EXPERIMENTAL INVESTIGATION ON THE NEAR-FIELD AEROACOUSTIC SOURCES OF A LOW SPEED AXIAL FAN

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Abstract

This paper describes a technique for the investigation of noise sources correlated to tip clearance flows in a low-speed axial fan. A detailed experimental acoustic study is carried out by examining the chord-wise evolution of rotor flow field in the proximity of blade tip in low-solidity impeller. The experiment is performed by keeping the rotor "frozen" inside an anechoic chamber. The Mach number, Reynolds number, and blade incidence angle are set in a static frame of reference in order to reproduce the rotor kinematics effects by controlling the airflow entering the 'frozen' fan rotor sector in the anechoic chamber nozzle. The near-field pressure perturbations are measured using a chord-traversed microphone. Near-field pressure data are then compared with theoretical predictions, experimental data, and numerical studies simulations performed on the same fan. In this way the validity of the developed experimental scheme is assessed. The purpose of the present program of work is to identify the change in near-field noise as a result of the chord-wise turbulent structures that are located close to the blade surface at the tip. The objective is to study the evolution of their paths along the chord, and thus to provide insights into the acoustic significance of the turbulent flow structures identified. The present program of work is facilitated by the existence of a detailed pre-existing experimental database on this fan.

1. Introduction

The minimisation of fan noise presents the designer with a challenge, understanding behaviour of fluid flow close to the blades. For a low-solidity fan, noise arises from sources in the near-field as a consequence of high sound pressures associated with turbulent flow structures. To mitigate the effects of turbulent flow induced fan noise, the designer requires a method for quantifying the acoustic implications of turbulent flow structures, thus enabling the fan acoustic signature to be derived. The acoustic signature is especially important when a fan is the main contributor to overall tone and broadband noise, as occurs in both low-speed ventilating equipment and high-bypass ratio turbofan engines, Ganz et al. (1998).

The advent of stringent environmental regulations with respect to noise production has stimulated academics and practitioners alike to pursue the development of concepts and technologies that are likely to reduce fan noise, either by attenuating noise propagation or by controlling the noise at source.

The present study focuses on a family of contemporary commercially available fans. Utilising an experimental technique for the chord-wise detection of blade noise sources, Bianchi (2007), the present study investigates the aero-acoustic performance of an improved blade tip configuration (designated 'TF' in the present study) developed by Corsini et al. (2007a, 2007b, 2008).

The objective of the study is to assess the aero-acoustic merits of the proposed tip configurations, which, according to a quantitative study by Corsini et al. (2007a), have been shown to be capable of controlling tip-leakage flow and vortex formation thus producing benefits in terms of an overall reduction in sound power levels. More specifically, the objective of the study is to identify, isolate, and understand the mechanism whereby the tip-flow vortices along the blade chord interact and in so doing generate noise emissions. As a first trial of the technique, two probes are used, and the results are presented in this paper. The investigation attempts to establish a cause-and-effect relationship between the various tip-flow dynamics and the radiated sound fields. The two microphones are located in an anechoic chamber (Figure 1 (a) and (b)); the first (near-field) is 15 mm far from the blade surface, 10 mm from the tip plate, and traversed along the chord. The second (far-field) 1,200 mm from the blade trailing edge, at 30° from the fan centreline, as recommended by Winkler et al. (2007). A cross-correlation is applied to near and far-field signals.

The technique proposed in the present program of work was based on previous research undertaken to correlate the noise emitted by a static wing profile in an air flow with that of helicopter propellers, Brooks et al. (1989). To this end, it concerns about the measurement of static noise data from an axial impeller sector rig adequately arranged in order to account indirectly for the effect of rotation of the impeller blades and the load condition of the blade tip. The experimental approach used can be characterised as a 'noise-source localisation technique'. Simultaneous sampling of pressure fluctuations in both the near and far-field are undertaken to enable the detection of aerodynamic noise sources along the chord to be combined with an analysis of near-field to far-field coherence to ascertain the signature mechanisms. The paper therefore deals with an initial verification of the aero-acoustic experimental method utilising data from microphones on frozen fan rotor blades facilitating the identification of noise sources in the tip gap region without the fan rotation.

