FAN NOISE PREDICTION FROM LOCAL EXPERIMENTAL SOURCE TERM AND NUMERICAL SOUND PROPAGATION

Maxime LEGROS[1], Yvon GOTH[1], Alain GUEDEL[2]

[1] *CETIM, 52 avenue Félix-Louat, 60300 Senlis, France*

[2] *CETIAT, 25 avenue des Arts, 69100 Villeurbanne, France*

SUMMARY

Modeling and numerical approaches are privileged ways to investigate the mechanisms of noise generation by fans. The paper explores a fan noise synthesis approach based on the numerical propagation of a noise source located on the fan blades, defined from experimental data obtained on wing profiles. The test of the method has shown that the source term adjusted on the Brooks-Pope-Marcolini trailing edge noise database was insufficient to represent the noise measured on a four blades fan. Some auxiliary source terms liable to fill the gap between the model and the experimental results are reviewed, and their relevancy is evaluated.

INTRODUCTION

Several numerical approaches can be used to predict the noise radiated by a fan, from the simpler band-octave correlation to the costly and technically challenging aeroacoustics computing. In an industrial context, a mid-way approach, relying on experimental data to define the acoustic source term, and on well-known computational method to propagate it, is still of interest.

The feasibility and evaluation of the efficiency of different approaches have been evaluated in a common research effort between the Technical Center of the Aeraulic and Thermal Industries (CETIAT) and the Technical Center of the Mechanical Industries (CETIM) located in France, and the Von Karman Institute (VKI) in Belgium. The present paper focus on the part handled by the CETIM, which consists in evaluating the approach using experimental wing profiles noise data extrapolated to a fan configuration.

The noise source database used here is the well-known Brooks-Pope-Marcolini database, and the experimental fan noise database is the one created in the CETIAT on an industrial fan.

APPLICATION OF WING PROFILE NOISE DATA TO A FAN

Brooks-Pope-Marcolini database

T. Brooks, D.S. Pope and M.A. Marcolini (BPM) have created an experimental database on the noise generated at the trailing edge of air wing profiles (NACA0012) for various profiles length, angle and airflow [1]. The experimental data are synthesized under the form of dimensionless spectrums giving the Sound Pressure Level (SPL) at an observer position – situated at mid span over the profile's trailing edge.

The physical references used for scaling are the flow Mach number M, the boundary layer displacement thickness δ^*, the spanwise length of the profile L, and the distance to the observer r_e. The scaled third octave band sound pressure level is given by:

$$Scaled\ SPL_{1/3} = measured\ SPL_{1/3} - 10\log\left(M^5 \frac{\delta^* L}{r_e^2}\right). \qquad (1)$$

The displacement thickness δ^* is a given function of the flow angle and the Reynolds number. The mathematical form of the scaled spectrums is detailed in reference [1], and is not given here.

This database has been used to compute the trailing edge noise of wind turbines [2] and has been implemented in the NAFNoise software [3].

Application to the fan

The BPM correlations are applied to an 800 mm diameter fan widely tested in the CETIAT in France [4]. The aerodynamic and acoustic performances of the fan have been tested with 2 and 4 blades, in free air and with a shroud (Figure 1).

Figure 1 – Experimental fan in 4 blades configuration with a shroud (doc. CETIAT)

The BPM correlations have been applied to this fan as follows:

- The blades have a thin profile, very different from the NACA0012 profiles. Therefore, the displacement thickness at the trailing edge is taken from a RANS calculation performed in CETIAT [5] rather than using the BPM correlations.
- The flow angle is computed from the chord orientation. The zero angle reference should have been obtained from the flow angle at no lift condition but this data was not available.
- Only the contribution of the turbulent boundary layer on the suction face of the blades has been taken into account (TBL_TE noise).

- No ‘bump’ associated to the bluntness noise was visible on the experimental data, so this contribution has been omitted. As regard the tip noise, the flow conditions on the blade tip of a shrouded fan is very different from the one at the free tip of a wing profile, and we consider that the tip noise BPM correlation is hardly transposable in this case.
- The blade is cut along the span in 6 radii (R179, R222 and so on) associated with 6 sources whose contributions are summed to get the total SPL at the observer position.
- The Sound Power Level (SWL) is computed from the SPL by using the directivity functions given in [1] and summing the contribution of the 4 blades. The result is compared with the measured SWL (Figure 2).

