Acoustic Shielding and Scattering Effects of a Propeller Mounted Above a Flat Plate

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ABSTRACT
Experiments were carried out within an aeroacoustic wind tunnel facility to investigate acoustic scattering and shielding effects of a propeller being placed above a semi-infinite flat plate. The position of the flat plate trailing edge was adjusted relative to the propeller which was tested in static conditions with a constant rotational rate of 5000 RPM. Far-field noise was collected by a pair of microphone arcs in the reflection and shadow zone regions respectively. Effects of installation on the overall sound pressure level and first blade passing frequency tone was studied. Moreover the magnitude-squared coherence and cross spectrum phase data between selected microphone pairs were analysed. Significant amplification and attenuation can be observed with changing relative locations due to complex acoustic interactions between the propeller and flat plate surface and trailing edge. There are locations with significant potential for noise attenuation and directivity manipulation in terms of tonal and broadband noise content of the propeller. Appreciable changes in

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The first blade passing frequency phase was seen when installed cases were compared to the baseline isolated propeller case. Reductions of up to 16.3 dB in the first blade passing frequency tone due to the presence of notable shielding were observed.

1. INTRODUCTION

With the push towards greener aviation, electrification of aircraft is being pursued by governments, industry and academia worldwide [1]. Design choices as a result of these efforts are increasingly capitalising on the numerous potential benefits of propeller-based propulsion architectures. Unlike conventional jet fuel powered aircraft, where jet fuel consumption will reduce the weight during flight, electric battery powered aircraft masses will remain constant [2]. A benefit of propellers is their low thrust specific fuel consumption which when paired with current limitations on battery storage and weight is vital for increasing the range of aircraft [3].

Concepts such as Leading Edge Asynchronous Propellers Technology (LEAPTech) which consists of multiple tractor propellers mounted at the leading edge of a wing have drawn attention through increasing the maximum lift coefficient of aircraft; offering maximum range at cruise conditions while maintaining takeoff and landing performance [4]. Engine failure in these concepts could have severe impacts on the stall behaviour of the aircraft [5] along with a noise penalty associated with the design [6]. As such, concepts such as a wing trailing edge mounted distributed propulsion system have been proposed [5].

Through positioning propellers on aircraft wings, complex aerodynamic and acoustic interactions of propellers with wing and airframe structures will be introduced. Noise generated by the propellers will radiate and interact with any adjacent structures leading to scattering of the sound waves produced. In addition, by incorporating structures such as wings as a physical barrier between the propeller noise source and the ground, potentially beneficial acoustic shielding effects can minimise the noise generated by engines and propellers and alter the directivity and magnitude of the noise generated. Many existing studies explore the aerodynamic and aeroacoustic performance of isolated propellers in various modes of operation such as in hover, transition and forward flight [7–9]. Limited existing literature considers the noise scattering and shielding effects due to interactions between propellers and wings or the more fundamental case of propeller-flat plate interactions.

Agarwal and Dowling [10] utilised boundary element calculations using a point monopole source above two dimensional geometries and a three dimensional "Silent Aircraft" geometry to evaluate acoustic shielding effects for low frequencies. Their results indicated a significant amount of shielding can be obtained in the shadow region where there is no direct line of sight between the noise source and observer. Müller et al. [11] also utilised boundary element method simulations to evaluate an over-the-wing propeller configuration and compared its performance to a conventional tractor setup in cruise conditions. Their simulations showed a reduction of 6 dB in the SPL on the ground when compared to a conventional configuration.

Stephens and Envia [12] explored the barrier theory and half-plane diffraction theory for shielding attenuation by conducting experiments with an open rotor positioned over a simplified wing. They found a short barrier positioned near the open rotor could provide up to an 8.5 dB reduction of noise at some directivities with tonal noise shielded in particular. Neither of the theories they compared to gave accurate results; over-predicting the attenuation levels.

