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Aerodynamic Noise of Fans

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Contributed Report 01

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AERODYNAMIC NOISE OF FANS

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1. GENERAL REMARKS ON FAN NOISE

Fans are used in many industrial, building and household applications, especially for ventilation, and are often considered as particularly noisy components. A large amount of work has been carried out for improving knowledge on fan noise generation and finding noise reduction means. These researches mainly rely on works initially performed on rotating machinery used for instance in aeronautic applications, but significant differences exist between the noise mechanisms of high speed fans of aircraft engines and those of low speed domestic or industrial fans. Furthermore, on account of the variety in the types of fans and the complexity of the internal flowfield, many unclear areas remain in the understanding and prediction of fan noise. Reference [1] presents a non-exhaustive state of the art of the knowledge in this field.

Three kinds of noise are met with on fans:

- **aerodynamic noise** : noise due to the interaction of the airflow with the impeller and the fixed components of the fan. Its contribution prevails in most cases
- **electromagnetic noise** : noise of the electric motor that drives the fan. The main noise source of the motor is due to the mechanical excitation of the stator by the magnetic field in the air gap between the rotor and the stator
- **mechanical noise** : noise of the bearings and transmission systems.

Electromagnetic and mechanical noise contributions to the fan noise level may become non negligible only at low rotational speed (below 500 to 1000 rpm).

Aerodynamic noise characteristics depend on parameters like type and geometry of the fan, impeller diameter, rotational speed, fan operating point, connection of the fan to the ductworks, … Airborne noise radiated within the fan ducts or through the openings is usually substantially higher than structureborne noise, which is due to the mechanical excitation of the fan support and casing by the vibrations of the rotor.

A typical fan noise frequency spectrum is made up of tones at multiples of the blade passage frequency BPF (BPF = B.N where B is the number of blades and N is the rotation speed in Hz), and of a broadband spectrum. The amplitude of the tones emerging from the broadband level is more or less important according to the type of fan, operating point or other parameters. Figure 1 shows an example of narrow-band sound pressure spectrum measured in a duct in front of an axial flow fan. Peaks at harmonics of BPF are clearly seen.

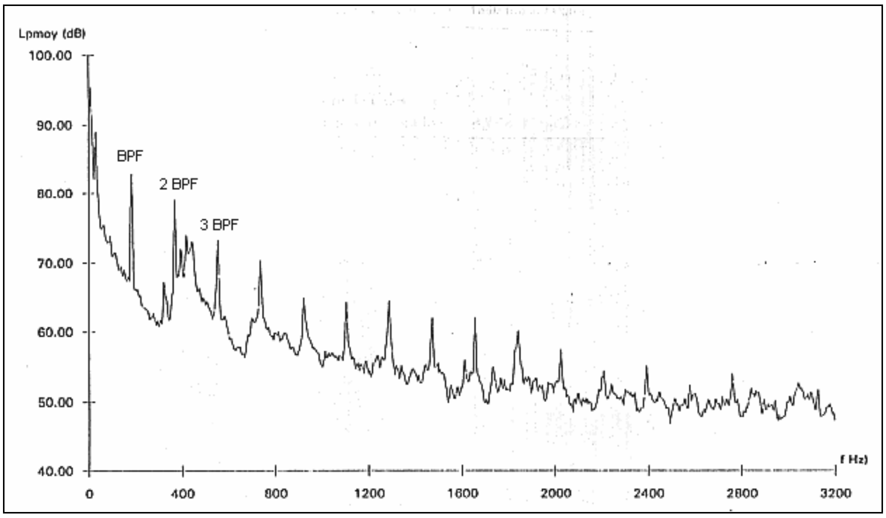

Figure 1 Example of sound pressure spectrum measured on an axial fan

Before presenting the different mechanisms that generate tonal and broadband noise it seems worthwhile to bring in preliminary information. First of all, aerodynamic noise has nothing to do with blade vibrations, the blades being considered as perfectly rigid. Unlike machines that work in heavy fluids such as water (pumps, marine propellers), blade vibrations do not play any significant role in the noise radiated by fans and other machines running in air. This explains why blade material (plastic, metal) has no significant effect on the noise level.