This paper is organised into three main sections. In section two the family of fans under investigation is described, followed by a description of the passive noise-control devices utilised. In section three the methodology adopted is described. The flow conditions and experimental set-up are then described; in which implications of the near-field pressure measurements are discussed. The paper concludes with section four where the main findings of the work summarised.

Nomenclature

Latin letters

f	*frequency*
H	*nozzle height*
Ks	*specific noise level,* $Ks = SPL - 10\log_{10}(V \cdot \Delta p_{tot}^2)$

ℓ	*blade chord*
L_p	*sound pressure level*
r	*non-dimensional chord* (s/ℓ)
s	*chordwise distance from the trailing edge*
t	*blade pitch*
U_c	*casing relative peripheral velocity*
V	*volume flow rate*

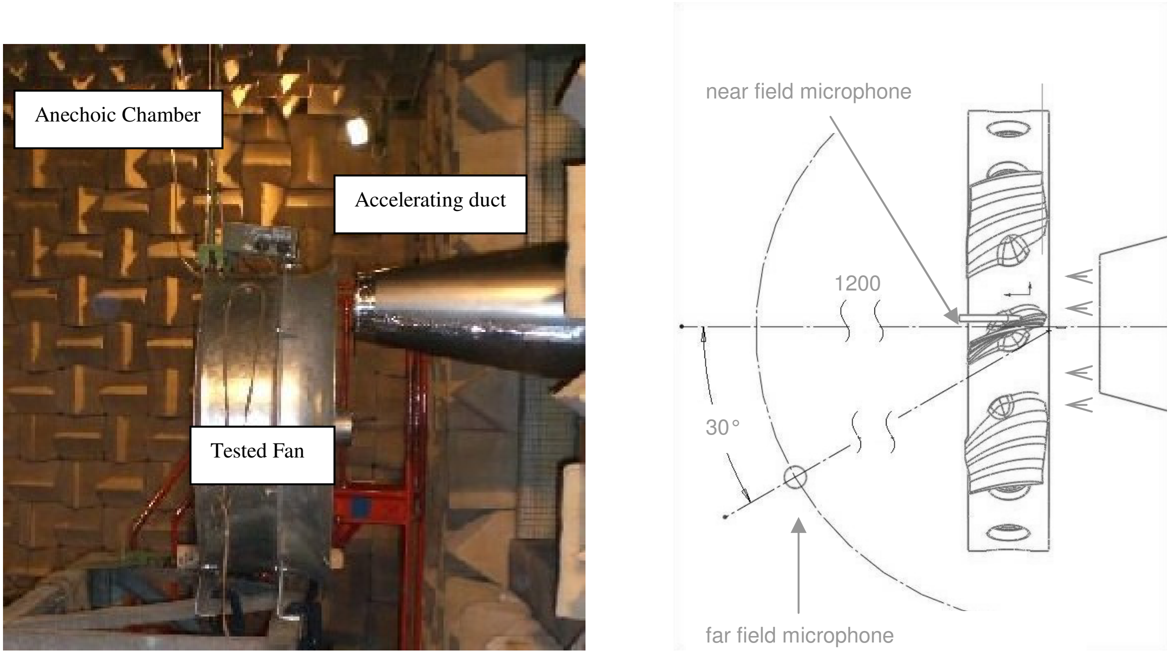
Greek letters

α_t	*Brooks correction angle*
α_T	*total correction angle*
ν	*hub-to-casing diameter ratio*
σ	*Brooks correction number* $\sigma=\left(\pi^2/48\right).\left(\ell/H\right)^2$
ξ	*Brooks correction factor*, $\xi=\left(1+2\sigma\right)^2+\sqrt{12\sigma}$
χ	*rotor tip clearance (% of the span)*

2. Description of the test rig

The test rig was set up in an anechoic chamber and consisted of an acceleration duct at the anechoic chamber inlet, Figure 1. As a first trial of the technique, two probes are used, and the results are presented in this paper. The investigation attempts to establish a cause-and-effect relationship between the various tip-flow dynamics and the radiated sound fields. The two microphones are located in an anechoic chamber (Figure 1 (a) and (b)); the first (near-field) is 15 mm far from the blade surface, 10 mm from the tip plate, and traversed along the chord. The second (far-field) 1,200 mm from the blade trailing edge, at 30° from the fan centreline, as recommended by Winkler et al. (2007). A cross-correlation is applied to near and far-field signals. The accelerating duct directed a free jet onto the impeller blade at design inlet angle and Mach number. The fan was placed after the duct, Figure 1 (a), to isolate the test zone from vibration and external noise, with a damper to maintain steady flow conditions. A booster fan sucked from the inlet plenum of the anechoic chamber, with flow then directed by the acceleration duct onto the airfoil. More details on the test rig, which was based on the work of Winkler et al. (2007), are available in Bianchi (2007).

