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EXPERIMENTAL INVESTIGATION INTO THE SUPPRESSION OF PROPELLER NOISE USING OVER-TIP-ROTOR LINERS

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ABSTRACT

This paper presents an experimental study on suppressing propeller noise in a short duct configuration by installing Over-Tip-Rotor (OTR) liners on the wall casing. Far-field noise measurements are reported alongside in-duct pressure measurements at the wall obtained using an axial and azimuthal microphone array installed upstream of the propeller plane. In-duct measurements reveal that the OTR liner is effective in reducing broadband noise, achieving up to 4 dB of noise reduction over 1-5 BPFs. The axial decay of tonal components was compared with an analytical solution based on the Green's function of an axial dipole source, requiring a large number of cut-off modes to match the experimental observations. The findings emphasise the importance of evanescent modes in compact duct acoustics, with direct implications for source modification, scattering effects, and far-field radiation.

Keywords: *OTR liners, propeller noise, noise suppression, ducted rotors*

1. INTRODUCTION

Compact ducted propellers, also known as shrouded propellers, have regained attention in the development of Unmanned Aerial Vehicles (UAVs) and Urban Air Mobility (UAM) solutions due to their potential advantages in thrust augmentation, noise reduction, and operational safety. Several studies have shown that incorporating a duct can lead to a significant increase in thrust compared to an open propeller configuration [1, 2]. The integration of a duct enhances safety by providing a protective barrier or blade containment. This feature is particularly advantageous in densely populated areas where UAVs and UAM vehicles are expected to operate.

Recent studies have investigated the effect of a short duct on propeller noise. Overall noise reductions can be achieved in some conditions, but the effect of the duct on noise radiation can vary significantly between hover and in-flight conditions. Malgoezar et al. [3] conducted experiments on both isolated and shrouded propellers in hover and in-flight conditions. In hover, the use of the duct reduced the Blade Passing Frequency (BPF) tone while increased broadband noise by up to 20 dB. In contrast, the increase in broadband noise was significantly lower in-flight conditions. Cuppoletti and Riley [4] also found an increase in tonal noise at all BPFs and in broadband noise when including a shroud in their experimental investigation of ducted and unducted propellers at hover and at constant RPM. More recently, Go et al. [5] studied a 12-inch propeller experimentally and numerically with and without a shroud, finding that the shroud reduced propeller loading by generating additional thrust. This led to lower tonal noise from the blades in comparison to an isolated propeller. However, while the shroud decreased tonal noise downstream, it increased it upstream compared to an isolated propeller.

Ducted propellers can accommodate the installation of acoustic treatments to further mitigate propeller noise. Acoustic liners are widely used in aero engines, and maximising the treatment area is desirable for noise reduction. The treatment of the area directly above the fan

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casing, i.e., Over-Tip-Rotor/Over-The-Rotor (OTR) liners, has been investigated experimentally by NASA over the last two decades [6] and has shown the potential of this technology to increase the treated area and enhance the suppression of fan noise.

The mechanisms of noise reduction of OTR liners have been investigated analytically [7–9], numerically [10, 11] and experimentally [6, 12] in recent years. The noise reductions are mainly attributed to a combination of: (1) conventional noise attenuation by the liner, which can be enhanced by a larger fluid particle oscillation through the acoustically treated wall due to the close proximity to the fan [8], and (2) source modification effects, which include both acoustic back-reaction effects changing the power output of the source [7, 11], and hydrodynamic changes affecting the unsteady blade loading [8, 10, 12].

Despite OTR liners were originally developed for aero-engine applications, recent work has been carried out to investigate their application for smaller, more compact, ducted propellers for UAV and UAM vehicles. The technology is particularly suitable for such applications due to the much lower area available for acoustic treatments. Some of these works include an experimental investigation by Zhong et al. [13] with OTR side-branch tubes to reduce tonal noise and the numerical work of Zhao et al. [10] showing the influence of the liner on the tip leakage flow.