Another idea, which is often put forward, is that it is worthwhile to increase the fan efficiency to reduce its noise level. This affirmation is most often contradicted by experience, since the physical mechanisms associated with noise and fan efficiency have no actual links. This assertion does not come in contradiction with the fact that the noise level of a fan is usually lower at its best efficiency point, but explains why two fans of same type and same efficiency may have very different sound levels.

2. NOISE ACCORDING TO THE TYPE OF FAN

2.1 Introduction

This section briefly describes the different aerodynamic noise sources according to the fan type. A more detailed presentation of the sound mechanisms will be given in section 3.

There are four main categories of fans:

- axial flow fans
- centrifugal fans
- mixed flow fans
- cross-flow fans.

Axial and centrifugal fans are the most widely used. The following sections provide condensed information on the acoustic features of these fans. More details on their aerodynamic and acoustic performance may be found in [1].

2.2 Axial flow fans

a) Tonal noise:

Tones at BPF and its harmonics are due to the periodic fluctuations of the blade load induced by the non-homogeneity of the mean flow velocity at the impeller inlet (figure 2). These load fluctuations occur at harmonics of the rotation frequency N, but the frequencies of the radiated tones are multiples of BPF.

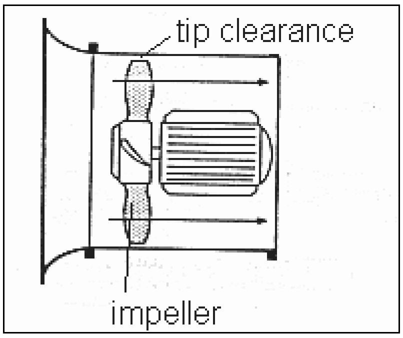

Figure 2 Axial flow fan

On vaneaxial fans (axial fans with fixed outlet guide vanes (OGV), figure 3) another noise mechanism comes from the interaction of the blade rotating wakes with the OGV.

The sources are located in this case on the vanes and their frequencies are still multiples of BPF.

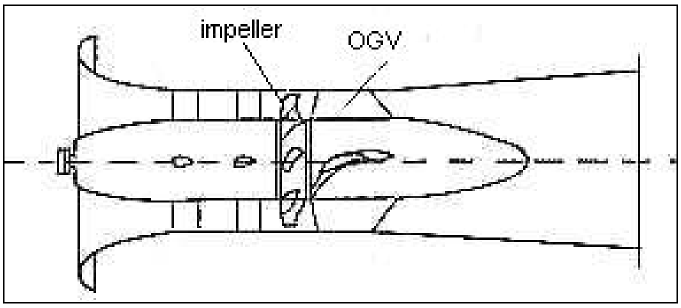

Figure 3 Vaneaxial fan

b) Broadband noise:

Three main broadband noise sources are encountered on axial fans:

- noise due the interaction of the incident turbulent flow with the impeller blades,
- blade self-noise (see section 3)
- tip clearance noise (noise associated with the highly perturbed flow in the radial clearance between the blade tip and the fan casing) .

On vaneaxial fans there is another source resulting from the interaction of the blade turbulent wakes with OGV or fixed downstream obstacles close to the impeller.

2.3 Centrifugal fans

a) Tonal noise:

The main cause of tonal noise radiation is associated with a non-homogeneity of the mean flow field at the impeller entrance, and for centrifugal fans with volute it is due to the interaction of the mean flow in the blade wakes with the volute cut-off (figure 4). In the latter case the source is located on the cut-off.

Centrifugal fans with radial blades (figure 5) are known to be particularly noisy, with a very strong tone at BPF. Conversely, tonal noise level of centrifugal fans with forward-curved blades (figure 6) is low since the impeller has many blades of small chord. Blade wakes are strongly attenuated when they reach the scroll cut-off if the radial clearance between the impeller and the cut-off is at least 10% of the impeller diameter, which is the recommended minimal value for low-noise fans.