A microphone was mounted on a bracket to allow it to be placed along the chord span with minimal disturbance of the air flow. The bare microphone was furnished with a nose cone and a correction factor applied to account for its presence. The microphone was then traversed from near the blade tip from leading to trailing edge of the blade in steps of 0.1 chord. To determine the path of turbulent noise sources in the near-field, measurements were made on both the pressure and suction side.



(a) (b)

Figure 1: Schematic arrangement of (a) the sector rig and (b) microphones set up.

2.1 Tested Fan

The present study was performed on a family of commercially available cooling fans, coded *AC90/6/28/TF*. In-service experience and previous studies, Bianchi et al. (2007a); Corsini et al. (2008a, 2008b) have indicated that this family of fans gives good acoustic performance with respect to the state-of-the-art. The investigated fan featured a six-blade un-swept rotor, with the blade profiles being a modified ARA-D configuration originally designed for propeller applications, Table 1.

	AC90/6 fans	
blade geometry	*hub*	*Tip*
ℓ / t	1.32	0.31
pitch angle (deg)	36	28
camber angle (deg)	46	41
solidity	1.24	0.3
fan rotor		
blade number	6	
blade tip stagger angle (deg)	62	
hub-to-casing ratio ν	0.22	
tip diameter (mm)	900.0	
rotor tip clearance χ	1.0	
rotational frequency (rpm)	700	

Table 1: AC90/6 fan family specifications: Blade profile geometry and rotor specifications

The fan blade, Figure 2, and the modified end-plate geometry (designated TF) were developed specifically to reducing noise emission. The TF configuration was originally inspired by a technique developed to control tip vortices and reduce induced drag on aircraft wings and catamaran hulls. The end-plate was designed in accordance with the theory behind control of tip vortices in aircraft, that is, proportional to the radial dimension of the leakage vortex to be controlled, which was estimated to be 0.1 to 0.2 blade spans in previous studies of rotors of axial compressors, Inoue et al. (1986) and fans Corsini et al. (2007a). The TF end-plate configuration derived from a systematic experimental evaluation of potential blade end-plate configurations. In the TF configuration the blade tip was modified by adding an end-plate along the blade pressure surface. This end-plate was of constant thickness (three times that of the datum blade's maximum thickness at the tip) and featured a square tail trailing edge.

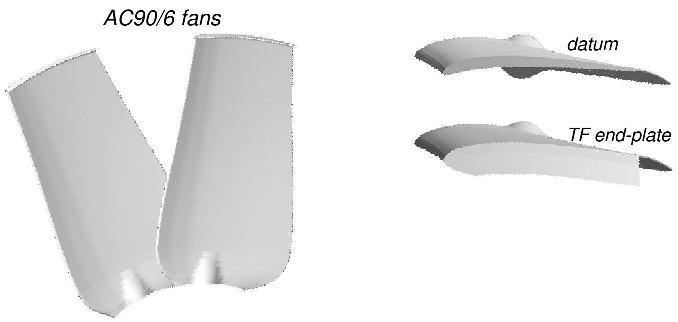


Figure 2: Test fan rotor blades and tip end-plates, not to scale (Corsini et al. 2008)

3. Methodology

3.1 Rationale for the analysis

The proposed experimental technique is here applied as a first trial to turbomachinery. The simultaneous sound pressure measurements are carried out correlating the signal from the microphone traversing the chord of the blade at the tip with that in the far-field, as described in section 2. As such, the microphone arrangement permits to eliminate the influence of noise ingestion from the nozzle airflow. As stated in the open literature, Laurendeau et al. (2007), the sound is actually generated by the turbulence in the blade-boundary layer; however, because turbulence is convected subsonically, it usually does not couple with the far-field. Nevertheless, it does generate a strong near-field, which causes a strong pressure fluctuation on the blade surface. To ensure that the flow past the trailing edge was continuous, a viscous wake had to be generated. The interaction of the sound generated in the wake with the surface upstream of the trailing edge caused wakes to propagate to the acoustic far-field.

