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Pressure-velocity phase averaged analysis of fan wakes for different blade shapes

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Abstract. The aim of this work is to study the correlation mechanisms underlying the aerodynamic field generated by fans of different shape and the perceived noise. Two different geometries were selected in order to see the influence of the blade shape on both the fluctuating pressure and the velocity field. Both fans have a diameter of 38 cm and were connected to the same electric motor to keep the same driving conditions. The fluid dynamic field was first characterized by using a classical Particle Image Velocimetry technique. Smoke particle were used to seed the surrounding air maintained at rest. The images were recorded for the three rotational speeds of the fan with the maximum frequency allowable by the PIV system, corresponding to 10Hz and for a duration that guarantees the statistics convergence. To study the spatial evolution of the released structures, two sets of images for each speed were acquired at axial distances 0 R and 0.5 R, being R the radius of the fan. Instantaneous and mean velocity and vorticity fields were obtained tracking the movement of the blade tip vortex. From the information obtained by the characterization of the fluid dynamic field, a new set-up including 3 microphones was built. The microphones were positioned in strategic axial positions in order to cope with the supposed position of the coherent structures. The fluctuating pressure and the velocity fields were simultaneously acquired at the same conditions of the preliminary test campaign. A home-made algorithm was used to retrieve the angular position of the blade and phase the simultaneous acquisitions. The velocity fields were finally cross-conditioned with the pressure fluctuations events selected with that algorithm, finalizing the objectives of the work.

1. Introduction

The problem of reducing fan induced noise and vibration has become very important in the last years in the aeroacoustic field and has led to an increased complexity of the blade geometry, primarily due to the need of low aspect ratio and of skewed shapes and has implied a rising interest on detailed measurements of the fan flow field, to be used for both new design approaches as well as for analyzing propulsive, acoustic, and structural performances.

The noise due to fans, as for propellers, is caused by different sources and is usually classified in a tonal (harmonic) and in a broadband part. A general and quite accepted definition leads to three origins for the broadband noise: noise related to the turbulence of the incoming flow (leading edge noise), noise produced by the interaction of the turbulent boundary layer over the blade surface with the trailing edge, noise generated by the possible separation of the flow on the blade airfoil [1].

In aeroacoustic research, the identification of flow structures involved in the generation mechanisms of aeroacoustic noise sources is indeed one of the major goal. It is difficult to predict the exact proportion
of the turbulent kinetic energy that is radiated as sound, since usually only a very small fraction of the complete energy is actually transferred into these far-field pressure fluctuations [2].

One way to solve this problem is the simultaneous measurement of the acoustic pressure in the far-field together with some other relevant near-field quantity [3, 4, 5].

The pressure field generated by a fan is strictly related to the induced velocity field [6]. Therefore, a detailed flow field analysis, relating the flow structures and the pressure signal, is considered useful to improve the knowledge on the noise mechanism. Experimental investigation also provides base-lines to improve and integrate theoretical predictions and support the flow modeling and the validation of computational codes. In the present study the pressure signals were correlated with the flow structures generated by the fan like the tip and hub vortex and the blade wake.

2. Experimental set-up and procedure

The measurements were conducted in the Laboratory of Aerodynamic and Aeroacoustic of the University 'Rome Tre'. The axial fans tested in this study have three forward swept blades (figure 1). The tip-to-tip diameter and hub diameter of the fans are 380 mm and 70 mm respectively, leading to a hub-to-tip ratio of 5.43. The blade shapes resemble commonly used propellers used in different transportation sectors. The first fan shape is close to a marine type propeller. The second is shaped like a scimitar sword with increasing sweep along the leading edge. It is typically used in aeronautic and it is characterized by an efficient aerodynamics that results in more power and reduced noise.

Both fans have a diameter of 38 cm and have been connected to the same electric motor that can be set at three different rotational speeds. The rotational speeds are:

- $\omega_1 = 750$ rpm, $\omega_2 = 925$ rpm, $\omega_3 = 1085$ rpm for Fan 1
- $\omega_1 = 930$ rpm, $\omega_2 = 1070$ rpm, $\omega_3 = 1160$ rpm for Fan 2.

Lower rotational speeds for the first fan are expected due to the higher blade drag.

Three experimental campaigns were conducted: the first was aimed at characterizing the velocity field of the fans, the second was aimed at characterizing the noise emitted by the fans and the third to establish the connection between the fluid dynamics and the emitted noise. The corresponding experimental set-ups are described in the following sections.