The current paper is an extension of a previous study by the authors investigating the reduction of shrouded propeller noise with OTR liners [14]. Far-field noise results were presented in [14] for two types of liners - a Single Degree of Freedom (SDOF) liner and a grooved metal foam liner - placed in an OTR position, upstream and downstream of the propeller. The modular shroud used in the experiment featured either a bellmouth intake or an unflanged intake. The geometry of the intake was found to have a major influence on the flow characteristics upstream of the propeller plane and the sources of propeller noise. The study found that OTR liners can reduce overall sound pressure levels by up to 5 dB near the propeller axis, with peak noise reductions in the PWL spectra reaching 6 dB in both tonal and broadband noise. The current study extends this previous investigation by instrumenting the propeller duct with an axial and azimuthal array to gain understanding of the source near-field and how it is impacted by the OTR liner.

2. EXPERIMENTAL SET-UP

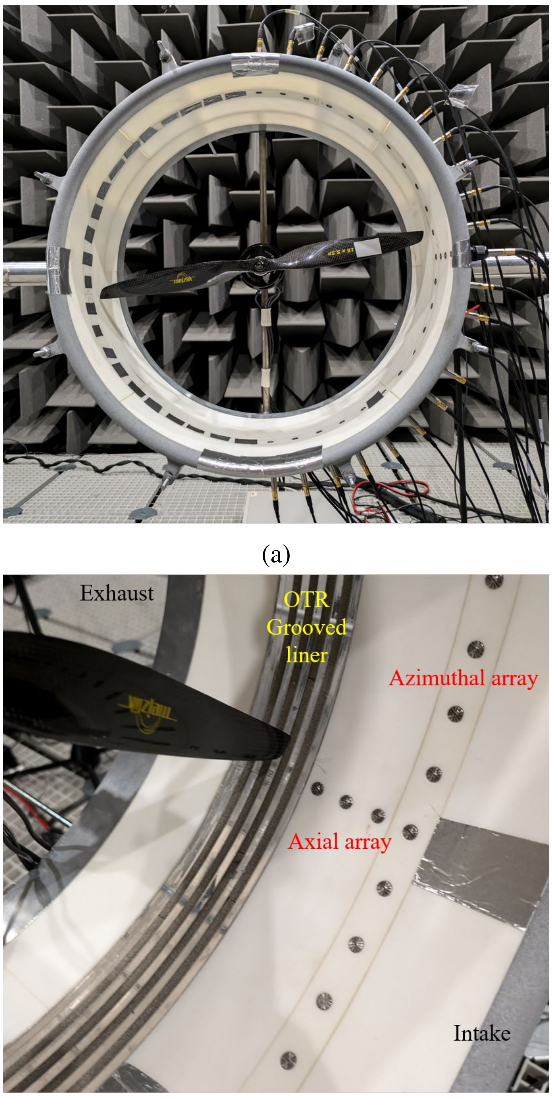
2.1 Shrouded propeller rig

The experiments were carried out on a modular ducted rotor rig with a single propeller, described in [14]. The propeller, motor, and loadcell are held on the shroud axis by a pair of vertical rods. The duct consists of a series of modular sections that allow for varying the length of the shroud, instrumenting the duct with in-duct microphones, installing acoustic treatments in the casing, and modifying the intake geometry. The current investigation was performed with a simple rounded intake and for two configurations: (a) hard wall baseline, and (b) an acoustic liner installed over the propeller tip. The picture of the rig for each configuration is shown in Fig. 1. In both cases, the length of the duct is L = 260 mm and the diameter is D = 410 mm, resulting in a compact ducted propeller configuration with $L/D \approx 0.6$. The propeller is at an axial distance z_{prop} = 105 mm from the duct exhaust.

The rotor was powered by a U7-V2.0 KV420 Brushless T-motor mounted on a MINI45 ATI 6-axis loadcell. The electronic speed controller used in conjunction with the motor was a Master Mezon 135 opto unit. An ICP Laser Tachometer sensor was used to measure the propeller rotational speed (Rotations Per Minute, RPM). A 2-bladed MEJZLIK propeller with a diameter of 16 inches was used in this investigation. All the results in this article were acquired with a constant thrust of the propeller of T = 10 N with a corresponding RPM of approximately N = 4600. The thrust provided by the shroud has not been considered in this investigation.

