# Experimental investigation of the noise emitted by two different propellers ingesting a planar boundary layer

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**Abstract.** Novel-aircraft concepts consider the possibility of placing the propulsor very close to the fuselage to ingest the incoming airframe boundary layer. In this configuration, the engine takes in flow at a reduced velocity, thus consuming less fuel in the combustion process. However, this induces a series of noise consequences that alter the noise perceived by an observer. The present work reports an experimental investigation to compare the far-field noise directivity emitted by two different propellers ingesting a boundary layer at two different states. The experiments have been performed in the anechoic wind tunnel at the University of Bristol. The experimental setup consists of a propeller placed in the proximity of a tangential flat plate, which represents a simplified model of a fuselage. Two tripping devices placed 1 m (6.5 rotor radii) upstream of the propeller have been used to generate distinct boundary layer thicknesses. Results from two distinct propellers with three and five blades have been compared, varying the advance ratio J from 0.56 to 0.98. Far-field noise has been acquired using a microphone array positioned in the plate plane. The data have been analysed in the frequency domain, providing an extensive characterization of the far-field directivity. Results show a general increase in noise when the propeller ingests a thicker boundary layer. Furthermore, a change in directivity pattern is observed varying the advance ratio, suggesting a variation of the underlying physics. Finally, considering different J, the overall noise emission appears to be dependent on the number of blades.

## Introduction

In the pursuit of more sustainable and efficient air transportation, researchers and engineers are continuously seeking innovative solutions to enhance aircraft performance. An approach that has garnered considerable attention is the concept of Boundary Layer Ingestion (BLI), which involves the ingestion of the slow-moving boundary layer air into the propulsion system of an aircraft. In fact, the boundary layer experiences lower velocities compared to the free stream airflow. This low-velocity air has significant kinetic energy remaining, which can potentially be harnessed to improve the overall aerodynamic efficiency of the aircraft. BLI aims to capture this underutilized energy by ingesting the boundary layer air into the propulsion system, thereby reducing drag. As a consequence, it has the potential to increase the propulsive efficiency of an aircraft by capitalizing on the kinetic energy in the boundary layer air [1]. By ingesting and re-energizing this slower-moving air, the propulsion system can produce more thrust for the same amount of fuel, resulting in improved fuel economy and reduced emissions [2,3]. However, one of the potential disadvantages of BLI is the increase in the aircraft noise emitted in the far-field [4,5].

**Experimental setup**

The experiments herein presented were carried out at the University of Bristol's Lawson anechoic wind tunnel. This facility is a closed-circuit, temperature-controlled wind tunnel that is 16.6 m long, 6.8 m wide, and 4.6 m high. The wind tunnel uses a nozzle with a contraction ratio of 8.4 and exit dimensions of 775 mm in height and 500 mm in width, which can achieve freestream velocities of up to 40 m/s and has a high flow uniformity across its exit plane. The anechoic chamber is acoustically lined with acoustic foam wedges and it allows for anechoic measurements down to 160 Hz, according to the ISO 3745 standardized testing procedure [6].

A general overview of the experimental setup is shown in Fig. 1 in which an array of 21 GRAS 40 PL microphones with a radius of 1.75 m (11.5 rotor radii) was positioned parallel to the plate. The array covers angles from $\theta = 35°$ to $\theta = 135°$ from upstream to downstream with $\Delta\theta = 5°$ between every microphone. Two propellers, one with three blades and the other with five blades, both featuring a common radius of R = 0.152 m, are mounted on a steel rig positioned 1 m (6.5 rotor radii) downstream of the wind tunnel contraction.