The results are given in Figure 2 in the case of a 4 blades fan with a 30 degrees pitch angle at a flow rate close to the nominal one (82% of the maximal flow).

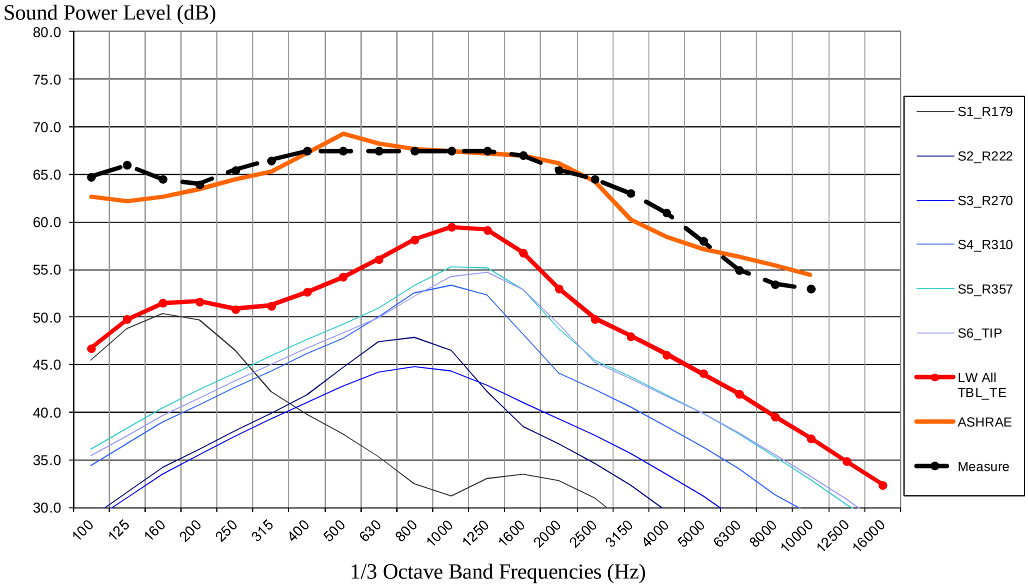

Figure 2 – Linear Sound Power Level (dB) for the 4 blades 30 degrees shrouded fan.

This graph shows:

- The SWL of each sources (S1_ to S6_ curves).
- The total SWL computed using BPM TBLE_TE correlation (LW All).
- The measured SWL (Measure).
- The SWL computed using the ASHRAE method, as referenced in [6]. This method, widely used in engineering’s applications, relies on a statistical approach to provide a reference spectrum for the SWL of fans operating close to their nominal point.

One notes that the SWL computed with the BPM method underpredicts the measured one by 8 to 15 dB.

The ASHRAE spectrum provides a SWL very close to the measured one: the measured SWL can be considered to be representative of an axial fan. Consequently; the under prediction is not due to a specific characteristic of the fan.

Figure 3 shows the results of the same approach applied to the same fan without shroud. The reference data have been extrapolated to 4 blades from the measurements made with the 2 blades fan [7]. In that case, BPM correlation for flat cut-off tip noise is included. The BPM correlation fits well with the experimental data, the tip contribution being dominant under 800 Hz and the TBL_TE contribution above.