With respect to those reference studies on aerodynamic noise generation from stationary bodies, i.e. wing profile, Brooks et al. (1989), the ducted fan experience however differs in many respects. First, because fan blades are not isolated, the flow can be influenced by the presence of an adjacent blade, and this can have a significant effect on acoustic scattering; the effect of this on the blade boundary-layer properties is unclear. Secondly, Brooks et al. (1989) measured an un-cambered airfoil, i.e. a symmetric NACA0012 profile, whereas fan blades typically have a significant camber. It has been argued by Chase (1972) however that the boundary-layer properties scale with the flow speed and the boundary-layer momentum thickness at the blade's trailing edge. If so, the experiences of Brooks et al. (1989) can be used in principle for a ducted fan set up provided that the similarity of blade trailing-edge wakes, Glegg (1998). Furthermore, the validity of the proposed methodology is supported by the evidence that boundary-layer separation was the main mechanism of noise generation, again given by Brooks et al. (1989), as such the authors concluded the difference between aerofoil profiles should not be be significant.

3.2 Flow corrections

The testing of an airfoil in a finite open wind tunnel causes flow curvature (and downwash deflection of the incident flow) that does not occur in free air. This effectively reduces the angle of attack, more so for larger models. Brooks et al., (1989) used lifting surface theory to develop a 2D open tunnel correction to angle of attack and camber. The corrected angle of attack (α), which is the angle in free air that gives the airfoil the same lift as α_t in the tunnel, was of interest in the present study.

Brooks and co-workers (1989) introduced a correction factor ξ that reads as:

$$\xi = (1+2\sigma)^2 + \sqrt{12\sigma}$$

with:

$$\sigma = \left(\frac{\pi^2}{48}\right) \cdot \left(\frac{\ell}{H}\right)^2$$

where: ℓ is the airfoil chord and H the nozzle height of the open jet dimension for the horizontally aligned airfoil. Using these factor, in case of a pich angle at the tip $\alpha = 28°$, it is possible to calculate the corrected anuglar setting α_t with the following expression:

$$\alpha_t = \xi . \alpha$$

where, being $\xi \cong 1.442$, and $\alpha_t = 40°$.

In the program of work reported in this paper, the blade in the rig was required to simulate also the effect of blade rotation with respect to the relative inflow kinematics. A second correction factor was therefore applied to compute the blade's relative airspeed and angle of attack. Because the fan rotates, the angle of attack and the flow speed vary along the span. It was decided that the flow behaviour and phenomena in the tip region should be investigated. In doing so, the present study made use of the significant database that exists on this family of fans from previous quantitative analyses, Corsini et al. (2007a, 2008,) Bianchi et al. (2007, 2008, 2008b).

A calculation method was developed in accordance with these requirements, providing an estimate of the global angle (α_T) that took into consideration both α_t and rotation effect. The calculation was performed for a rotational speed of 700 rpm, which gave U_c ~ 33 m/s. Thus:

$$\alpha_T = 103^{\circ}$$

for a corrected air speed at tip about 32 m/s.

4. Results and discussion

Measurement of pressure perturbations around the isolated blade, enabled changes to be identified in the Lp, as measured along the chord on the pressure side of the blade, Figure 3. The sound pressure level spectra were measured on the pressure and suction sides of the fan blades in proximity of the blade tip gap. Figure 3 depicts the Lp cross spectrum at the blade pressure side, the near-field microphone was placed 15 mm from the blade surface and 10 mm from the blade tip, and it was traversed along the chordwise direction from the leading to the trailing edges of the blade using eleven 'r' chordwise positions. Previous studies Corsini et al. (2007); Bianchi et al. (2007, 2008b) had shown that the tip noise of a fan is significantly influenced by a breakdown phenomenon occurring along the blade chord. Utilising numerical analysis, Corsini et al. (2007, 2008) established that the breakdown occurs on the suction side. The tip-leakage flow, controlled by a modified tip configuration, was sucked through the gap between the tip feature and the casing. As a consequence, the still-collapsing vortex was chaotic on the pressure side, and thus produced mainly broadband noise. This became tonal when moving to the suction side through the tip gap. It was accelerated and, assuming a coherent structure, it collapsed. The reason for broadband noise being dominant on the pressure side is that this side of the blade stresses the vortex on the tip end-plate surface, resulting in a chaotic diffusion of the vortex structure. When this high turbulent flow has enough energy, it crosses the tip plate and passes through the tip gap to the suction side. There it starts rotating and diffuses in the flow stream leaving the trailing edge.