More recent studies by Viera et al. [13] investigated experimentally the level of shielding and directivity of the noise source and its relation to the shielding body geometry. Their experiments considered a monopole source shielded by a flat plate and a NACA 64-008 A wing, and a propeller shielded by the same wing. Experimental results in these configurations were compared to a noise shielding prediction model based on the Kirchhoff integral theory and the Modified Theory of Physical Optics (MTPO) [14]. When a dipole approximation was used to model the propeller, the best agreement with experimental data was found.
Carley [15] presented an analysis of far-field noise from a rotating source placed near the edge of a semi-infinite plate. The analytical model he developed considered both shielding of noise from a wing and any scattering effects by the trailing edge. The model was found to compare favorably to a full numerical evaluation of the acoustic field.

The present study aims to improve our understanding of propeller-airframe interaction with a fundamental propeller-flat plate set-up. By studying experimentally the impact of propeller location with respect to the trailing edge of a flat plate, it is hoped that further insights into the acoustic scattering and shielding which takes place when a propeller is mounted on a wing will be uncovered. The paper is organized as follows: Section 2 explains the experimental methodology with descriptions of the experimental facility, the test rig and experimental set-up as well as the data acquisition; Section 3 provides the results of the experiments and discussion. Section 4 concludes the manuscript.

2. EXPERIMENTAL METHODOLOGY

2.1. Experimental Facility

The experimental tests were carried out in an open jet, close-circuit aeroacoustic wind tunnel at the University of Bristol. The wind tunnel has an acoustically treated interior and is fully anechoic down to 160 Hz. The interested reader is advised to refer to Mayer et al. [16] for a full description of the facility.

Two far-field, 14-element polar microphone arrays were mounted on the sides of the test setup positioned 1 m from the centre of the propeller plane of rotation, as shown in Figure 1. The arrays consisted of ¼ inch diameter GRAS 40PL free-field microphones with a flat frequency range from 10 Hz to 20 kHz and an upper limit of 142 dB. These side arrays offered far-field noise measurements between \( \theta = 20^\circ \) and \( \theta = 150^\circ \) on both sides of the flat plate (see definition of polar angle in Figure 1). Each microphone array was centred on the primary noise source, the propeller hub.

![Figure 1: Schematic of the test setup giving a simplified view of the set-up with various parameters labelled. Two 14-element microphone arrays located in the shadow zone and reflection zone are visible.](image)

2.2. Test Rig and Set-up

In the present study, noise scattering and shielding characteristics were investigated between a semi-infinite flat plate and a propeller. The two-bladed carbon fibre propeller has a diameter, \( D \), and a fixed pitch of 0.2286 m. The propeller was driven by a 40 A T-Motor Antigravity MN4006 brushless DC motor. The motor had 24 poles and was selected to drive the propeller to avoid any structural
resonance and to reduce the noise characteristics of the motor as much as possible [17]. Control of the motor and propeller was achieved by adjusting the throttle of an electronic speed controller (ESC) to change the rotational rate, $\Omega$. An ICP laser tachometer was used to provide a one-per-revolution signal to accurately determine $\Omega$ via a National Instruments LabVIEW control system. A 6-component ATI mini40 multi-axis load cell was fitted behind the motor to collect thrust and torque data. The propeller test rig has been used successfully in previous studies which can offer more detail on the test setup [7, 9, 18].

The propeller test rig was positioned in the middle of the anechoic chamber and acoustic characterisation of the propeller was performed in static flight conditions. During the test, noise data were collected for $\Omega = 5000$ RPM. A flat plate with a height of 1.5 m (6.56 D), length of 1.7 m (7.44 D) and thickness of 0.012 m (0.052 D) was translated parametrically, changing the distance between the plane of rotation of the propeller and the flat plate trailing edge. Throughout the tests the propeller was kept in the same location, with the flat plate moved in the L and H directions (see Figure 1). The flat plate is hereon referred to as "semi-infinite". The full test metrics can be seen in Table 1.