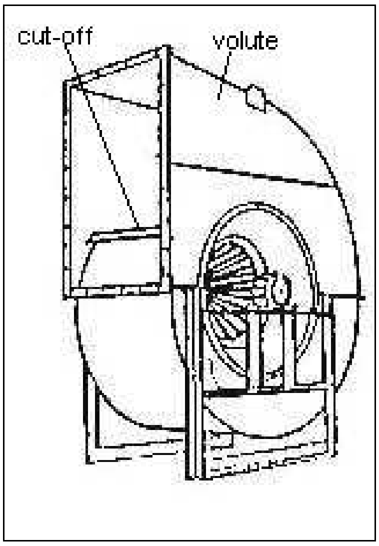

Figure 4 Centrifugal fan

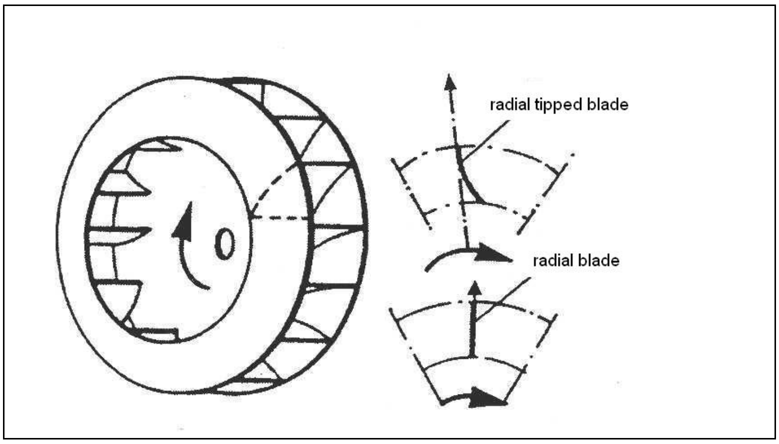

Figure 5 Centrifugal impeller with radial blades

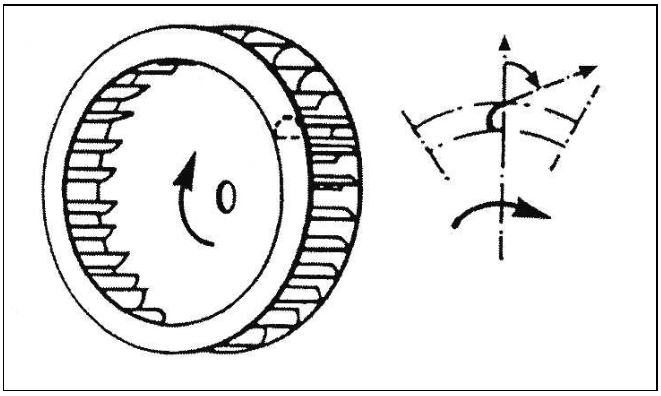
Figure 6 Centrifugal impeller with forward-curved blades

b) Broadband noise:

Broadband noise mechanisms on centrifugal fans are similar to those on axial fans, except tip clearance noise which has no equivalent on centrifugal fans. On the other hand, the interaction of the turbulent flow at the impeller exit with the cut-off and the whole volute is a significant source of broadband noise.

Forward-curved fans have acoustic characteristics that differ from the other centrifugal fans because of the flow pattern within the impeller. On this type of fan broadband noise is linked with the flow structure within the whole fan, instead of the flow pattern between the blades that influences self-noise. This feature explains the evolution of the overall sound level with the fan operating point, which is different on the forward-curved fans and on the other centrifugal fans. On the latter the sound level is the lowest at the best efficiency point (BEP) since in this case the blades are well adapted to the flow incidence, while on forward-curved fans the noise level increases continuously with flow rate, without reaching a minimum at the BEP.