Three tonal 'spots' can be identified at chord positions 0.4, 0.6, and 0.8 (Figure 3). The first was at chord 0.4 and approximately 1,000 Hz. It was possible using numerical studies to verify that 0.4 chord is the point at which the vortex on the pressure side passed through the tip gap to the suction side, Corsini et al. (2007, 2008). The spots all had a tendency to show a raised Lp level and as such the authors speculate might also indicate the presence of a vortex.

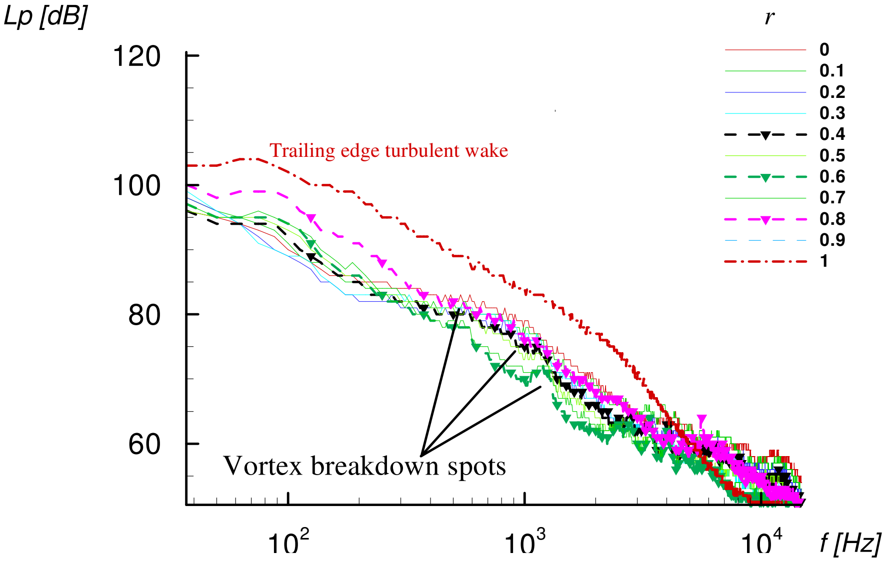


Figure 3: Chord-wise Lp cross spectrum at pressure side, measured 15 mm far from the blade.

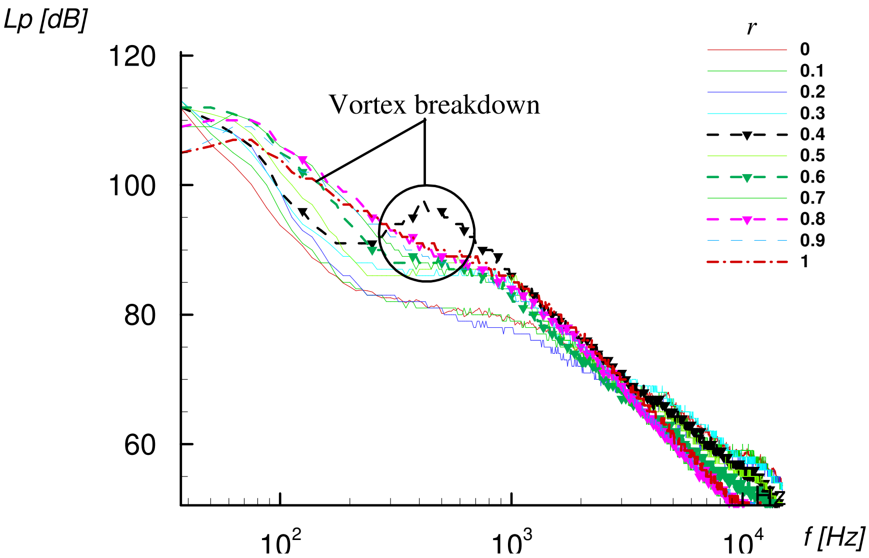


Figure 4: Chord-wise Lp cross spectrum at suction side, measured 15 mm far from the blade.

