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REVIEW OF NOISE PREDICTION METHODS FOR AXIAL FLOW FANS

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ABSTRACT
This paper will review some methods to predict aerodynamic noise produced by rotating blades in low Mach number, low to medium speed axial flow fans with an emphasis on broad band noise. The term 'method' used here indicates that the emphasis is put on schemes which include more or less the relevant source mechanisms. The literature surveyed is far from being complete and somewhat arbitrary. Some guidance was given by the idea, that the methods should not be too complex and relatively easy to handle by a fan designer. To the knowledge of the authors none of the more advanced noise prediction methods is used routinely in fan design. A reason might be that the required inputs parameters as inflow and boundary layer parameters are not known in a traditional aerodynamic design procedure.

1 - INTRODUCTION
This paper will review some methods to predict aerodynamic noise produced by rotating blades in low Mach number, low to medium speed axial flow fans with an emphasis on broad band noise. The term 'method' used here indicates that the emphasis is put on schemes which include more or less the relevant source mechanisms. Following LOWSON [1] one can classify noise prediction methods into three groups:

- Class I: Predictions giving an estimate of overall level as a simple algebraic function of basic machine parameters
- Class II: Predictions based on separate consideration of the various mechanisms causing fan noise, using selected fan parameters
- Class III: Predictions utilising full information about the noise mechanisms related to a detailed description of geometry and aerodynamics, e.g. they require computation of local blade element velocities and angles of attack.

The entire aerodynamic noise from fans considered here is usually caused by the fluctuating forces on the fan blades. The most important mechanisms are

- *periodically unsteady blade force* due to inflow distortions (spatially nonunifom inflow, unsteady inflow)
- *stochastically unsteady blade forces* due to incident turbulence (IT), turbulent boundary layer / trailing edge interaction (TBTE), turbulent boundary layer / blade surface interaction (TBS) and flow separation (FS)

In this paper mainly the latter sources are considered. The literature is far from being complete. Their selection even seems somewhat arbitrary. Some guidance was given by the idea, that the methods should not be too complex and relatively easy to handle by a fan designer.

2 - EXAMPLE OF A CLASS I – PREDICTION METHOD
The popular German VDI-Richtlinie VDI 3731, Blatt 2 [2] is a typical class I − prediction method. The idea dates back to REGENSCHEIT and is published in [3]: The overall radiated sound power W of a

fan is proportional to the aerodynamic losses P_{loss} in the fan and a measure for the flow velocity in the fan

$$W \propto P_{loss} \cdot \left(\frac{u_2}{a}\right)^m \tag{1.1}$$

u_2 is the circumferential velocity at the impeller's outer diameter D_2, a the speed of sound, and m the so called Mach number exponent which has to be determined experimentally but is assumed to be constant for a given type of fan (centrifugal, axial, etc.). If the losses are expressed by the overall performance data of the fan (flow rate $\dot{V}$, total pressure rise Δp_t and efficiency η), one obtains

$$W \propto \left[\frac{\dot{V}\Delta p_t}{\eta} - \dot{V}\Delta p_t\right] \cdot \left(\frac{u_2}{a}\right)^m = \left[\dot{V}\Delta p_t\left(\frac{1}{\eta} - 1\right)\right] \cdot \left(\frac{u_2}{a}\right)^m \tag{1.2}$$

or expressed as levels (with the reference values $\dot{V}_0$=1 m^3/s and Δp_0=1 Pa)

$$L_w = L_{W spez} + 10 \cdot lg\left[\frac{\dot{V}\Delta p_t}{\dot{V}_0\Delta p_0}\left(\frac{1}{\eta} - 1\right)\right] + 10m \cdot lg\left(\frac{u_2}{a}\right) dB \tag{1.3}$$

[2] reports the measured specific sound power levels as a function of the Mach number u_2/a for various types of fans and even normalized octave − sound power spectra in terms of the overall sound pressure level and the octave band levels $\Delta L_{W okt} = L_{W okt} - L_W$ as a function of the Strouhal number $Sr{=}fD_{\ 2}/u_2$. This method can serve to obtain a first approximation of the overall sound power level and its spectral components from very few and readily available input parameters. Of course it clearly does not provide the influence of more detailed design parameters, the working point or inflow conditions.

3 - COMPLEX PREDICTION METHODS

The methods described in this section are more or less class II − methods. It seems that a truly class III − method is not available so far.

3.1 - SHARLAND

SHARLAND's method [4] is fundamental for many later studies on fan noise and therefore described briefly. His starting point is a flow containing rigid surface under the assumption of acoustic compactness (characteristic dimensions of the surface $\ll \lambda$) which radiates into the free field due to pressure fluctuations over the surface:

$$W = \frac{\omega^2}{12\pi\rho a^3}\int\int_S \overline{p^2} A_c dx_1 dx_2 \tag{2.1}$$

$\overline{p^2}$ is the mean square pressure *difference* fluctuation, thought of as a local lift fluctuation per unit area (thus the integration is over only one side of the closed surface S), A_c the correlation area. From that SHARLAND derives working equations for the three noise mechanisms IT, TBTE and TBS; e.g for IT under the assumptions that

- the blade chord C is much smaller than the size of the approaching turbulent eddies Λ,
- the turbulent velocity fluctuation w normal to the surface is much smaller than the local mean velocity U parallel to the surface

and with a lift curve slope Φ such that $C_L = \Phi w/U$, here $\Phi = 0.9\pi$, and a correlation area $A_c = U^2/\omega^2$ (from former jet turbulence investigations) he obtains

$$W = \frac{\rho}{48\pi a^3}\int_H \Phi^2 U^4 \overline{w^2} C dx_2 \tag{2.2}$$

The entire method requires the local mean velocity U parallel to the blade surface and the velocity fluctuations of the incidence turbulence $\overline{w^2}$ as aerodynamic input parameters. However, due to the assumptions and simplifications this method does not yield any frequency information of the radiated sound power.