2.4 Mixed flow fans

Noise mechanisms on these fans (figure 7) are very similar to those of axial fans with or without OGV.

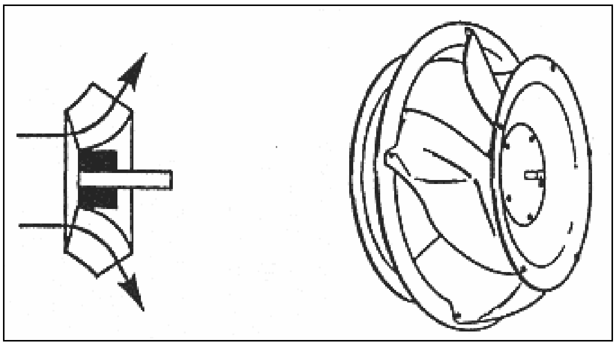

Figure 7 Impeller of a mixed flow fan

2.5 Cross-flow fans

Aerodynamic and acoustic characteristics are strongly influenced by a vortex, whose position in the impeller depends on the operating point (figure 8). The evolution of the overall sound power level with volume flow is similar to that of forward-curved centrifugal fans, i.e. the level continuously increases with flow without reaching a minimum at the BEP. Like on forward-curved fans, the noise seems to be influenced by the general flow pattern within the whole fan more than by the fine structure of the flow on the blade sides.

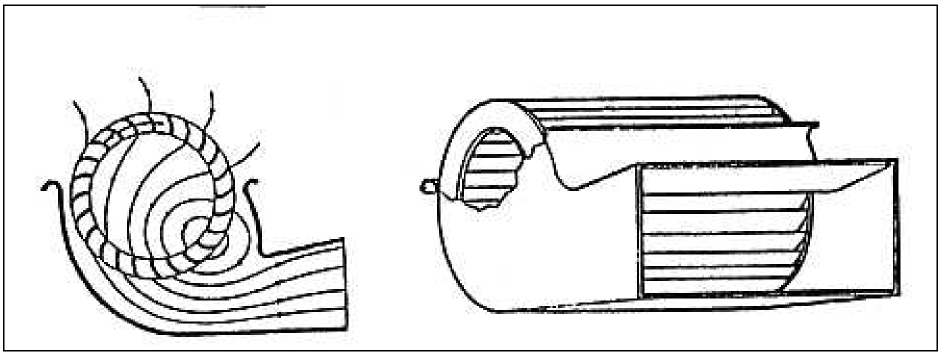

Figure 8 Cross-flow fan

3. MECHANISMS OF AERODYNAMIC NOISE GENERATION

3.1 Introduction

According to Lighthill's acoustic analogy, aerodynamic noise sources may be separated in:

- monopole sources (fluctuations of volume flow associated with the displaced air volume by the rotating blades)
- dipole sources (aerodynamic forces exerted by the flow on the blades and fixed components of the fan)
- quadrupole sources (fluctuating shear stress of the turbulent flow between the blades).

On low tip speed machines like most of the fans, it can be shown that only dipole noise brings a significant contribution to the overall level. Furthermore, only the unsteady forces exerted on the blades are important, the effect on noise of the steady load being negligible when the tip Mach number is lower than 0.3.
We now describe these different dipole noise mechanisms, which generate either tonal or broadband noise

3.2 Periodic unsteady loading noise (tones)

When the mean flow velocity at the impeller inlet is non uniform, especially along the circumferential direction, a periodic variation in amplitude and angle of attack of the relative mean velocity W occurs at the blade leading edge during the rotation (figure 9). This fluctuation of W induces a periodic fluctuation of the blade loading at multiples of the rotation frequency N, which for a fan with B equidistant blades leads to emission of tones at BPF = B.N and its harmonics. This non-homogeneity of the impeller inlet velocity may have many different causes: wakes of upstream fixed obstacles such as struts, non-homogeneous flow due to an elbow or dissymmetry in the inlet ductworks, etc…