2.2 Microphone instrumentation

The experiments were carried out at the Institute of Sound and Vibration Research's anechoic chamber of dimensions 6.7 m × 6.7 m × 4.9 m. The walls are acoustically treated with open-cell polyurethane wedges whose cut-off frequency is 70 Hz. Far-field noise measurements were obtained by using 3 1/4" GRAS 40PL-10 CCP microphones located in the forward arc (upstream of the propeller). The microphones were located at a distance of 2.5 m centred on the propeller rig and at polar angles of ϕ = 0°, 45°, and 90°, where 0° is on the propeller axis. In-duct pressure measurements were performed by using an axial and azimuthal array in a cross-configuration, as shown in Fig. 1b. A total of 25 quarter-inch GRAS 40PL-10 CCP microphones were flush mounted on the intake casing, 3 (+1) on the axial array (z_{axial} = 32 − 85 mm upstream of the propeller plane), and 22 in the azimuthal array (z_{azm} = 85 mm upstream of the propeller plane), equally spaced between $\theta = 0°$ and $180°$. The data were acquired for a duration of 10 s at a sampling frequency of 40 kHz.



(a)

(b)

Figure 1: Ducted propeller rig; photograph of the rig with for the (a) hard wall baseline (front view), and (b) OTR liner configuration (detailed view of instrumentation).

2.3 Acoustic liner properties

The acoustic liner considered in this investigation is a grooved liner in which the annular grooves are filled with a nickel chromium alloy metal foam flush with the inner wall of the duct. This is a semi-locally reacting liner that is locally reacting in the axial direction and non-locally reacting in the azimuthal direction, as described in [15, 16]. The liner has a Percentage Open Area POA= 44% [1], a cavity depth d = 17.5 mm and a porosity of the metal foam $\sigma = 90\%$. The total length of the liner module on the tip of the propeller is $l = 50$ mm long, as for the hard-wall baseline configuration.

3. FAR-FIELD NOISE REDUCTION

The aim of this section is to present the far-field noise spectra for the hard wall baseline and the acoustically treated configuration. Results are only presented for the microphone on-axis ($\theta = 0°$) for brevity. The far-field PWL noise spectra integrated in the forward arc and the directivity of these two configurations were presented in the preceding investigation [14].

The Sound Pressure Level (SPL) spectra for the hard wall baseline and lined configurations are shown in Fig. 2a. Measurements of the flow characteristics upstream of the propeller for the 'lip' intake, used in the current investigation, identified a region of flow separation at the lip centred around 90% of the radius [14]. This was related to significantly higher levels of tonal and broadband noise than with a streamlined bellmouth intake that prevents such separation from occurring. The current configuration with the 'lip' intake, therefore, presents stronger tones than the bellmouth, likely caused by the periodic chopping of eddies in the incoming separated flow (tonal) and turbulence leading edge interaction noise (broadband). This discussion is recalled here to explain the strong broadband component of the SPL spectra in Fig. 2a, which becomes dominant over tonal noise from about 10 $\times$ BPF.

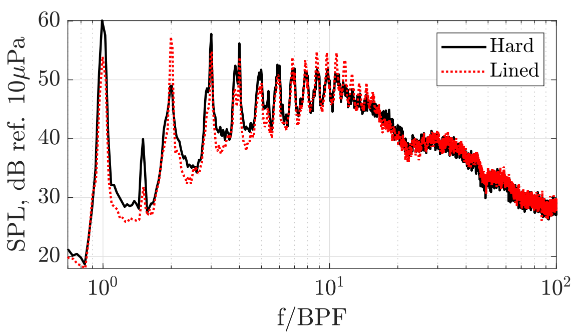
The noise sources outlined above are arguably independent of whether a hard or lined configuration is considered, other than possible hydrodynamic modifications on the source caused by the OTR liner, which shall be discussed in further detail later in the paper. The results in Fig. 2a show that the OTR liner yields modest reductions

[1] This POA only accounts for the grooved area relative to the total liner area and not the open area of the metal foam within the grooves.

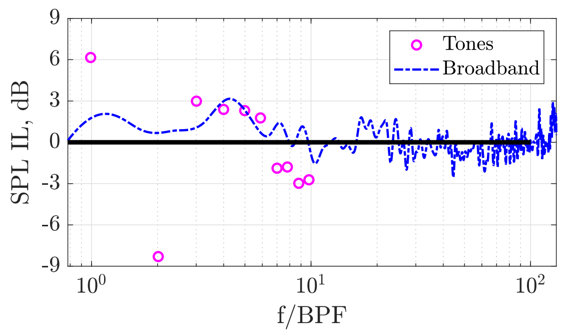
in broadband noise of 1-3 dB at frequencies between BPF and 10 $\times$ BPF. The first BPF tone is reduced by 6 dB, but the reductions are smaller at other harmonics, and the higher harmonics in the liner configuration can even be larger than for the hard wall baseline. The same results are shown in Fig. 2b in the form of SPL Insertion Loss (IL), that is,

