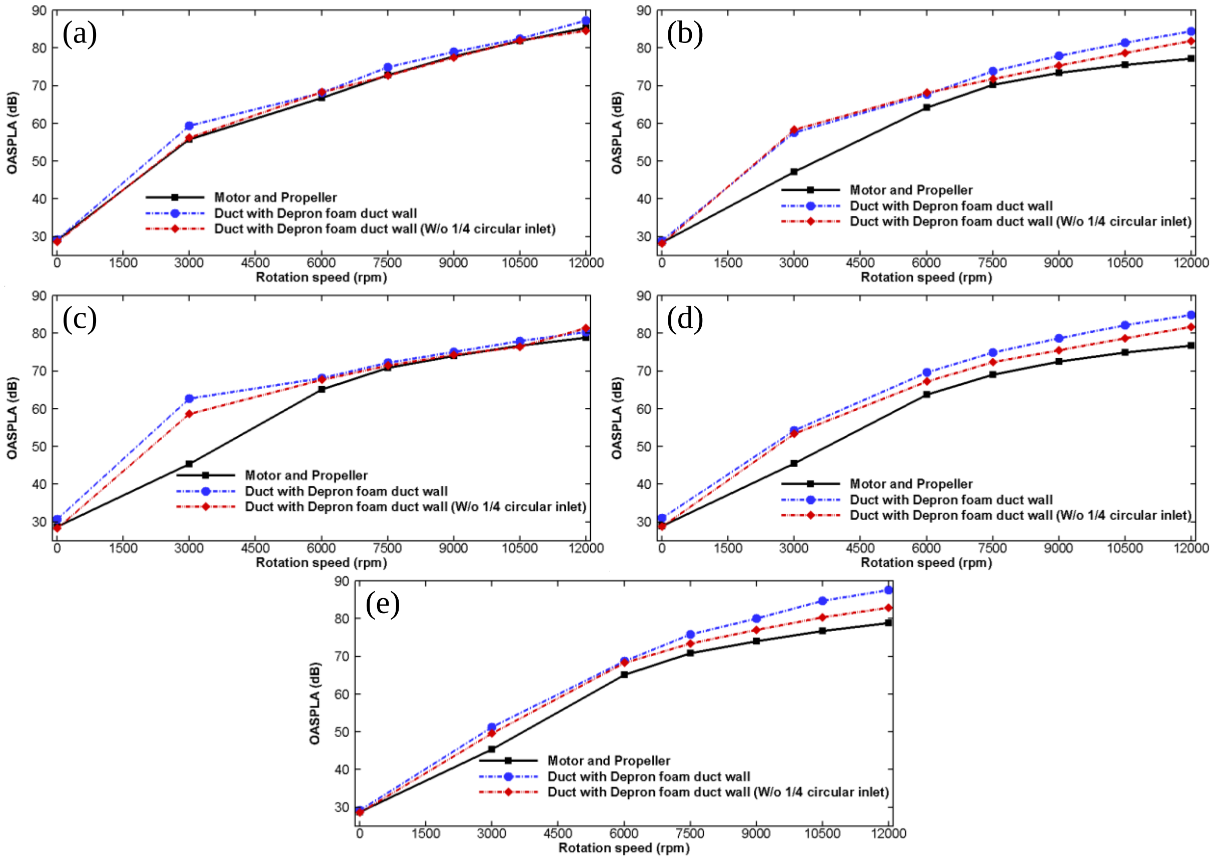


Figure 6: The acoustic performance of the duct with and without the 1/4 circular inlet. (a) Measured at Point 1; (b) Measured at Point 2; (c) Measured at Point 3; (d) Measured at Point 4; (e) Measured at Point 5

5. Conclusions

A light weight duct silencer design is primarily explored in the present paper. The main conclusions are listed in the following: 1) It is found that though the 1/4 circular inlet design is reasonable for smoothing the incoming flow, but the 3D printing cannot has a good surface, therefore, it generates extra noise; 2) Various duct wall materials are tested, it is found that for these rigid duct wall materials, their acoustic performance is the same, so in the design, only need to consider the weight of the materials; 3) Duct wall can generate extra noise, it can be solved by using the hyper elastic materials.

In the next step, the duct design with the micro-perforate duct wall will be fabricated and tested.

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