Design of low noise fan

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In this paper the design process of a new generation low noise axial fan is described. The emphasis is on the practical use of acoustic knowledge issued from published work and engineer know-how. The use of data issued from numerical simulation is also presented.

In this paper we relate how acoustic knowledge issued from published work and engineer know-how was applied in a practical manner in the design process of a new axial fan « Fläkt-Woods AXIPAL 3i ». The design process was conducted in 2000/2001.
The objectives for the new fan were to improve the existing fan power efficiency and reduce noise level.
This work was conducted using :

- analysis of fan acoustic data and knowledge,
- testing of a few prototypes,
- 3D numerical simulations.

The fan range features the following characteristics :

- diameter: 355 mm to 1250 mm,
- 2 to 6 blades,
- adjustable blade pitch at stay.

Throughout the design process, care was undertaken to minimise known narrow and broadband aerodynamic noise generation mechanisms that we classify in three main parts, discussed in this paper, i.e.:

- the blade specific noise,
- the tip clearance noise,
- the upstream and downstream interaction noise.

Blade specific noise

Choice of chord length and blade number

Sharland [1] has shown that blade acoustic power is generally linked to the blade force fluctuations as follows:

$$P = \frac{\rho_0}{48 \cdot \pi \cdot c_0^3} \int_{env} C \cdot W^4 \cdot S_c < \left[\frac{\partial C_L}{\partial t} \right]^2 > dr \qquad (1)$$

where:
P : acoustic power (W)
ρ_0 : density of air (kg/m³)
c_0 : speed of sound (m/s)
C : blade chord (m)
W : flow relative velocity around the blade (m/s)
Sc : correlation surface of the pressure fluctuations on the blade (m²)
C_L : instationary lift coefficient of the blade
r : coordinate along the span
env : span
< > : temporal average

A prominent noise generation mechanism is the interaction of the swirling structures of the turbulent boundary layer with the trailing edge. Starting from Sharland formulation, Fukano

[2] has derived an expression of the trailing edge noise that can be written as follows:

$$P = \frac{\pi \cdot \rho_0 \cdot B}{1200 \cdot c_0^3} \int_{env} D(r) \cdot W(r)^6 \, dr \qquad (2)$$

where:

P : spectrum integrated sound power (W)
ρ_0 : density of air (kg/m³)
C_0 : sound celerity (m/s)
B : blade number
env : span
D(r) : wake thickness at the trailing edge (m)
W(r) : relative velocity at the trailing edge
r : coordinate along the span

Hence we see that noise depends on the wake thickness at the trailing edge, given by:

$$D = D_t + D_j + D_e \qquad (3)$$

where:

D_t Blade thickness at the trailing edge
D_j Boundary layer thickness on pressure side
D_e Boundary layer thickness on suction side

From Fukano results, we can conclude that ways to reduce the noise level are to:
design trailing edges as thin as possible, in the limits permitted by the manufacturing process,
design blade profiles as smooth as possible to decrease the thickness of the boundary layers on pressure side and suction side. This supposes to resort to an appropriate manufacturing process and material.
The application of these results to the AXIPAL 3i range was to choose composite material injection that enables a good control of blade shape and roughness.

Fukano's formula (3) can be simply expressed in terms of blade number B and chord length C (6) by using empirical boundary layer thickness equation (4):

$$D = D_t + 0.09 \cdot C \cdot \mathrm{Re}_c^{-0.2} \qquad (4)$$

$$P \propto B \int C(r) \cdot W(r)^6 \cdot \mathrm{Re}_c^{-0.2}(r) \cdot dr \qquad (5)$$

$$P \propto B \cdot C^{0.8} \qquad (6)$$

where:

P : spectrum integrated sound power (W)
Re_c: Reynolds number based on chord C and relative velocity W
D_t: blade thickness at the trailing edge (m)
B : blade number

C: chord length at radius r (m)
W: relative velocity at the trailing edge (m/s)
ν: air kinematic viscosity (m/s)
ρo: air density (kg/m³)

These results are corroborated by Carolus [3] who obtained a similar equation for P:

$$P \propto B \cdot C^{0.6} \qquad (7)$$

Influence of chord length and blade number on fan performance:
As a first approximation, for similar blade shapes, fan performances are preserved if the following product is constant:

$$P_F \propto B \cdot C \qquad (8)$$

with:

P_F : fan pressure performances (Pa)
B : blade number
C: chord length at radius r (m)

Ways to reduce the noise level

From formulas expressing noise power level P (6) and (7) and Fan pressure P_f (8) we can point out that it is advisable to reduce the number of blades B and increase the profile chord length C while keeping constant the product B.C, as illustrated in figure 1.
Optimising dB(A) noise level, that attenuates low frequencies leads to the same choice, since Fukano observed that a fan provided with few blades of large chord generates less noise in the high frequencies (>1kHz) than a high blade number/small chord fan.