$$\mathrm{IL} = \mathrm{SPL_H} - \mathrm{SPL_L} \quad , \quad \mathrm{dB}, \tag{1}$$

where $\mathrm{SPL_H}$ and $\mathrm{SPL_L}$ are the SPLs for the hard and lined configurations, respectively. The SPL IL in Fig. 2b is separated into the tonal and broadband contributions. Tonal SPL IL is only plotted up to 10 $\times$ BPF since broadband noise becomes dominant at higher frequencies. The observations from Fig. 2a are now clearer, and it also becomes evident that a strong noise increase is caused by the liner at the 2 $\times$ BPF tone, with some increase of tonal noise also at 6-10 $\times$ BPF. The broadband noise at frequencies above 10 $\times$ BPF is not significantly affected by the liner at this measurement location on the propeller axis.



(a) Sound Pressure Level (SPL)



(b) Insertion Loss (IL)

Figure 2: Far-field SPL and IL spectra at $\theta = 0°$.

4. IN-DUCT PRESSURE MEASUREMENTS

This section aims to present the pressure characteristics on the duct wall to understand the effect of the OTR liner on the near-field of the source and the propagation in the duct. To highlight the compactness of the problem, key length scales of the problem are compared to the wavelength at BFP ($\lambda \approx 2.2$ m) and harmonics in Table 1, namely duct diameter D, duct length L, and liner length l.

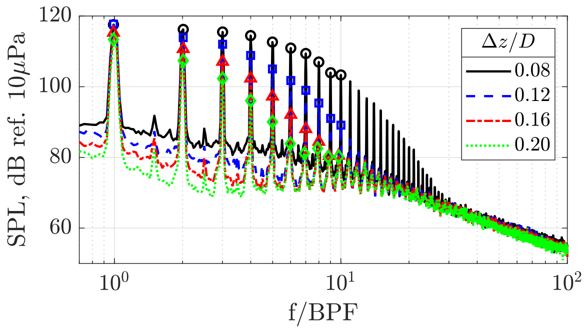
Table 1: Compactness of the problem at BPF and harmonics.

Frequency	D/λ	L/λ	l/λ
BPF	0.18	0.12	0.02
2 $\times$ BPF	0.37	0.23	0.05
3 $\times$ BPF	0.55	0.35	0.07
5 $\times$ BPF	0.92	0.59	0.11
10 $\times$ BPF	1.85	1.17	0.23

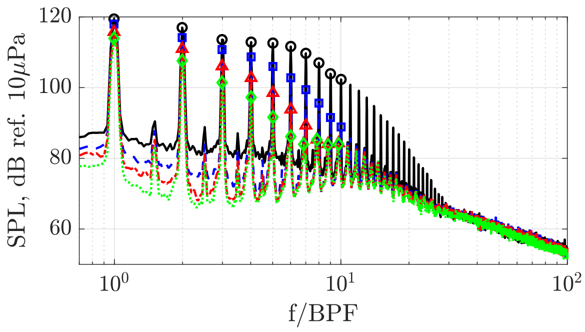
The compactness of the problem highlighted in Table 1 suggests that the role of evanescent or cut-off duct modes excited by the propeller and the struts can have a significant impact on the problem:

- Contributions to the far-field noise from evanescent modes scattered at the intake/exhaust [17].
- 'Trapped' modes in the short duct caused by evanescent modes reflected at the intake/exhaust.
- In the liner case, the effects of the acoustic back-reaction on the source can be significant at these low frequencies (low D/λ), which have been reported to be stronger for $e/\lambda < 0.5$ [7], were e is the distance between the source and the duct wall.
- Also in the case with the liner, scattering of evanescent modes acoustically close to the impedance discontinuity (low l/λ) can have a significant effect on the noise reduction performance [11].

The SPL spectra, measured along the axial array, are shown in Fig. 3a and Fig. 3b for the hard wall and lined configurations. Also shown are the tonal amplitudes of the first 10 BPFs. The distances Δz shown in the legend are relative to the propeller plane. The general trends in both configurations show a rapid decay of the tonal components when increasing the axial separation distance to the source plane Δz. Furthermore, significant decay in broadband noise of up to 10 dB can also be observed in both cases for frequencies below 10 $\times$ BPF.



