Boundary layer ingested ducted fans: an experimental aeroacoustics study

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Introduction

Fan system noise is a widespread industrial concern, especially within the aerospace sector, where the turbulence-ingestion noise (TIN) from rotating fans poses various design challenges. Next-generation aircraft feature boundary layer ingestion (BLI) ducted fan propulsion systems, partially embedded to ingest turbulent boundary layers, addressing emission concerns. These BLI ducted fans offer fuel-saving benefits, but their noise characteristics change with airframe design, thereby affecting the nature of noise emission.

Most BLI research focuses on the noise characteristics of open propellers/rotors/fans ingesting planar turbulent boundary layers developing over flat surfaces [1, 2] . Limited noise study exists on BLI ducted fans, particularly in the context of non-planar (or adverse) boundary layers developing over curved surfaces [3]. This research addresses the limited study of BLI ducted fans ingesting an adverse pressure gradient boundary layer. This study considers an installed ducted fan configuration adjacent to a curved S-plate, resembling the rear fuselage of the ONERA NOVA aircraft concept [4].

Experimental methodology

The test rig features an electric ducted fan positioned next to a curved S-plate. The ducted fan, based on the Bell X-22A design, utilises a straight duct of constant cross-sectional area. The fan is constructed using the NACA-23012 blade profile, has a diameter (D) of 254 mm, and a pitch-to-diameter ratio P/D of 0.85. Additionally, an S-plate setup with curvature induces adverse pressure gradient boundary layer. The ducted fan is mounted in the region of high adverse pressure gradient, signifying ingesting separated and distorted flow. The measurement instruments employed in the University of Bristol (UoB) aeroacoustics facility are: (i) wind tunnel with anechoic chamber, (ii) AT4125 T-MOTOR motor for speed control, and (iii) ATI F/T Mini 40 load cell, and (iv) GRAS 40PL microphones.

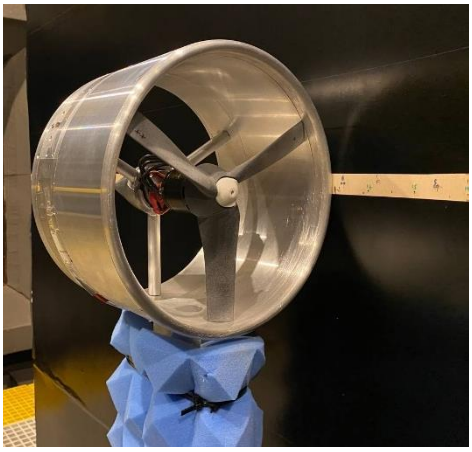

Fig. 1 Experimental setup of a BLI ducted fan in the aeroacoustics wind tunnel at the University of Bristol

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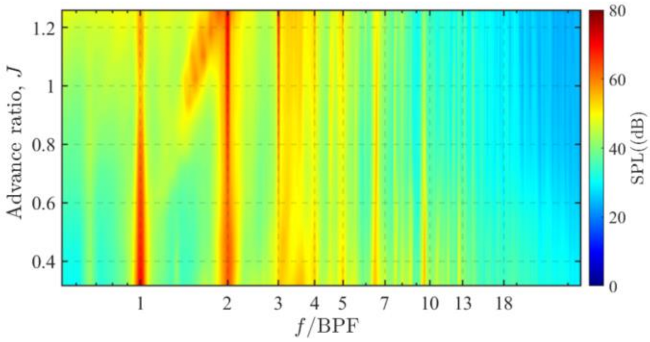

Fig. 2 Noise signature of installed ducted fan at 6000 rpm.

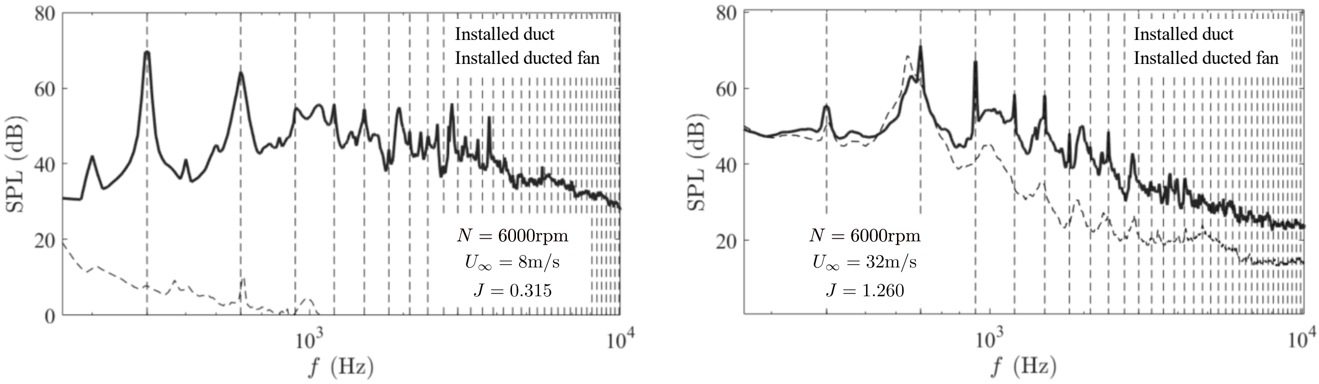

Fig. 3 SPL signatures at high-thrust ($J = 0.315$) and low-thrust ($J = 1.260$) levels.

Results and discussions

Figure 2 shows noise radiation distribution for ducted fans at various advance ratio, defined in terms of inflow velocities. The far-field noise in a BLI ducted fan arises from rotating fan, duct, and distorted boundary layer flow interactions. Fan noise varies with rotational speed, with consistent noise signatures at the blade passing frequency and harmonics. On the other hand, duct noise, unaffected by speed, exhibits a consistent feature with ascending noise trend. Figure 3 illustrates noise signatures for BLI ducted fan at high and low thrust levels. At high thrust (J=0.315), noise is mostly influenced by the interaction of rotating fan and boundary layer. The spectral broadening and broadband humps observed due to this interaction mechanism is known as the haystacking phenomenon. At low thrust (J=1.260), duct noise becomes significant, resulting in combined interactions and distinct noise features for BLI ducted fan. The spectral broadening and hump features observed in the low-thrust case do not arise exclusively from the haystacking, but rather emerged from the combined effect of haystacking and duct noise.

Conclusion

In conclusion, this study examined the aeroacoustics of BLI ducted fan ingesting an adverse pressure gradient boundary layer, uncovering key noise source mechanisms. In the high-thrust regime, the BLI ducted fan noise exhibited a signature characterised by blade passing frequencies coupled with haystacks. Conversely, in the low-thrust regime, the noise signature included blade passing frequencies coupled with duct acoustics and haystacks.

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