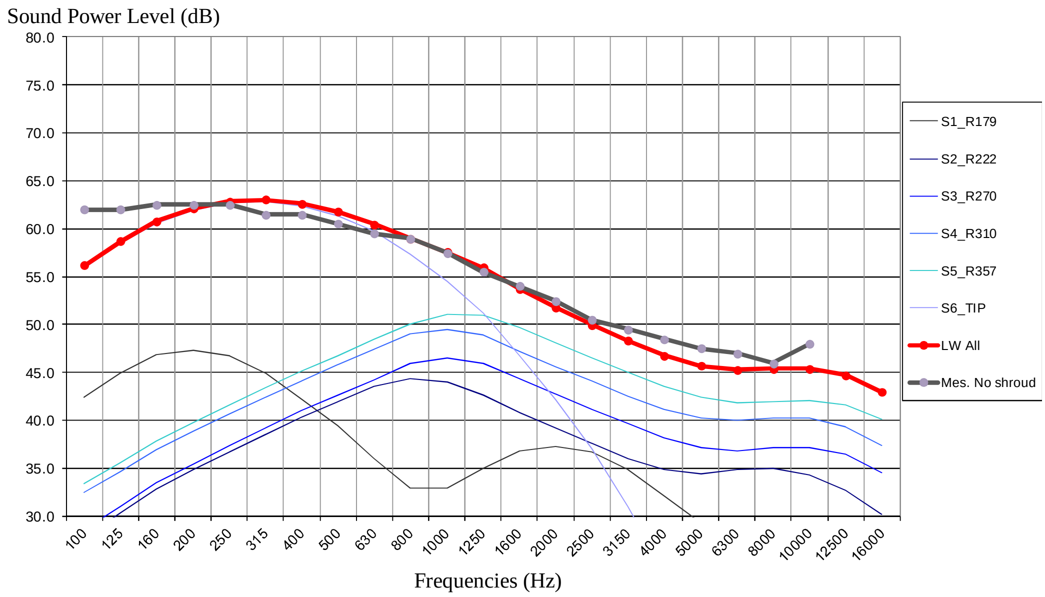

Figure 3 - Linear Sound power level (dB) of the 4 blades 30 degrees fan without shroud.

Synthesis

The BPM approach strongly underpredicts the SWL generated by a fan inserted in a shroud, while it correctly predicts the SWL of the unshrouded fan. The existence of a specific sound source associated with the interaction between the fan and the shroud has to be considered.

The nature of this source is not clear yet. One may think to:

- the interaction between the tip vortexes and the shroud,
- the noise generated by the inlet turbulence interacting with the leading edges of the blades,
- the noise generated by the interaction of the leading edge of the blade’s tip with the turbulence of the boundary layer on the shroud,
- an acoustical amplification effect due to the shroud,
- the noise related to the laminar separation bubble on the suction face. This bubble can be seen on the RANS calculation (Figure 4).

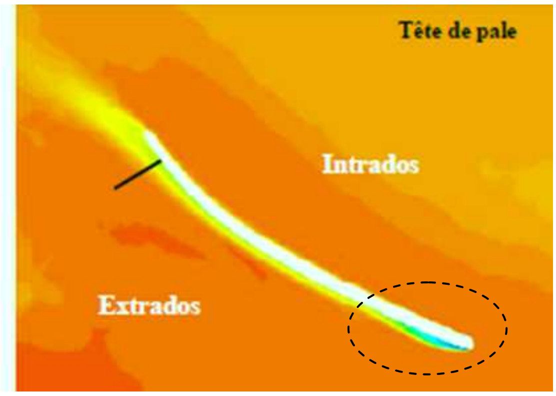

Figure 4- RANS calculation of the flow around a blade, showing the recirculation bubble

These assumptions are investigated in the following sections, whether using a Finite Elements approach, or relying on elements available in the technical literature.

THE FINITE ELEMENTS NUMERICAL APPROACH

Upon the assumption of a low Mach number, the inhomogeneous Helmholtz equation including the aeroacoustics terms derived from the Lighthill's analogy writes:

$$k^2 P + \Delta P = -\frac{\partial}{\partial x_i}\frac{\partial}{\partial x_j}\left(\rho u_i^{'} u_j^{'}\right). \quad (2)$$

where P is the fluctuating pressure, ρ the fluid density, and u'_i the fluctuating velocity of the fluid.

An approximation, currently used in low Mach number aeroacoustic studies, simplifies the source term which can be obtained from an incompressible transient fluid flow computation (see Equation (3)). This assumption does not consider the feedback mechanisms (acoustic waves interacting with the flow). It allows decoupling the fluid flow computations and the acoustic propagation ones which are easier and cheaper to handle than a fully compressible coupled model.