(a) Hard wall



(b) Lined

Figure 3: Axial variation of the wall SPL spectra for the hard wall and lined configurations.

The decay in tonal SPL at the harmonics of the BPF is found to be close to exponential. The SPL decay for the first 3 BPFs is shown in Fig. 4a for both the hard wall and lined configurations. Also shown is a linear fit of the tonal levels along the array. The decay rates in dB/m are summarised in Table 2. It can be observed that the decay is similar in both configurations, which is expected since these measurements are obtained at the hard wall section upstream of the propeller.

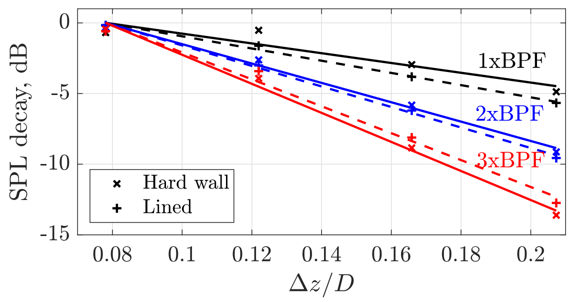
The measured decay of the BPF tone is compared with analytical predictions [7] in Fig. 4b. The predictions are obtained by evaluating the wall pressures at the wall of an infinite hard wall duct containing a point axial dipole located at 95% of the radius. The Green's function formulation used in this instance [7] is obtained from the monopole Green's function in Rienstra and Tester [18]. The number of modes included in the solution is controlled by the Cut-Off Ratio (COR). The definition used here for the COR for a mode with radial wavenumber α, at frequency ω and mean flow Mach number M is

$$\text{COR} = \frac{\alpha\sqrt{1-M^2}}{\omega} \quad . \tag{2}$$

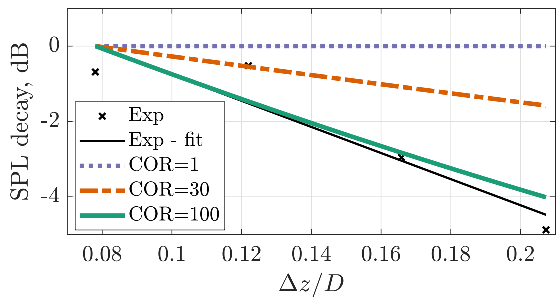
For a given COR, all the modes with α smaller than $\omega\text{COR}/\sqrt{1-M^2}$ are therefore included in the solution.

Table 2: Tonal decay rates in dB/m for the lined and hard wall configurations.

BPF	Hard wall	Lined
1	-84.5	-105.4
2	-167.2	-177.1
3	-250.8	-223.3



(a) Measured decay of the BPF, 2xBPF and 3xBPF tones.



(b) Measured and predicted decay of the BPF tone.

Figure 4: Decay of tonal SPL along the axial array.

The analytical solutions shown in Fig. 4b are obtained with a COR of 1, 30 and 100. For the case with COR=1, only cut-on modes are included in the solution.

At the BPF frequency, only the plane wave is cut-on. The other two cases, COR=30 and COR=100, include a certain number of evanescent modes. At the BPF frequency, COR=30 corresponds to a total of 20 evanescent modes included in the solution and COR=100 corresponds to a total of 425. The comparison in Fig. 4b shows that a large number of evanescent modes are required in the analytical solution to obtain the rapid decay observed in the experiment. This result highlights the importance of the cut-off modes in the current problem and the need for further investigation to clarify its impact on the noise reduction characteristics of OTR liners and the noise radiation to the far-field.

The Insertion Loss spectra are presented in Fig. 5 to appreciate more clearly the effect of the OTR liner in the in-duct pressure field. It is observed that the liner only has a modest effect of ± 2 dB in the tonal noise, and that the variation across different axial locations is within 2 dB. In contrast, 4 dB of broadband noise reduction can be observed at most microphone locations for frequencies below 10 $\times$ BPF, with some variation across the array. In particular, weaker reductions are observed in the microphone closest to the propeller plane ($\Delta z = 0.08$).