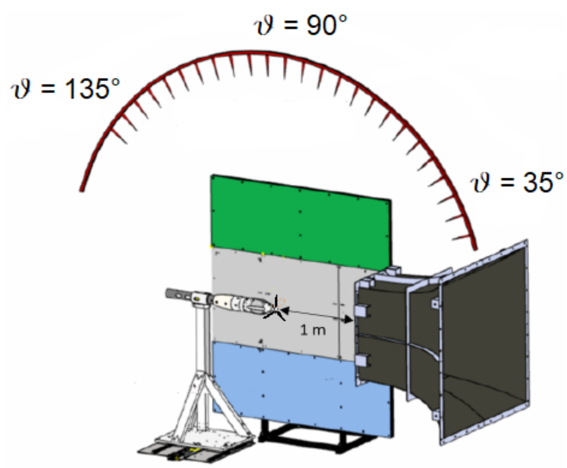


*Fig. 1: Experimental setup.*

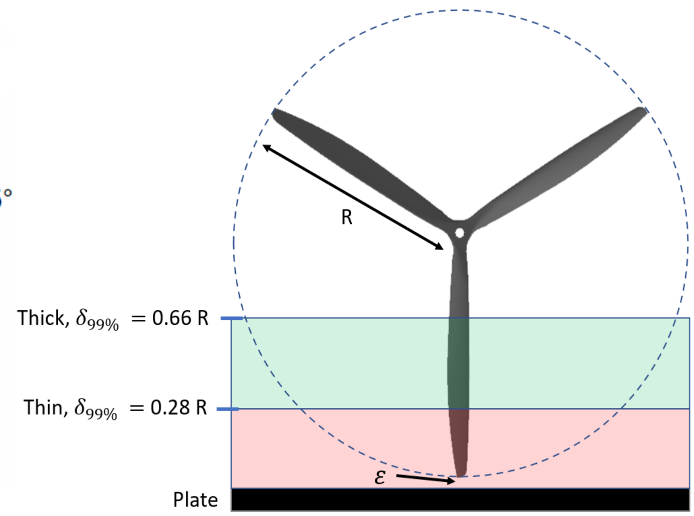


*Fig. 2: Boundary layer thicknesses at the propeller location.*

Both propellers share the same airfoil shape and geometry, ensuring consistent baseline characteristics for comparison (see [4]). The wind tunnel velocity is fixed at $U_\infty = 20\ m/s$, while the propeller RPMs are varied to achieve a range of advance ratios spanning from J = [0.56, 0.98]. Two Aluminium metal foam porous material tripping devices, referred to as 'Thick' and 'Thin', were strategically placed after the contraction exit to manipulate the boundary layer thickness at the propeller location. The Thick tripping device had a thickness of 10 mm, while the Thin tripping device had a thickness of 5 mm. Prior to the experimental measurements, a preliminary hot-wire test campaign was conducted to assess the boundary layer thickness and the turbulence intensity (TI) at the propeller position. The results showed that the boundary layer thickness was $\delta = 0.66$ R with TI = 7.76% for the Thick trip and $\delta = 0.28$ R with TI = 3.89% for the Thin trip, as shown in Fig. 2. These measurements were obtained without the propeller installed and served as an estimation of the boundary layer ingested by the propeller during subsequent experiments. In all presented results, a tip gap of $\epsilon = 5\ mm$ ($\epsilon/R = 0.03$) was maintained between the propeller tip and the plate.

## Results

Four representative advance ratios were chosen to compare the three and five-bladed propellers: J = 0.56, J = 0.65, J = 0.75, J = 0.98, where $J = U_\infty/nD$, with $n = RPM/60$ and $D = 2R$. For each microphone the Overall Sound Pressure Level (OASPL) was calculated as:

$$OASPL = 10log_{10}\int_{f_1}^{f_2}\frac{PSD}{P_{ref}^2}df\,,\quad [dB]$$

where $f_1 = 160\,Hz$ which is the wind tunnel cut - off frequency, $f_2 = 10000\,Hz$, $P_{ref} = 20\cdot10^{-6}\,Pa$ and PSD indicates the Power Spectral Density of the signal evaluated with the Welch's method. Fig. 3 displays the OASPL results as a function of polar angles for both the three-bladed and five-bladed configurations, considering various values of J. The figure distinguishes between the thicker boundary layer cases, represented by dashed lines with cross markers, and the thinner boundary layer cases, represented by solid lines with dots.