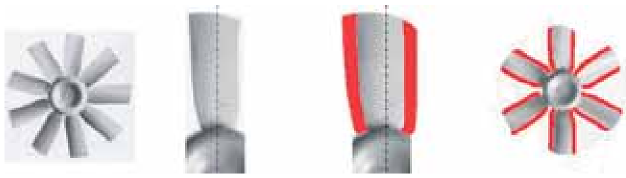

Fig. 1 : Application to the AXIPAL 3i range:

The fan features a small number of large chord blades (figure 2)

Fig. 2 : Noise and Blade load distribution

Free vortex law

To optimise the efficiency, it is appropriate to distribute the load uniformly along the span of the blade from the foot up to the tip (rule referred to as « constant circulation » or « free vortex »). This rule results in designing blades whose chord length grows continuously from the head up to the foot.

Noise as a function of the load repartition along the blade

Carolus [3] compared the acoustic characteristics of various low-pressure axial flow fans with different chord length and

different radial distribution of the load. In this study, he concluded that it is preferable to load the head of the blade than to distribute the load uniformly along the span.
It is advisable to design a blade whose chord length at the head is at least equal or higher than the chord length at the foot, which is exactly the opposite of what recommends the classical design rules.

Application to the AXIPAL 3i range:
Figure 3 shows the increase of chord length near the tip.

Fig. 3 : Chord length near the tip

Noise vs. blade sweeping

Fuest and Carolus [4] measured the fluctuations of pressure inside the boundary layer of two different axial fans, one swept, and the other not. They found that the amplitude of these fluctuations as well as the noise power level were lower for the fan fitted with swept blades.
Application to the AXIPAL 3i range:
The different profiles are swept forward, especially at the blade head (figure 3).

Tip clearance noise

Influence of the tip clearance on the noise power level

Near the tip clearance the flow becomes three-dimensional and creates a vortex, called wing-tip vortex, which takes fluid from the pressure side and swirl it around to the suction side. This vortex increases turbulence and boundary layer thickness on suction side.
To reduce the noise level, it is advisable to reduce the tip clearance, but that requires a perfectly round and rigid casing. The solution for AXIPAL was to design a welding free casing, with low deformation, and to ensure roundness by 4 arms at 90° (figure 4).

Fig. 4 : Solution for AXIPAL

The blade tip received also a special patented device in order to limit wing-tip vortex strength (figure 5).

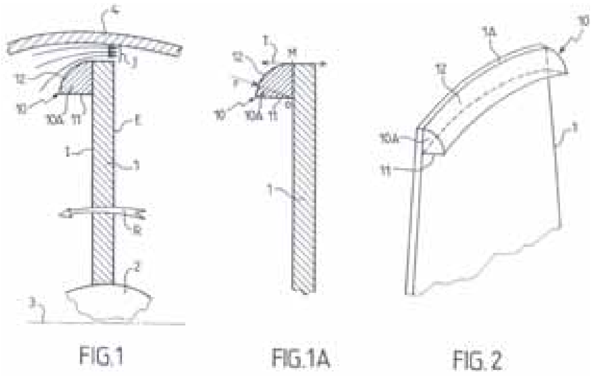

Fig. 5 : Limitation of the wind-tip vortex strength

Upstream and downstream flow interaction noise

Interaction noise of incidental flow with the blades

Narrow band noise
Non uniformity of the average speed at the fan inlet leads to a periodic variation of the average force on each blade. This is the source of emission of narrow band noise at the blade passage frequency (BPF) and its harmonics. The non-homogeneity on the circumference is the determining parameter.

Broad band noise
If the incidental flow is strongly turbulent, we can have the emission of a broad band noise.
All these phenomena due to the incidental flow interactions with the blade are gathered in what is called the “system effect”.