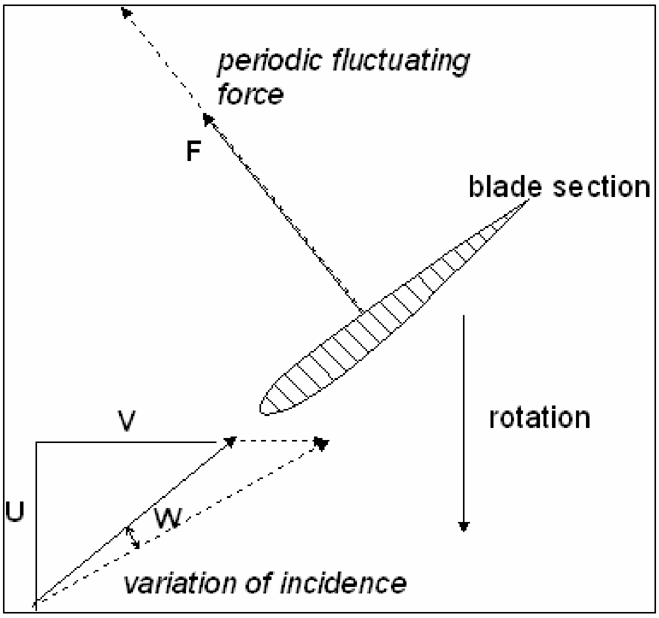

Figure 9 Velocity triangle at the blade leading edge

Prediction of the tonal sound levels requires to assess periodic blade loading, which can be evaluated from the mean flow velocity field at the impeller entrance and from an aeroacoustic transfer function relating the incident velocity to the distribution of forces on each blade.

Fixed obstacles at the impeller discharge, such as OGV, motor struts or volute cut-off, are also sources of tonal noise because of the interaction of the rotating blade wakes with these obstacles. The prediction of the noise generated by these obstructions is not much different from the one used for predicting tonal noise radiated by the impeller itself.

3.3 Turbulence ingestion noise (broadband)

The mechanism is similar to the one mentioned above for tonal noise. Turbulent velocity at the impeller inlet leads to random fluctuations of amplitude and angle of attack of the relative velocity W, which results in random blade load fluctuations and broadband noise emission. A similar phenomenon occurs when downstream obstacles like OGV chop the rotating turbulent wakes of the blades.

This mechanism has been modelled by a number of researchers (see references in [1]). Input data to the model are, in a simplified way, the turbulence level and the spanwise correlation length of the fluctuating velocity in a section close to the blade leading edge. The shape of the noise spectrum due to turbulence ingestion depends on the ratio of the characteristic scales of the turbulent eddies over the blade spacing. If these scales are much smaller than the blade spacing, the resulting spectrum is of broadband type since the sources on the blades are totally uncorrelated. Conversely, if the turbulent scales are much larger than the blade spacing, the sources are more or less correlated on the different blades and the sound spectrum shows humps centred on multiples of BPF.
Turbulence ingestion noise, which is a major cause of acoustic installation effect [7], is mainly observed in the low and medium frequency range of the sound spectrum.

3.4 Blade self-noise (narrowband or broadband)

Blade self-noise refers to all the acoustic phenomena associated with the impeller rotating in a nearly non turbulent flow without upstream or downstream flow obstructions and, for axial flow fans, with a reduced tip clearance. Self-noise sets the bottom level of a fan for a given operating point, the other sources like turbulence ingestion noise (see 3.3) or tip vortex noise (see 3.5) providing an extra contribution to this minimum level. This noise mechanism has a direct link with the characteristics of the unsteady flow in the boundary layer on both sides of the blades. Noise sources are located on the blade trailing edge as mentioned below.
This phenomenon is not only met with on rotating blades, but also on fixed airfoils with or without incidence in a flow field, such as struts, louvers, aircraft wings, … A number of researches has been made on fixed airfoils. They are much easier to perform than on rotating blades and they can provide valuable information (see below).