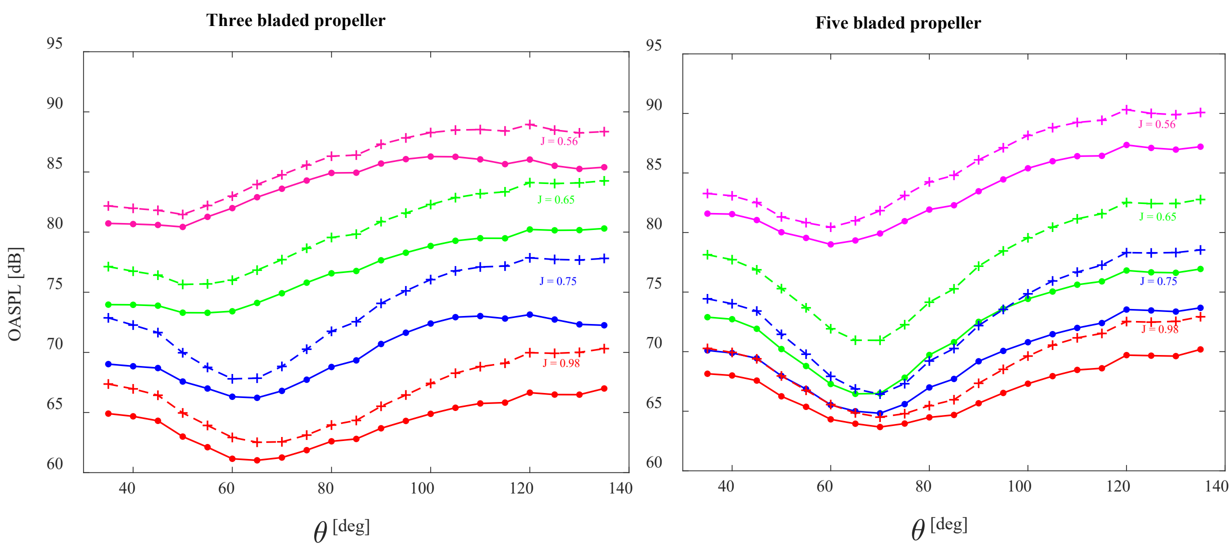


*Fig. 3: OASPL for three-bladed propeller (left) and five-bladed propeller (right). Dashed lines with cross markers refer to the thicker boundary layer (Thick) whereas solid lines with dots refer to the thinner boundary layer (Thin).*

In both configurations, the ingestion of a thicker boundary layer by the propeller leads to an amplified level of noise across all polar angles. This increase in noise is attributed to heightened pressure fluctuations on the propeller blades, induced by turbulence within the thicker boundary layer. The effect is particularly pronounced at higher polar angles (wake side), specifically for J values of 0.65 and 0.75. Additionally, a noticeable change in noise emission directivity is observed at high J, characterized by a distinct dip around $\theta = 70°$. This change is more pronounced in the five-bladed configuration. As a result, comparing the two plots in Fig. 3, a general trend of increased noise is evident in the three-bladed case compared to the five-bladed case, considering equal J values.

## Conclusions

This study aimed to investigate the far-field noise characteristics of propellers operating in close proximity to a flat plate, ingesting a boundary layer with two different thicknesses. We compared the experimental results obtained from two propellers with three and five blades, with the advance ratio varying from J = 0.56 to J = 0.98. Far-field noise data were acquired using a microphone array positioned in the plate plane. The results of the study revealed a general increase in noise levels when the propeller ingested a thicker boundary layer. This observation underscores the influence of boundary layer thickness and turbulence intensity on noise generation. Additionally, variations in the advance ratio led to changes in the noise directivity pattern, suggesting alterations in the underlying physics of noise emission. Finally, considering different advance ratios, the overall noise emission appeared to exhibit a trend based on the number of propeller blades with a general increase considering the three-bladed case. In a potential future development, varying the thickness of two boundary layers while maintaining the same turbulence intensity could help differentiate their individual impacts on far-field noise.

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**References**

[1] Smith L, 1993, Wake Ingestion Propulsion Benefit, Journal of Propulsion and Power 9 74–82. https://doi.org/10.2514/3.11487

[2] Ahuja J and Mavris D, 2021, A Method for Modeling the Aero-Propulsive Coupling Characteristics of BLI Aircraft in Conceptual Design, AIAA Scitech Forum 2021. https://doi.org/10.2514/6.2021-0112

[3] Yildirim A, Gray J, Mader C and Martins J, 2021, Performance Analysis of Optimized STARC-ABL Designs Across the Entire Mission Profile, AIAA Scitech Forum 2021. https://doi.org/10.2514/6.2021-0891

[4] Zaman I, Falsi M, Zang B, Azarpeyvand M and Camussi R, 2023, Experimental Parametric Investigation of the Haystacking Phenomenon for Propeller Boundary Layer Ingestion, AIAA AVIATION 2023 Forum. https://doi.org/10.2514/6.2023-4054

[5] Zaman I, Falsi M, Zang B, Azarpeyvand M and Camussi R, 2023, Effect of Tip Gap on Nearfield and Farfield Acoustics of Propeller Boundary Layer Ingestion, AIAA AVIATION 2023 Forum. https://doi.org/10.2514/6.2023-4055

[6] Mayer Y, Kamliya Jawahar H, Szoke M, Showkat Ali S and Azarpeyvand M, 2019, Design and Performance of an Aeroacoustic Wind Tunnel Facility at the University of Bristol, Applied Acoustics 155 358–370. https://doi.org/10.1016/j.apacoust.2019.06.005