Measurements taken on the suction side of the blade, Figure 4, localised the points, r = 0.4, at which vortex breakdown occurred, and for r = 0.6 the Lp coincided with the low frequencies at an Lp similar to the trailing-edge wake shear level. As such, it was possible to identify the effective position of the vortex breakdown. A sudden peak in Lp for chord position 0.4, localised in the range of 400 Hz, indicates that the vortex had broken down and was emitting tonal noise at 400 Hz. The collapsing vortex at 0.4 chord on the suction side of the blade appears to have increased the noise level up to 0.8 chord. Tonal peaks in Lp were found which, from their radial position and range of frequency, could relate to the bursting of the tip-leakage vortex. This bursting of the tip leakage vortex has been reported in previous studies of this blade configuration under these operating conditions, Corsini et al. (2007). The characteristic rotation frequency of this collapsing vortex was 400 Hz.

Measurements taken on the suction side of the blade, with the microphone located 150 mm from the blade surface and 50 mm of span distance from the tip, indicated that the collapsed vortex was still continuing its rotation, Figure 5. As it rotated, the vortex maintained an emission frequency of 200 Hz. This emission frequency was lower because the vortex became weaker (in both pressure level and rotation number) further away from the blade. For the same reason, the vortex radius increased. Far from the blade surface, the vortex, after it had burst, became bigger but weaker. The vortex path diverged and its radius increased, thus producing more turbulent broadband noise than near the blade surface. An effect of this 'turbulent tail' was increased broadband noise from the wake shear released from the trailing edge. The effect of the 'turbulent tail' was not observed in data taken from the suction side of the blade (Figure 4). This might indicate that, at this distance from the blade, the vortex fed the turbulent shear of the trailing edge. This shear might have interfered, during the rotation, with the next blade thus constituting a noise source.

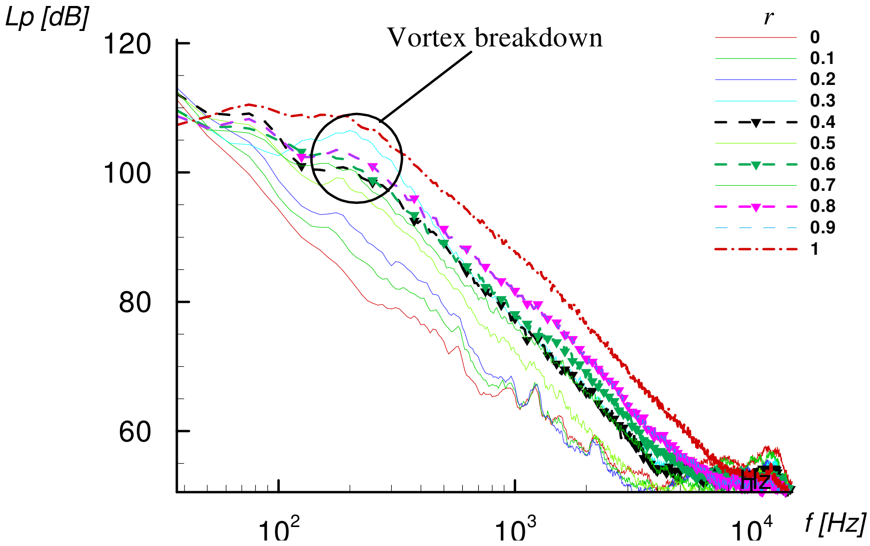


Figure 5: Chord-wise Lp cross spectrum at suction side, 50 mm from the tip plate, 150 mm far from the blade.

It is apparent that the technique developed and reported here facilitates detection of collapsing vortex position, thus confirming the quantitative analysis. Work is ongoing to further refine the frozen rotor technique described in this paper.

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