Table 1: Summary of the key parameters varied in the experiments conducted.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating D (m)</td>
<td>0.2286</td>
</tr>
<tr>
<td>Condition $\Omega$ (RPM)</td>
<td>5000</td>
</tr>
<tr>
<td>Location $L/D$</td>
<td>-1, -0.8, -0.4, -0.1, 0, 0.1, 0.4, 0.8, 1, 1.5, 2</td>
</tr>
<tr>
<td>$H/D$</td>
<td>0.6, 0.75, 1</td>
</tr>
</tbody>
</table>

2.3. Data Acquisition

The noise measurements from all far-field microphones were collected simultaneously with PXI-4499 sound and vibration modules using a National Instruments data acquisition system. The far-field microphone data were sampled at a frequency of $2^{16}$ Hz for a duration of 16 s.

The noise data in this paper is presented in terms of the frequency-dependent energy content of the pressure fluctuations, this is defined as the Sound Pressure Level (SPL):

$$SPL = 10 \log_{10} \left( \frac{\phi_{pp}}{p_{ref}^2} \right),$$

where $\phi_{pp}$ is the power spectral density of the measured far-field pressure fluctuations and $p_{ref}$ is the reference sound pressure of $2 \times 10^{-5}$ Pa. The power spectral density was determined for the pressure fluctuations by using Welch’s method [19]. Through the application of a Hanning window and by segmenting each time-series data into 32 equal lengths with 50% overlap. As such, a frequency resolution of $\Delta f = 1$ Hz was achieved. The Overall Sound Pressure Level (OASPL) was calculated by integrating the SPL spectra with respect to the frequency from 160 Hz to 20000 Hz corresponding to the facility cut off frequency and the maximum frequency of human hearing [20].

3. RESULTS AND DISCUSSION

In this section, the results for the varying acoustic performance of the propeller are presented. The effects of moving the propeller parametrically along the semi-infinite plate surface in terms of L and H are shown. Insights into the noise scattering and shielding mechanisms present when the propeller is placed close to the flat plate are discussed.
3.1. Far-Field Results

In order to determine the effects of acoustic shielding and scattering when a propeller is in operation close to a flat plate surface, a baseline acoustic performance must be established with which cases can be compared. The noise spectrum of the propeller operating in isolation without any plate interaction is presented in Figure 2, in order to evaluate the baseline acoustic characteristics of the propeller as well as any potential sources of contamination.

![Noise Spectrum](image)

Figure 2: SPL for the isolated propeller running at 5000 RPM compared to the unloaded motor noise in static conditions. The data were collected by the $\theta = 90^\circ$ microphone with the results presented in terms of the frequency domain and the blade passing frequency number ($m$).

The propeller sound pressure spectrum of the microphone signal at the plane of rotation is compared with the unloaded motor noise in Figure 2; it is clear that there is minimal noise contamination from the motor overall. There is a region between 1500 - 2000 Hz which shows some contamination as well as in the high frequency region of 8000 Hz and above. In the lower frequencies there is minimal contamination of the results and they can be considered reliable. It is worth noting that due to the chamber anechoic frequency range, results lower than 160 Hz will be less reliable than at higher frequencies.

The noise spectrum presented in Figure 2 contains both tonal and broadband noise which can be attributed to the propeller loading and thickness noise along with airfoil self-noise. To simplify the interpretation of the tonal components of the noise spectra at low frequencies, the far-field noise results are presented on the right hand side of Figure 2 in terms of the blade passing frequency number, $m$, i.e. $m = f / BPF$. A dominant spectral peak is observed at the first blade pass frequency (BPF) as indicated at $m = 1$ or 166.67 Hz, the BPF harmonics can be also seen at $m = 2$ and 3; corresponding to 333.33 Hz and 500 Hz respectively. The harmonics are less prominent at $m = 2$ and 3, with the third harmonic almost completely masked by the low-frequency broadband noise. Below 160 Hz there is also a sub-harmonic of the BPF peak at $m = 0.5$ or 83.33 Hz which is associated with the shaft rate noise.

3.2. Overall Sound Pressure Level

The data for each spatial location and microphone directivity within the parametric study can be aggregated into OASPL polar plots. By plotting the OASPL we can easily inspect the noise magnitude and directivity trends of the propeller when a flat plate is introduced to the system.