When the source term is computed from an incompressible fluid, it can be written as

$$\frac{\partial}{\partial x_i}\frac{\partial}{\partial x_j}\left(\rho u_i^{'} u_j^{'}\right) = -\Delta P^{'} \quad (3)$$

Where $\Delta P'$ is the Laplacian of the incompressible fluid pressure fluctuations.

Equation (2) can then be rewritten as follows:

$$k^2 P + \Delta P = \Delta P' \quad (4)$$

If the pressure term is split in $P = P' + p$, where p is a complementary term that is equal to the acoustic pressure in zones where no sources are present, one gets:

$$k^2 p + \Delta p = -k^2 P' \quad (5)$$

Equations (4) and (5) are formerly equivalent even if the complementary term p has no real physical meaning in the zones where sources are present. As it doesn't require a second order derivative on the source term P', the Equation (5) – providing sturdier calculations than Equation (4) – has been used for the followings computations.

Following Caro [8], the finite elements approach presents some advantages over the boundary elements method when volume sources of aeroacoustic type are involved, so all calculations use this approach.

The variational form of Equation (5) is

$$\forall q, \quad \int_\Omega k^2 pq d\tau - \int_\Omega \frac{\partial p}{\partial x_i}\frac{\partial q}{\partial x_i} d\tau + \int_{\Gamma_x} jk\frac{\rho c}{z} pq ds = -\int_\Omega k^2 P' q d\tau + \int_\Gamma jk\rho c u_n q ds \quad (6)$$

where:

- Ω is the volume while Γ and Γ_x are the boundaries of the domain.
- u_n the normal velocity on the boundaries,
- ρ and c are respectively the fluid's density and celerity while Z is the acoustic impedance of the external boundaries.

On the external boundaries Γ_x, delimitated by a sphere in 3D and a circle in 2D, the anechoic conditions are approximated by an impedance term presented in Equations (7° and (8).

$$z = \rho c \frac{jkr}{1 + jkr} \qquad \text{(7) in 3D}$$

$$z = \rho c \frac{jkr}{0.5 + jkr} \qquad \text{(8) in 2D}$$

where r is the radius of the external boundary.

The finite element mesh covering the fan and its surroundings is shown in Figure 5. It counts 75 000 triangular surface elements and 500 000 tetrahedral volume elements.

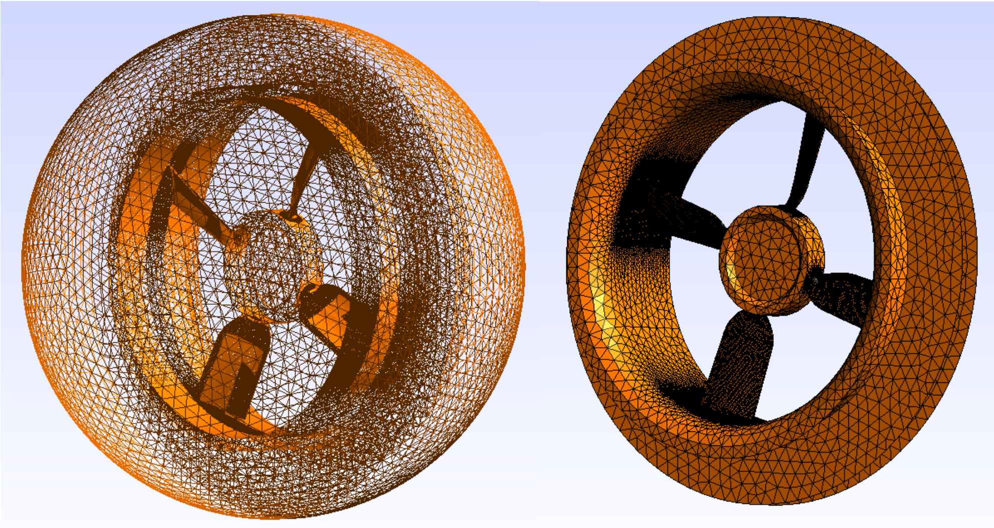

Figure 5 - Surrounding Air volume (left), fan and shroud mesh (right)