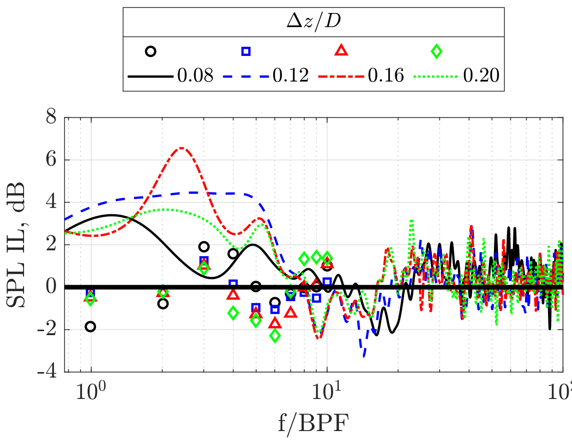
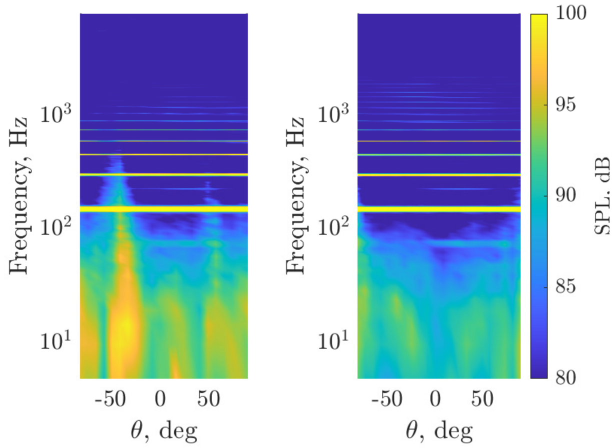


Figure 5: Axial variation of the Insertion Loss measured at the duct wall.

Very little variation in SPL IL would be expected between microphones in the axial array since they are all located in the hard wall section upstream of the liner. The differences observed in Fig. 5 may therefore be attributed to a different distribution of the modal amplitudes between the hard wall and lined case between the two configurations caused by (1) changes on the source caused by the OTR liner (source modification effects), and/or (2) modal scattering at the impedance discontinuity between the OTR liner and the hard wall section.

The azimuthal microphone array is now used to show the SPL spectra variation along the circumference over the 180° aperture of the array. This is presented in the form of contour plots in Fig. 6a and Fig. 6b for the hard wall and lined configurations, respectively. The wall pressure fluctuations around the duct present significant non-uniformity, especially at low frequencies below the first BPF, with up to 10 dB variations along the circumference. These results suggest significant non-uniformities in the flow field, potentially caused by the separation at the inlet lip, the development of the boundary layers, or non-uniformities in the impinging flow itself. Further investigation is needed to characterise the flow in the duct and provide insights into this discrepancy. However, the frequencies at which the liner has been found to be most effective in reducing noise in the far-field and in the in-duct axial array results are not affected by this contamination (the axial array is located at $\theta = 0°$).



(a) Hard wall (b) Lined

Figure 6: Azimuthal variation of the wall SPL spectra for the hard wall and lined configurations.

5. CONCLUSIONS

This paper has presented an experimental investigation on the reduction of propeller noise with Over-Tip-Rotor liners on a modular compact ducted propeller rig. In-duct wall pressure measurements indicate that OTR liners are effective in reducing broadband noise, yielding some 4 dB of noise reduction at frequencies between BPF and 5xBPF. This is in contrast to a modest effect of the liner of only ± 2 dB in tonal noise. Conversely, the far-field results (on axis) show up to 6 dB of noise reduction at the BPF tone and almost 9 dB of noise increase at the 2xBPF tone. The axial decay in the amplitude of the tones was compared to an analytical solution based on the Green's function of an axial dipole source. A large number of cut-off modes were required in the analytical solution to match the decay observed in the experiments. The main observation of this investigation is the importance of the evanescent modes in such compact ducts. This has direct implications for the source modification and scattering effects associated with OTR liners and in the radiation of these evanescent modes to the far-field. Future work is planned to understand the flow non-uniformities in the duct and the sources, as well as to investigate further the role of evanescent modes in hard and lined compact ducts.