2.1. PIV experimental set-up

A sketch of the set-up lay-out is shown in figure 2. For what concerns the PIV experimental set up, it is shown in the lower part of figure 2. The fan is mounted vertically allowing the slipstream to develop freely in the downstream direction. A Programmable Timing Unit (PTU) provides the trigger signals to synchronize a cross-correlation camera (with a maximum resolution of 2,360 px x 1,776 px), and a double cavity Nd-Yag laser (200 mJ/pulse at 10 Hz each), to allow the image acquisitions. The digital cross-correlation video camera allows the recordings of two separate images (one for each laser pulse) within a few microseconds at a maximum camera frame rate of 15.0 Hz.
The following Cartesian reference system is adopted: O-XYZ with the origin O in the intersection between the fan disk and the rotation axis, the X axis oriented radially and Y axis parallel to the axial direction (see figure 3). The instantaneous velocity fields were acquired at a distance of 0.5 m in x-direction from the fan axis, imaging an area of about 13x10 cm first at an axial distance of 0R and then at 0.5R as shown in figure 3. This has been done to investigate the fan wake evolution highlighting the effect of vortex released at blades trailing edge.

The air was seeded with smoke particles having a mean diameter of about few micrometers in order to correctly follow the flow field. A high uniform seeding density in the region of interest was achieved as well guarantying a correct cross-correlation analysis. Mie-scattering images are not reported for the sake of conciseness.

The PIV system was arranged to measure the axial and transversal velocity components simultaneously. In view of the symmetry of the fan flow and of the steady conditions the light sheet is located on the X-Y plane and the axial component of the velocity (component along the Y axis) and the radial one (component along the X axis) are acquired together.

![Figure 3: Cartesian reference and selected interrogation areas.](image1)

The PIV image analysis was carried out using the software Davis La Vision. 2000 couples of images were acquired at the maximum frequency available from the PIV system to evaluate the mean velocity field (sum of axial and radial component) and the mean vorticity field.
2.2. Fluctuating pressure measurements experimental set-up
Pressure measurements were performed by using three microphones (Microtech Gefell M360) mounted as shown in figure 4. The pressure signals were acquired for 120 s at the sample rate of 100 kHz using the software LabVIEW. The acquisition data unit used is a NI PXI-6143 (8 channel, 16 bit, 250 kS/s) with a controller NI PXIe-8840 Quad-Core model. A sketch of the experimental set up is reported in the upper part of figure 2.

![Microphone positions](image1)

**Figure 4:** Microphone positions.

The position of the microphones with respect to the fan is shown in figure 4. Two microphones are positioned at a distance of 2 cm from the disk plane and one at a distance of 24 cm in axial direction and aligned with one of the two microphones in the disk plane.

2.3. Simultaneous measurements experimental set-up
The experimental set up is shown in figure 2, a BNC- cable connection links the PTU to the acquisition system. The synchronising trigger signal is acquired together with the pressure signals.

The same settings of the previous preliminary test campaigns have been kept apart from the number of images recorded by the PIV system, reduced from 2000 to 1200. This was mandatory for simultaneous measurements since the number of samples is too large for the buffer capacity of the DAQ.

![Microphones position and selected interrogation area](image2)

**Figure 5:** Microphones position and selected interrogation area for simultaneous measurements.

Figure 5 shows the microphones position and the selected field of view of 13x10 cm. The aim of this acquisition is to understand the effect on the fluid dynamic field due to the passage of a single blade.
In order to cross-condition the velocity field with the pressure, a cross conditioning algorithm has been developed [8]. The algorithm consists in the following steps:

- Acquire simultaneously pressure and first laser trigger signals;
- Arbitrary choice of a pressure ramp representing the passage of a blade;
- Cancellation of the peaks corresponding to the other two blades;
- Reconstruction of an equivalent signal representing the trigger of the laser;
- Overlap the signals;
- Find time instants where the peak of the ramp and the trigger intersect;
- Retrieve the corresponding images.

At the end of the automatic process the number of selected images is reduced to the 10% of the total amount. In this way a conditional relation between the velocity field and the pressure fluctuations is found.

3. Experimental results
In the following PIV and pressure measurement results and the correlation of the pressure signals with the flow structures are reported.

The pressure field shows periodical fluctuations at a fundamental frequency corresponding to the blade-passing frequency (highlighted in figures 6 and 7 with black arrows). Each three peaks of the pressure signal in time domain identify the traces of the tip vortices shed from the three blades. Figure 6 reports the Sound Pressure Level (SPL) at the higher rotational speed for the first fan obtained for a signal in the near field and in the far field; same results are shown for the second fan (figure 7).