The directional behavior of OASPL of the propeller-plate interaction noise for different spanwise locations ($L/D$) is plotted in Figure 3. The propeller to plate surface distance is fixed at $H/D = 0.6$. 
The OASPL is presented for both the shielded shadow zone and unshielded reflection zone to reveal the shielded and reflected noise characteristics compared to the isolated propeller case. In general the noise directivity follows a cardioid shape with undulations for both the isolated and installed cases. The general shape of the installed cases follows that of the isolated propeller with minor magnitude variations across $\theta = 30^\circ$ to $\theta = 150^\circ$. The noise radiates towards the upstream, near plane of rotation, and downstream emission angles. The highest noise level is observed when the propeller is at the trailing edge of the plate for both shadow and reflected zones ($L/D = 0$). Further increase in $L/D$ leads to a decrease in sound pressure level and reaches the minimum for $L/D = 2$ at the reflected zone. An increase in the spanwise location of the propeller is less sensitive in decreasing the noise level at the reflected zone. In all cases where the propeller is in close proximity to the flat plate, the noise in the reflection zone increases compared to the isolated case from 1 to 3 dB in all directivities.

![OASPL plotted for a variety of L/D locations.](image)

Within the shadow zone there is a significant noise decrease observed when the flat plate is introduced. The level of noise reduction typically intensifies as $L/D$ increases, showing the increasing amount of acoustic shielding occurring. At the larger angles from $\theta = 120^\circ$ to $\theta = 150^\circ$ the OASPL drops from the isolated case in a roughly linear manner with increasing $L/D$. There is a transition towards more complex behaviour moving from $\theta = 90^\circ$ to shallower angles of $\theta = 20^\circ$, in the shadow zone. Each of the $L/D$ locations between $L/D = 0$ to $L/D = 1$ begin, apart from $L/D = 0.4$, to converge as the angles become sharper towards $\theta = 20^\circ$. While at $L/D = 2$, where one can expect a maximal amount of acoustic shielding and minimal interaction with the flat plate trailing edge, the directivity pattern is analogous to the isolated propeller in terms of its variations across the polar angles. There is a large drop across all of the directivities of up to 11.5 dB at this spanwise location. At $L/D = 0.4$ the noise level and directivity pattern are drastically different from the other results. $L/D = 0.4$ is the quietest propeller location between $\theta = 60^\circ$ and $\theta = 20^\circ$ with a maximum noise reduction of 11.7 dB in the shadow zone. The distinct behaviour at $L/D = 0.4$ indicates the presence of a more complex interaction between the propeller and the flat plate trailing edge beyond the impacts of pure acoustic shielding.
3.3. Blade Passing Frequency

To further investigate the complex interactions taking place between the propeller and the flat plate, it is useful to isolate the dominant tonal noise contributions in the low frequency range. In real world applications, low frequency tonal noise reduction in designs is essential for public acceptance and certification as factors such as tonality will create the most annoyance to the public from rotors [21]. The directivity of the sound pressure level peak at m = 1 is plotted in Figure 4 for different L/D cases; the baseline isolated propeller case is also included. Unlike OASPL directivity, the BPF is directed towards the plane of rotation for the isolated propeller. However, when the plate is introduced, propeller-plate interactions have a considerable impact on the direction of BPF tonal noise propagation.

\[
\text{Isolated} \quad L/D = 0 \quad L/D = 0.1 \quad L/D = 0.4 \quad L/D = 0.8 \quad L/D = 1 \quad L/D = 2
\]

<table>
<thead>
<tr>
<th>L/D</th>
<th>SPL(_{m=1}) (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Reflection Zone</td>
</tr>
<tr>
<td>0.1</td>
<td>Shadow Zone</td>
</tr>
</tbody>
</table>

Figure 4: SPL at m = 1 for a variety of L/D locations.