6. ACKNOWLEDGMENTS

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7. REFERENCES

[1] S. Yilmaz, D. Erdem, and M. S. Kavsaoglu, "Performance of a ducted propeller designed for UAV applications at zero angle of attack flight: An experimental study," *Aerospace Science and Technology*, vol. 45, pp. 376–386, 2015.

[2] T. Zhang and G. N. Barakos, "High-fidelity numerical analysis and optimisation of ducted propeller aerodynamics and acoustics," *Aerospace Science and Technology*, vol. 113, p. 106708, 2021.

[3] A. M. Malgoezar, A. Vieira, M. Snellen, D. G. Simons, and L. L. Veldhuis, "Experimental characterization of noise radiation from a ducted propeller of an unmanned aerial vehicle," *International Journal of Aeroacoustics*, vol. 18, no. 4-5, pp. 372–391, 2019.

[4] D. R. Cuppoletti and T. Riley, "Time-Resolved Flow Field and Acoustic Measurements of a Ducted and Unducted Rotor," in *28th AIAA/CEAS Aeroacoustics Conference, 2022*, 2022.

[5] S. T. Go, M. J. Kingan, Y. Wu, and R. N. Sharma, "Experimental and numerical investigation of the sound field produced by a shrouded UAV propeller," *Applied Acoustics*, vol. 211, p. 109523, 2023.

[6] D. L. Sutliff, R. F. Bozak, M. G. Jones, and D. M. Nark, "Investigations of three over-the-rotor liner concepts at various technology readiness levels," *International Journal of Aeroacoustics*, vol. 20, no. 5-7, pp. 826–866, 2021.

[7] S. Palleja-Cabre, B. J. Tester, and R. J. Astley, "Modelling of ducted noise sources in the proximity of acoustic liners," *Journal of Sound and Vibration*, vol. 517, no. October 2021, p. 116548, 2022.

[8] Y. Sun, X. Wang, L. Du, and X. Sun, "On the flow-acoustic coupling of fan blades with over-the-rotor liner," *Journal of Fluid Mechanics*, vol. 941, pp. 1–35, 2022.

[9] S. Palleja-Cabre, B. J. Tester, and R. J. Astley, "Modeling of Over-Tip-Rotor Liners for the Suppression of Fan Noise," *AIAA Journal*, vol. 60, no. 11, pp. 6361–6373, 2022.

[10] P. Zhao, Z. Zhao, and C. Yang, "Investigation of the orifice flow of over-the-rotor liner and its interaction with the rotor flow field," *Physics of Fluids*, vol. 35, no. 10, 2023.

[11] R. R. Subramanyam, S. Palani, P. Chaitanya, and S. Palleja-Cabre, "On the noise reduction mechanisms of over-tip liners," vol. 43, pp. 29–43, 2024.

[12] S. Palleja-Cabre, I. Saraceno, and P. Chaitanya, "On the modification of tip leakage noise sources by over-tip liners," *Physics of Fluids*, vol. 36, no. 2, 2024.

[13] T. Zhong, C. Yang, and M. Åbom, "Tonal noise reduction of an electric ducted fan using over-the-rotor acoustic treatment," *Applied Acoustics*, vol. 205, p. 109298, 2023.

[14] S. Palleja-Cabre, E. Macey, P. Chaitanya, and P. Joseph, "Reduction of shrouded propeller noise with Over-Tip-Rotor liners," in *30th AIAA/CEAS Aeroacoustics Conference, 2024*, vol. AIAA 2024-, pp. 1–14, 2024.

[15] S. Rienstra, "Contributions to the theory of sound propagation in ducts with bulk-reacting lining," *Journal of Acoustical Society of America*, vol. 77, no. 5, pp. 1681–1685, 1985.

[16] S. Palleja-Cabre, B. J. Tester, R. J. Astley, and H. Beriot, "Impedance modelling of acoustically treated circumferential grooves for over-tip-rotor fan noise suppression," *International Journal of Aeroacoustics*, vol. 0, no. 0, pp. 1–17, 2020.

[17] B. Baddour, P. Joseph, A. McAlpine, and R. Leung, "Acoustic radiation characteristics of cutoff modes from ducts," *Journal of Sound and Vibration*, vol. 541, no. June, p. 117306, 2022.

[18] S. W. Rienstra and B. J. Tester, "An analytic Green's function for a lined circular duct containing uniform mean flow," *J. Sound Vib.*, vol. 317, no. 3-5, pp. 994–1016, 2008.