Blade self-noise can be split up into two distinct mechanisms:

- trailing-edge noise associated with the laminar or turbulent boundary layer on the blade
- vortex shedding noise.

These mechanisms may sometimes be superimposed, especially when the characteristics of the blade boundary layers are different on the pressure and suction sides.

a) Blade trailing-edge noise

Blade trailing-edge noise is most often the main high frequency broadband noise source on fans, so that its contribution to the overall A-weighted sound power level is usually very significant. This noise occurs when the turbulent boundary layer is convected past the blade trailing edge, the turbulent energy of the wall pressure fluctuations being converted into acoustic energy that radiates to the far field. One of the analytical models implemented to predict far-field sound level from the wall pressure fluctuations is due to Amiet [2]. As shown in [3] the input data of this model are the power spectral density and the spanwise coherence length of the aerodynamic pressure fluctuations on the suction side near the trailing edge. Prediction deduced from this model has been very favourably compared with experiment, for instance on a flat plate in incidence in an anechoic wind tunnel [4]. The input data may be obtained from measurements, if it is possible. In this case the accuracy of the prediction is very good. If measurements are not easy to perform, for instance on a rotating blade, the input data may be deduced from a hybrid approach using measured data on fixed airfoils and CFD calculations. Uncertainties are much higher in this case.

This model applies to attached or separated turbulent boundary layer on the suction or pressure side. Separation occurs when the angle of attack increases or if the blade camber is too large. On a flat plate a flow separation appears at the leading edge, even at zero degree incidence, with a reattachment on the blade at a distance that increases with the angle of attack (figure 10). When the airfoil incidence increases the level of the low frequency part of the spectrum continuously increases, while the high frequency part decreases [4], [5].

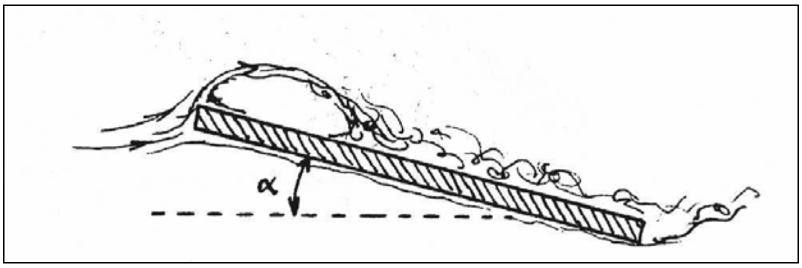

Figure 10 Flow separation on the leading edge of a flat plate in incidence

If the airflow at the impeller inlet is not turbulent and if the blade tip speed is moderate, boundary layer on the blade sides may be laminar. If the trailing edge thickness of the airfoil is thin compared with the boundary layer thickness and if the angle of attack is moderate, a very intense whistle may occur at high frequency. This phenomenon is due to a feedback loop mechanism between the flow instabilities in the boundary layer and the sound field radiated by the trailing edge. This noise results in a very narrowband hump centred on a frequency f ~ U/e, where U is the mean flow velocity outside the boundary layer and e is the blade trailing edge thickness. This noise vanishes when the boundary layer becomes turbulent or when the flow incidence increases [5]. One of the noise control means is to make the incident flow turbulent, for instance by inserting a strut close to the impeller inlet section.

b) Vortex shedding noise

This noise, which is due to the von Karman vortex streets in the blade wakes (figure 11), occurs when the angle of attack is low and when the trailing edge thickness of the airfoil is large compared with the boundary layer thickness. It is similar to the well-known aeolian noise of cables or poles in the wind. This noise is of narrow band type, with a hump centred on a frequency f ~ 0.2U/e (where U is the mean flow velocity and e is the airfoil thickness at the trailing edge). The hump most often emerges from the broadband spectrum due to trailing-edge noise [4].
Bevelling the blade trailing edge may eliminate this noise. It also disappears when the angle of attack increases, i.e. when the boundary layer at the trailing edge becomes larger than the airfoil thickness. On axial fans the relative velocity varies spanwisely along the trailing edge, in such a way that the hump is broader that the one observed on a fixed airfoil in a uniform airflow, but the phenomenon remains basically the same [6].