In the reflection zone, in line with the trends seen in the OASPL directivities, the flat plate increases the magnitude of the BPF in all of the L/D locations and polar angles up to a maximum of 12.2 dB. The maximum BPF magnitude is at \(\theta = 120^\circ\) for the isolated case at 55.8 dB. The maximum BPF in the reflection zone when the flat plate is introduced is when L/D = 0 and at the same angle of \(\theta = 120^\circ\) with a magnitude of 61.7 dB. Similar to the OASPL trends, the cases in which the plane of rotation of the propeller was close or in line to the flat plate trailing edge (L/D = 0, 0.1) gave significant noise increase in the BPF tone; up to 4 dB greater than the cases with larger L/D values (L/D = 0.4, 0.8, 1, 2). This suggests that there is a scattering interaction between propeller and trailing edge which influences the BPF tonal intensity in the reflection zone. As the propeller moves further away from the trailing edge the dominant interaction with the flat plate will gradually become the reflection from the plate surface and there will be a smaller degree of interaction with the trailing edge. It is clear from reflection of the flat plate that the BPF tone increases by at least 1 dB when the flat plate is introduced between the angles of \(\theta = 70^\circ\) to \(\theta = 150^\circ\). The directivity pattern shifts drastically between \(\theta = 20^\circ\) to \(\theta = 70^\circ\) where the noise increases significantly compared to the isolated case. This is likely due to some combination of reflection and trailing edge scattering.

In the shadow zone, the directivity of the BPF tone becomes more complex. Between \(\theta = 90^\circ\)
and $\theta = 150^\circ$ the presence of the flat plate reduces the BPF noise at all of the L/D locations. The largest reduction in the BPF is seen at L/D = 0.4 and $\theta = 100^\circ$ with a reduction of 16.3 dB. L/D = 0.4, much like the trends seen in the OASPL plots in Figure 3, shows aberrant behaviour compared to the other plate locations. It is clear that generally the flat plate interactions reduces the tonal noise in the directivities behind the propeller plane of rotation ($\theta > 90^\circ$). With the overall noise reduction being most significant at shallow angles ($\theta < 90^\circ$) this suggests that there is a large amount of high frequency broadband noise reduction in these directivities, indeed, at $\theta = 20^\circ, 30^\circ, 40^\circ$ the BPF tone is amplified or similar to the baseline isolated propeller case. L/D = 0.4 shows the most interesting behaviour in the shadow zone, it has the lowest BPF magnitude for most directivities and at angles such as $\theta = 20^\circ$ where the flat plate increases the magnitude of the tone. It is clear there is a complex interaction both in terms of shielding and trailing edge scattering occurring at this location which necessitates further inspection and analysis.

3.4. Coherence and Cross Spectrum Phase

To help shed more light on how the propeller is interacting with the flat plate within the shadow zone and the resulting acoustic effects, the magnitude squared coherence can be estimated to measure the similarity of the unsteady pressure signals being detected between a pair of microphones. Using this, indications of how the pressure waves are interacting in terms of scattering and shielding and thereby affecting propagation of certain frequencies into the far-field can be determined. The magnitude-squared coherence is a function of frequency normalised to yield values between 0 and 1, with 1 showing strong correlation between the signals and 0 showing little to no correlation between the signals. The magnitude-squared coherence, $C_{xy}$, between two signals $x$ and $y$ can be calculated with the following equation:

$$C_{xy} = \frac{|P_{xy}(f)|^2}{P_{xx}(f)P_{yy}(f)}, \quad (2)$$

where $P_{xx}$ and $P_{yy}$ are the power spectral densities of two microphone signals $x$ and $y$, and $P_{xy}$ is the cross power spectral density. The magnitude-squared coherence function was calculated using Welch’s overlapped averaged periodogram method [19].

Additionally, the cross spectrum phase, $\Theta_{xy}$, can be calculated to elucidate the phase relationship between noise signals at each microphone. It can be estimated by considering the real and imaginary parts of the cross power spectral density:

$$\Theta_{xy}(f) = \tan^{-1} \left( \frac{\text{Im}(P_{xy}(f))}{\text{Re}(P_{xy}(f))} \right) \quad (3)$$

Both the magnitude-squared coherence and the cross spectrum phase are plotted in Figure 5 for the $\theta = 50^\circ$ and $\theta = 150^\circ$ microphones in the shadow zone. By plotting the magnitude-squared coherence, significant frequency-domain correlations between both signals can be identified and thereby useful frequency ranges in which phase estimates are valid are ascertained. These directivities were selected as the microphones are located in two regions of the shadow zone with different behaviour both in terms of OASPL and the BPF. By looking at the phase and coherence in this microphone pair further information about the complex interactions between the propeller and flat plate can be determined. In Figure 5 the corresponding magnitude-squared coherence and phase information for the isolated propeller is also plotted to provide a baseline case for comparison.