AUXILIARY SOURCES REVIEW

The volume source $-\int_{\Omega} k^2 P' q d\tau$ from Equation (6) is set up as a surface term multiplied by the boundary layer thickness δ in order to ease the implementation in a standard finite element code – see Equation (9). As we are looking for a relative result between different configurations, the definition of the source term can be approximated.

$$-\int_{\Omega} k^2 P' q d\tau \rightarrow -\delta \int_{\Gamma} k^2 P' q ds \qquad (9)$$

Acoustic effect of the shroud

The acoustic effect of the shroud is computed by comparing the SWL generated by a turbulent boundary layer source located on the blade, with and without a shroud. The structure of the source is based on a modified Corcos model [9]. The fluid pressure fluctuations on the surface are set as:

$$P' = (1 + \alpha_x \frac{\omega}{U_c} |x|) e^{-j\frac{\omega}{U_c}x - \alpha_x \frac{\omega}{U_c}|x| - \alpha_y \frac{\omega}{U_c}|y|} \qquad (10)$$

where x is in the chordwise direction and y in the spanwise direction. U_c is the convection velocity equal to 70 % of the main flow velocity. The coefficients a_x and a_y use the standard values α_x=0.1 and a_y=0.7.

It can be seen in Figure 6 that the acoustic response curves of the system with and without the shroud show an amplification effect due to the shroud over 200 Hz, but this effect stay of low magnitude (2 to 6 dB) and can't explain by itself the differences previously observed. The curves plotted in Figure 6 have been obtained using a source term of unitary amplitude.

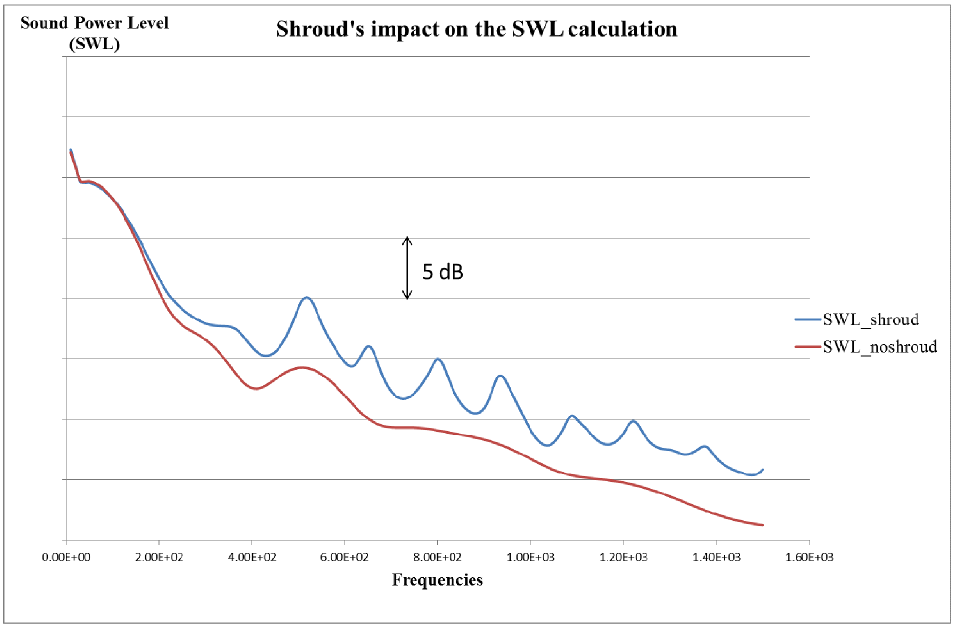

Figure 6 - Frequency response curves for the fan with and without the shroud

Interaction with the shroud boundary layer

The boundary layer on the shroud may interact with the blades' tips and, thus, create a noise source that may be relevant in the application case. The noise generated by this source is estimated thanks to a similar approach as the one that relies on the Amiet's model to predict the leading edge noise of a profile submitted to incoming turbulence [10].

This model requires the turbulent characteristics of the shroud boundary layer (incident flow velocity U and turbulent rate T_w) and its thickness to define the length of the blade leading edge submitted to this flow.