The lower frequency and its harmonics, red arrows in figures 6 and 7, correspond to the shaft rate and identify the pressure fluctuations due to the fan hub [6], [7].

The signals show a different behavior and amplitude as a consequence of the different interaction with the flow structures of the fan wake. Increasing the distance from the fan disk, the phenomenon of transition wake occurs, the peaks in the SPL at the blade rate frequency decreases gradually and becomes of the same order of the lower frequency corresponding to the shaft rate [6], [7], [9].

Figure 6: Sound pressure level of Fan 1 at the higher rotational speed.
Figure 7: Sound pressure level of Fan 2 at the higher rotational speed.

Figures 8 and 9 show the mean vorticity field obtained from the images selected with the algorithm previously explained. In the same figures the pressure at the microphones located in the nearfield at the reference position of $\theta = 0^\circ$ is also highlighted. The angular blade position chosen corresponds to the peak in the pressure signal, shown in the figures with a red dot.

The main flow structures, like the viscous wake shed from the blade trailing edge (green areas) and the tip vortex (purple areas) are clearly present.

The maximum values of the pressure are achieved simultaneously to the passage of the tip vortex core. This result clarifies that the tip vortex is the most important pressure fluctuation source in the fan wake. Increasing the distance from the fan disk these vortices start to dissipate and lose their intensity.

The starting point of such an instability seems to be the interaction between the actual blade wake and the tip vortex of the previous one that takes place because of the different pitch angle of their helical paths [6],[9].
Figure 8: Vorticity fields (b) in phase with the blade position (a) at higher rotational speed. Fan 1.

For the second geometry the wake distortion and the interaction between vortices released from different blades occurs more rapidly and at lower distances from the disk plane.

Figure 9: Vorticity fields (b) in phase with the blade position (a) at higher rotational speed. Fan 2.
From the PIV measurements the mean vorticity field is obtained for the two fans at the three rotational speeds. Figure 10 shows the reconstructed vorticity fields at the higher rotational speed. Both images are obtained at an axial distance of 0 \( R \) and 0.5 \( R \) from the fan plane.

Purple areas represent the section of the vortex released at the tip of every blade. As the theoretical models predict a contraction of the freestream towards the fan axis is clearly evident for both geometries. Moreover, for the second one the values of the vorticity in the area closer to the fan plane are higher but the wake dissipates more quickly.

![Figure 10](image-url)

**Figure 10**: Reconstructed mean vorticity fields at higher rotational speed. Fan 1 (a). Fan 2 (b).

At the end, the analysis of the noise generated by the two fans is conducted. The values of the maximum SPL and the OASPL (OverAll Sound Pressure Level) are reported in Table 1, both for the near field and the far field. Coherently with the previous results, in the near field the highest values are obtained for Fan 2, as effect of the higher intensity of the vortex and of the pressure fluctuations. On the contrary, in the far field, since the wake of Fan 2 brakes down more quickly, the highest values are recorded for Fan 1.

| Rotational Speed | Near field | Max SPL | OASPL |
|------------------|------------|---------|-------|
| \( \omega_1 \)   | Fan 1      | 84      | Fan 1 | 86    |
|                  | Fan 2      | 87      |       | 90    |
| \( \omega_2 \)   | Fan 1      | 86      | Fan 2 | 90    |
|                  | Fan 1      | 90      |       | 92    |
| \( \omega_3 \)   | Fan 1      | 87      | Fan 2 | 92    |
|                  | Fan 2      | 92.5    |       | 94    |

**Table 1**: SPL and OASPL for both fans in the near and far field.
4. Conclusions

Velocity and vorticity 2D fields and pressure fluctuations were measured downstream two fans with different blade geometries for three rotational speeds.

The performed experimental study allows to correlate the fan flow field structures, like the blade wake and the tip vortex, with the pressure signal at a selected rotational angle. The results point out that, within the slipstream contraction, the highest values of the pressure fluctuations correspond with the tip vortex passage. Hence this flow structure is the most important one in generating the pressure field in the fan flow.

Downstream of the slipstream contraction the phenomenon of vortex breakdown occurs more rapidly in the second fan due to the higher velocity of the mean flow caused by the different blade shape.

The analysis conducted in the Fourier domain also evidenced the presence of pressure contributions due to the blade and shaft rotation rates as well as to the shedding of vortices from the blades trailing edge. The analysis of the generated noise underlines the differences between the wake structures for the two geometries. In the nearfield Fan 2 produces the highest SPL and OASPL values while in the far field the ‘noisiest’ geometry correspond to Fan 1 for which the wake’s distortion and dissipation are slower.

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