It is clear from Figure 5 that there is high coherence amongst the majority of low frequency noise signals in each of the L/D cases. Most notably at $m = 1$ there is consistently high coherence values for both isolated and propeller-plate cases regardless of L/D. At L/D = 0.1 there is a small reduction of coherence seen in the BPF.

The cross spectrum phase for the isolated propeller case is close to 0 at the first BPF. Once the flat plate is introduced there is a shift in the phase at the BPF for each L/D case. When the propeller is
in line with the trailing edge of the flat plate at L/D = 0 the phase at \( m = 1 \) shifts more out of phase compared to the isolated case. As the flat plate moves and the propeller is increasingly shielded at L/D = 0.1, the phase becomes more closely matched to the isolated scenario (i.e. more in phase). It then shifts more drastically out of phase once the propeller is positioned at L/D = 0.4 consistent with the rapid changes seen in both the OASPL in Figure 3 and BPF in Figure 4. The BPF phase shifts further out of phase at L/D = 0.8 which then roughly stabilises as the propeller is positioned further into the flat plate towards L/D = 2. The phase shift at L/D = 0, 0.1 and 0.4 is likely to be dominated by scattering interactions with the trailing edge along with some extent of acoustic shielding with the plate surface itself. At L/D = 0.8, 1, 1.5 and 2 the dominant effect will likely be down to shielding with smaller interactions with the trailing edge. The sharp shifting in phase relative to the changes in position in and around the trailing edge suggests a complex scattering interaction which is sensitive to the BPF wavelength and distance from source. With the phase shifting sharply at L/D = 0.4 when moved from L/D = 0.1, it is clear there is a tipping point of the propeller-plate interactions both in terms of shielding and scattering.

To better show the changes in phase with varying values of L/D, the phase difference with respect to the isolated case at the BPF \( \Delta \Theta_{m=1} \) is plotted in Figure 6. The phase difference at L/D = 0.4 shows a change in gradient and drastic shift from 17.3° to 40.4° degrees. The phase difference reaches a maximum at L/D = 0.8 with a value of 68.5°. The phase then seems to roughly stabilise between 49.4° to 68.5° degrees as shielding effects increasingly dominate. Overall it is clear the presence of the flat plate introduces significant phase changes to the BPF which has a dependency on the proximity of the propeller to the trailing edge.

4. CONCLUSIONS

A considerable experimental test campaign was carried out parametrically to investigate the acoustic shielding and scattering effects of a propeller mounted above a semi-infinite flat plate. The experiments were conducted in an anechoic wind tunnel and the acoustic noise has been studied. The results have revealed the presence of complex acoustic scattering and shielding interactions between the propeller and the flat plate trailing edge and surface. Significant levels of noise attenuation was found in multiple directivities of the shadow zone at various propeller positions relative to the trailing edge of the flat plate. In the reflection zone amplification of the noise is seen at all locations. There is significant interactions of the BPF tone with the flat plate and changes have been seen in terms of its magnitude, magnitude-squared coherence and cross spectral phase. The location of L/D = 0.4 shows particular promise in manipulating the directivity and attenuating the noise of the BPF tone. The results signify the importance of propeller location relative to a flat plate trailing edge with indications of interactions necessary for consideration in real world configurations.

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REFERENCES


Figure 5: Magnitude-squared coherence and cross spectrum phase between the $\theta = 50^\circ$ and $\theta = 150^\circ$ microphones plotted for different L/D locations in the shadow zone.
Figure 6: Difference in phase at $m = 1$ between the isolated case and various L/D locations.