In the Amiet's theory, the SWL's prediction is done following three steps: get the load fluctuations induced by the impact of the incident burst, then build an analytical and aero-acoustical transfer function, and finally predict the Sound Power Level using a far-field radiation hypothesis.

Here, only the load fluctuations on the blade tip surface are computed using the Amiet's model. The sound propagation is computed using the finite element model. This allows taking into account the acoustic influence of the shroud.

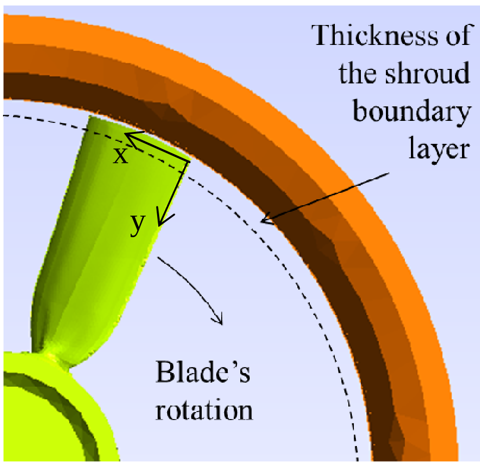

Figure 7 - Blade's section excited by the turbulence of the shroud boundary layer

The blade span excited by the shroud boundary layer is equal to the thickness of the shroud boundary layer withdrawn from the gap between the blade's tip and the shroud (Figure 7).

The Amiet model relies on a 2D turbulence model, assuming an infinite extent of the incoming turbulence in the transversal (y) direction. This is clearly a poor model for the boundary layer turbulence. It is only used here since we are trying to get only an order of SWL under the influence of this term. The model will be improved when the detailed data coming from a transient CFD analysis of the systems will be available.

The resulting distribution of the loads fluctuations are shown in the Figure 8. As expected, the load is concentrated at the leading edge of the blade.

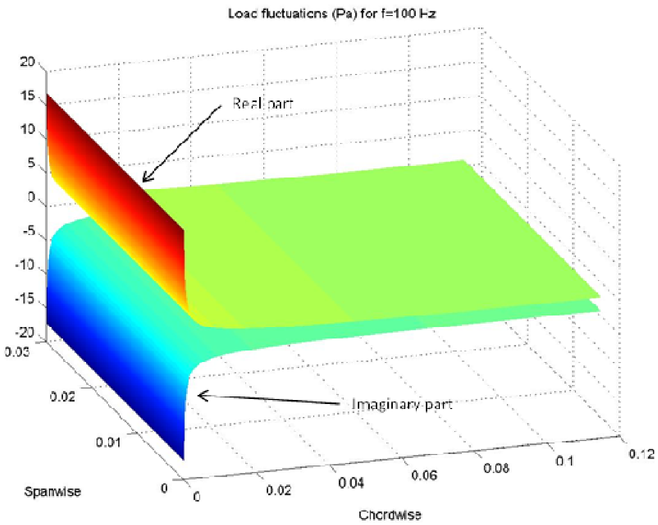

Figure 8 - Load fluctuations distribution at f=100 Hz

The Sound Power Level calculation is performed for different values of the turbulent rate T_w. As shown in the Figure 9, moderate turbulence is sufficient to get a SWL close to the measurements for frequencies over 200 Hz. Then the interaction between the blade tip and the shroud boundary layer can be a seen as a potential candidate for the missing source, and deserve further studies.