Application to the AXIPAL 3i Range:
It is necessary to take into account that a system effect can partly destroy the acoustic gain brought by a low noise fan as the AXIPAL 3i range. The choice was made of a large casing with a large radius integrated bell mouth cone entry that prevents performance loss due to poor upstream flow conditions.

Interaction noise of blade wake interaction with downstream obstacles

The rotating wake of each blade creates a periodic variation of the average force exerted by the flow on each downstream obstacle.

This is at the source of the emission of narrow band noise at the blade passage frequency (BPF) and its harmonics
By the same mechanism the turbulent wakes of the blades are the source of the emission of broad band noise.

Application to the AXIPAL 3i Range
Care was undertaken to avoid obstacles located in the impeller wake, such as electrical connection boxes, or motor feet.

The arms supporting the motor were studied carefully over the whole fan performance curve in order to obtain arm surface at the leading edge as aligned as possible with the incidental flow. This was done using numerical simulations (described in §5). This is illustrated by figure 4.

3D numerical simulations

Aim of the simulations

The numerical simulations were performed in order to obtain the following information:
- Visualisation of the flow on the blade surface, to show separation vortices, if any,
- blade exit flow angles, to design the motor arms,
- pressure field for fan performance predictions.

Means

The 3D simulations were performed with the commercial code Fluent. Calculations assumptions are described hereafter:
3D stationary,
- moving frame model,
- k-ε turbulence model,
- cyclic boundary conditions.

The 300 000 tetrahedral mesh was representing the inlet cone, the pipe, the blades and hub, and the motor with its arms.
Figures 6 and 7 show typical results provided by simulations. The detailed velocity angles were used when designing the motor arms geometry (shown at figure 4).

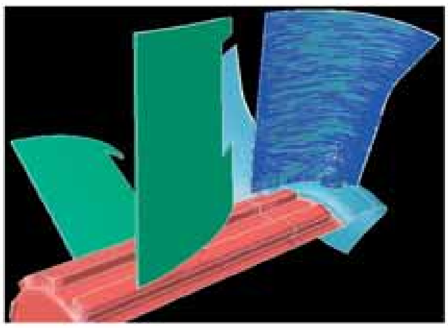

Fig. 6 : Simulations results

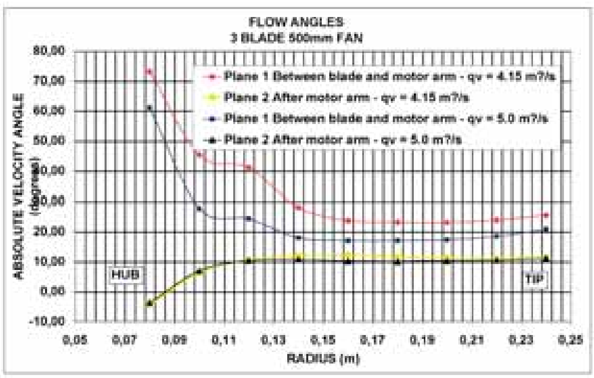

Fig. 7 : Simulations results

Final results

Compared to the former generation fan, the new AXIPAL 3i range provides improved performances in both aerodynamics and acoustics fields:
- up to 10% on power efficiency,
- between 2 and 9 dB(A) reduction on noise level.

Figure 8 shows the noise level of new (red lines) and former generation (blue lines) fans plotted on the performance curve range.

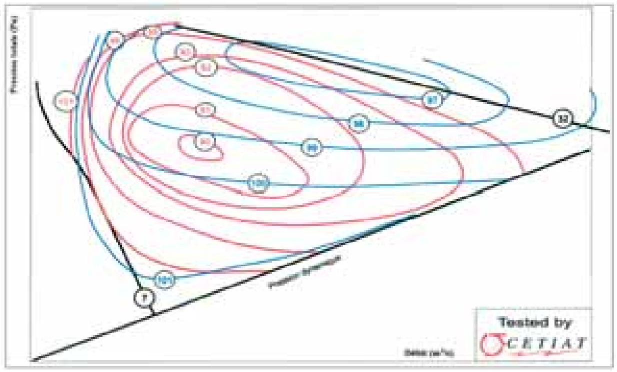

Fig. 8 : Noise level of new and former generation fan

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