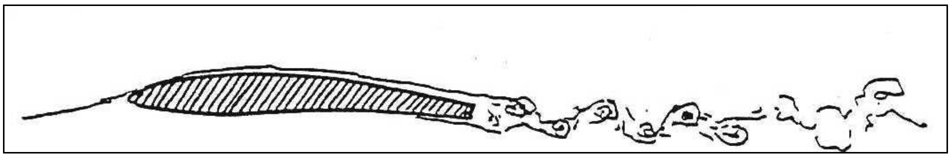

Figure 11 Vortex shedding in the wake of an airfoil

3.5 Tip vortex noise (broadband)

This noise only concerns axial and mixed flow fans. The flow in the tip clearance is turbulent and rather complex because of local phenomena (tip vortices, leakage flows) associated with the pressure difference between the pressure and suction sides of the blades. Noise may be due to the interference of the tip leakage vortex of a blade with the casing and the adjacent blade. No prediction model has been implemented to account for this mechanism quantitatively.
It is well known that a reduction of the radial tip clearance is usually beneficial for the fan aerodynamic and acoustic performance on axial fans with or without OGV. It is not that true on propeller fans (axial fans with a ring surrounding the impeller instead of a casing), probably because of the strong radial component of the flow velocity at the impeller inlet [1].

4. CONCLUDING REMARKS

The objective of this paper was to present a brief state of the art of the knowledge on fan noise mechanisms, with a qualitative description of the models developed to predict the noise levels associated with these phenomena. The final goal of these researches is orientated towards the design of low-noise fans and the minimisation of acoustic installation effects.

Tonal noise mechanisms are now well known and sound level prediction is more and more precise, even if some difficulties remain to get accurate input data to the models and adequate transfer functions between the incident mean flow field and the blade periodic loading.

Broadband noise, including narrow band noise due to vortex shedding, provides a major contribution to the fan overall A-weighted level, especially at low speed (i.e. below 1500 rpm). That is why it is important to understand and endeavour to reduce the broadband noise level as well. Even if a considerable work has already been done on this topic, many unknown factors remain in the understanding and modelling of the phenomena at the origin of broadband noise. For instance, tip vortex noise is not fully understood and even less predicted.

Researches on fixed isolated airfoils are much easier to do than on rotating blades, while they may provide valuable information for the development and validation of models that apply to fans, especially to axial and backward-curved centrifugal fans. Forward-curved centrifugal and cross-flow fans are less concerned since their sound characteristics seem to be preferably influenced by the overall flow pattern within the whole fan, more than by the aerodynamic pressure fluctuations in the blade boundary layers.

References

[1] A. GUEDEL: *Acoustique des ventilateurs.* Edition PYC Livres, Paris (1999)

[2] R.K. AMIET: Effect of the incident surface pressure field on noise due to turbulent flow past a trailing-edge. J. Sound Vibration, Vol. 57(2) (1978)

[3] M. ROGER, S. MOREAU, A. GUEDEL: Broadband fan noise prediction using single-airfoil theory – Parts 1 and 2. Proceedings of Fan Noise 2003, Senlis, France (2003)

[4] A. GUEDEL, M. ROGER, C. TRUFFINET, S. MOREAU: Prediction of fan broadband noise. Proceedings of International Conference on Fans, London (2004)

[5] T. BURGAIN: Contribution du bruit propre des pales au bruit à large bande des ventilateurs centrifuges. Thèse de Doctorat ECL 98-09 (1998)

[6] T. FUKANO, H. SARUWATARI, H. HAMAKAWA: Prediction of spectral distribution of broadband noise generated from an axial flow fan.
Proceedings of Internoise 2000 (2000)

[7] A. GUEDEL: Prediction of the noise installation effect induced by a bend at the inlet of an axial flow fan. Proceedings of Fan Noise 2003, Senlis, France (2003)

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