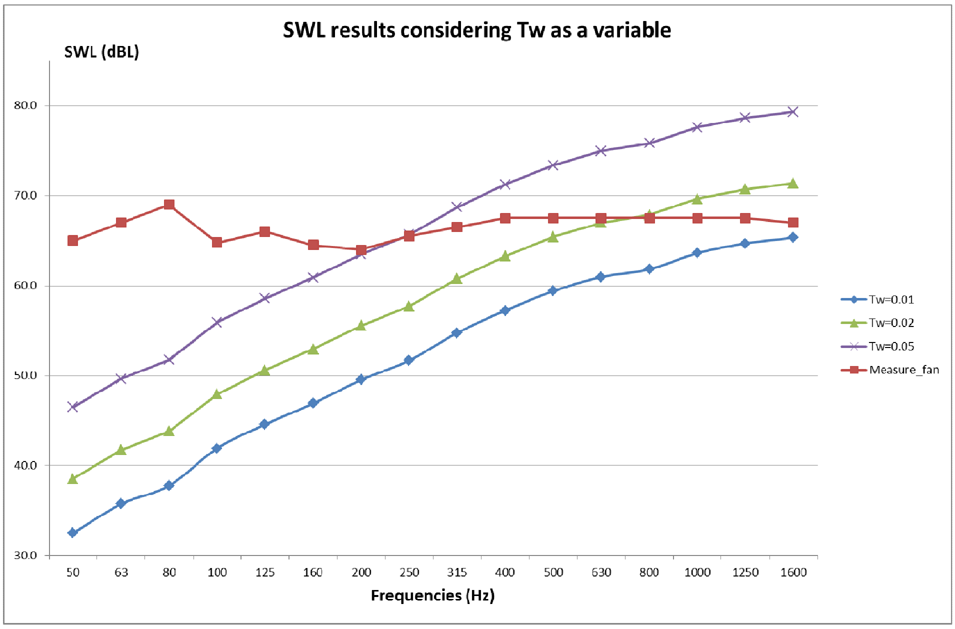

Figure 9 - Variation of the SWL considering different values of the turbulent rate

Leading edge turbulence interaction

The BPM approach focuses on the trailing edge noise, considering that this contribution is dominant on the leading edge noise for the wing profiles tested.

In our case, Y. Rozenberg [11] has shown that the leading edge noise can be important in the case of high level of incoming turbulence generated by grids, but remains low for the incoming turbulence levels that are expected in a test room. Then this contribution is not expected to account for the difference observed between the calculated and experimental noise level.

Laminar separation bubble

The pressure fluctuations spectrums acquired on the surface of a thin blade profile similar to the one tested here by Y. Rosenberg in the wind tunnel of ECL show a local high level in the top of the suction side where the separation bubble may happen (Figure 10).

An aeroacoustic computation made by S. Moreau's team at Gauss [12] shows that the laminar bubble can be a noise source of the same order of magnitude as the trailing edge source (Figure 11).

These elements point out that this source has to be taken in consideration in general, even if there are interactions with the shroud. Further studies can be made even if strong pressure fluctuations are not a proof of efficient acoustic radiation taking place away from a singular point such as an edge,

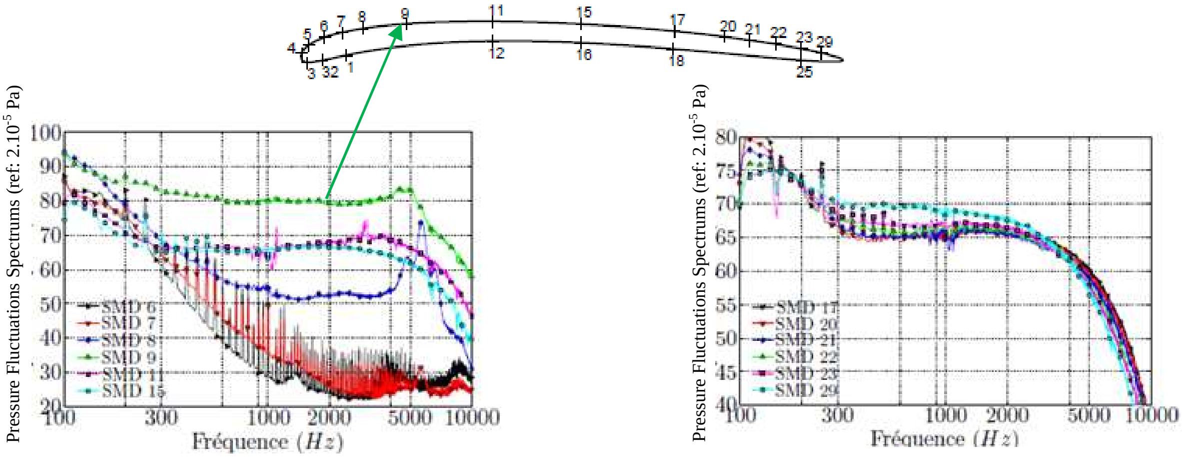

Figure 10 - Pressure fluctuations (DSP) on a thin profile blade [9]

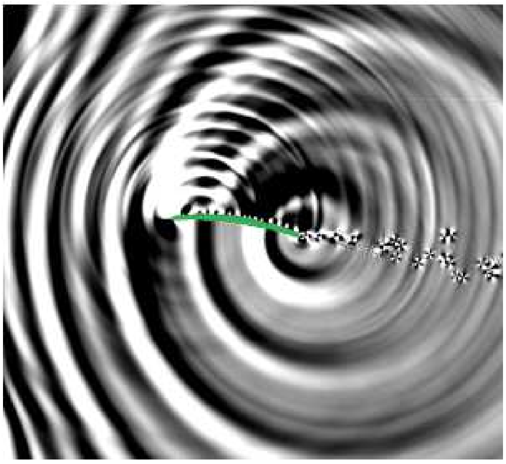

Figure 11 - Aeroacoustic computation on a thin profile
showing the noise source associated to the laminar bubble [12]

Interaction between blades' tips vortexes and the shroud

This noise source is considered to be important. The evaluation of its contribution will be done later on when the transient fluid flow computation results will be available from the other teams working on that project.

CONCLUSIONS

The Brooks-Pope-Marcolini database used to predict the sound power radiated by a fan, while giving a good prediction in the case of a fan in free air, strongly underpredicts the noise radiated by the fan inserted in its shroud. The fan noise prediction must therefore accounts for an additional noise source associated with the interaction between the fan and the shroud.

The nature of that source is unclear for now, but we suspect that the blade tip vortexes or/and the interaction between the blade tip and the shroud boundary layer plays a first-order part. Some experimental and computational literature data has shown that the laminar separation bubble should be considered too.

The transient flow and aeroacoustic computations that are planned in the future developments of this study are expected to give more insight in what is, finally, the main source of noise in a fan and its shroud.

REFERENCES

[1] T. F. Brooks, D.S. Pope, M. A. Marcolini – *Airfoil Self-Noise and Prediction* – NASA Reference Publication 1218, **1989**

[2] P. J. Moriarty – *Modelling of Aeroacoustic Noise From Wind Turbines* – World Renewable Energy Congress VIII, **2004**

[3] P. Moriatry – *NAFNoise User's Guide* – National Wind Technology Center, **2005**

[4] A. Guédel, Y. Rozenberg, M. Roger, G. Perrin – *Prediction of fan broad noise* – Third International Symposium Fan Noise 2007, Lyon, France, **2007**

[5] M. Robitu, A. Guédel, to be published in Fan 2015 symposium, **2015**

[6] A. Guédel – *Acoustique des ventilateurs* – PYC Editions, **1999**

[7] A. Guédel, A. Finez – *Prévision du bruit de bord de fuite d'un ventilateur hélicoïde* – Internal report NTV 2009/005, CETIAT, **2009**

[8] S. Caro, R. Sandboge, J. Iyer, Y. Nishio – *Presentation of a CAA formulation based on Lighthill's analogy for fan noise* - International Symposium Fan Noise 2007, Lyon, France, **2007**

[9] M. Aucejo – *Vibro-acoustique des structures immergées sous écoulement turbulent* – INSA Lyon - Hal Archives ouvertes **2010**

[10] L. D. Santana, W. Desmet, C. Schram – *Extension of the Amiet theory for compact leading edge airfoil noise prediction* – Proceedings of ISMA 2014 - **2014**

[11] Y . Rozenberg – *Modélisation analytique du bruit aérodynamique à large bande des machines tournantes : utilisation des calculs moyennés de mécanique des fluides* – Thesis Ecole Centrale de Lyon - **2007**

[12] S. Moreau, *http://www.calculquebec.ca/fr/grand-public-et-media/recherche/55-moreau*