Can these models which are based on as single surface in a flow be applied to a rotating fan rotor? Some justification is given by the following arguments: As shown by MORFEY et al. [5] the sound spectrum of a rotating broad band source is unaffected by its rotation, i.e. by the Doppler shift. Duct walls, intake bells and other reflecting surfaces may not influence the overall radiated power as long as their representative dimensions are comparable with, or greater than, $\lambda/4$, i.e. if the acoustic radiation is at relatively high frequency ([4]). Further, assuming mutually incoherent radiation from each blade, the sound power has just to be multiplied by the number of blades on the rotor.

3.2 - KÖLTZSCH

KÖLTZSCH [6] modified SHARLAND's model in order to incorporate more realistically the frequency dependence of the radiated sound. As SHARLAND he takes the three mechanisms IT, TBS, TBTE into account.

IT. Starting from eq. (2.2), introducing the number of rotor blades z and assuming that all variables do not vary along the span H, the power spectral density becomes

$$\frac{dW}{df} = \frac{0.81\pi}{48}\frac{z\rho}{a^3}CU^4\frac{d\overline{w^2}}{df}H \tag{2.3}$$

The spectral density of the mean squared velocity fluctuations is taken as a curve fit from experiments as a function of the Strouhal number $Sr_\Lambda = f\Lambda/U$, where f is the frequency and Λ the turbulent length scale:

$$\frac{d\overline{w^2}}{df}\cdot\frac{U}{\overline{w^2}\Lambda} = f\left(Sr_\Lambda\right) \tag{2.4}$$

TBS. Here Költzsch uses a different acoustic model: The unsteady forces on a blade are modelled as a line force in the plane of the rotor which radiates in a duct with reflecting walls and mean flow:

$$\frac{dW}{df} = \frac{\pi}{2}\frac{z}{\rho a^2}\frac{f}{D^2\left(1-\nu^2\right)^2}\frac{d\overline{F_A^2}}{df}\Psi \tag{2.5}$$

ν is the hub to tip ratio, Ψ a radiation function which is approximately 1 for low mean flow Mach numbers. The spectral density of the unsteady blade forces is related to the wall pressure fluctuations via the correlation lengths taken from MUGRIDGE [7]

$$\begin{cases} \dfrac{d\overline{F_A^2}}{df} = \dfrac{1}{5\pi}HC^2U\dfrac{1}{f}\dfrac{d\overline{p'^2}}{df} & \text{for } Sr_C \leq \dfrac{2}{\pi} \\ \dfrac{d\overline{F_A^2}}{df} = \dfrac{2}{5\pi^2}HC^2U\dfrac{1}{f^2}\dfrac{d\overline{p'^2}}{df} & \text{for } \dfrac{2}{\pi} \leq Sr_C \leq \dfrac{15}{\pi^2} \\ \dfrac{d\overline{F_A^2}}{df} = \dfrac{6}{\pi^4}HU^3\dfrac{1}{f^3}\dfrac{d\overline{p'^2}}{df} & \text{for } \dfrac{15}{\pi^2} \leq Sr_C \end{cases}$$

where $Sr_C = fC/U$.

The spectral density of the wall pressure fluctuations is estimated by a polynomial fit to measured wall pressure fluctuations under a turbulent boundary layer (TBL) on a flat blade and an empirical constant. Here the important input parameter is the displacement thickness of the TBL which is taken from the well known relation for a flat plate.

TBTE. KÖLTZSCH's model for the lift fluctuations due to vortex shedding is a slightly modified version of SHARLAND's, but still does not regard any frequency dependence.

KÖLTZSCH's method again requires U, the turbulent intensity of the inflow and now, in contrast to SHARLAND, the length scale of the turbulent inflow and the boundary layer displacement thickness on the blade as aerodynamic input variables. This leads to results which more realistically give a frequency dependence of the radiated sound power.

3.3 - FUEST

In order to incorporate a simple acoustical model into numerical mean flow computations (3D-RANS-methods) FUEST [8] again started from eq. (2.1). But rather modelling each noise generation mechanism individually he measured the wall pressure fluctuations and the correlation area and tried to correlate them with detailed mean flow parameters as the local mean velocity and the boundary layer displacement thickness on the blade. This work is currently going on in the department of the authors in order to incorporate the inflow parameters as length scale and turbulent intensity [9].

3.4 - BROOKS, POPE and MARCOLINI

An extensive study of the *airfoil* noise problem has been undertaken by BROOKS et al. [10]. In this context their investigations of TBS, TBTE and FS are of special interest. Their approach uses empirical fits to the spectra measured to provide a final prediction. It is based on the normalisation $SPL = K + 10\log\left(\pi Ma^5\delta^* L/r^2\right)$, where SPL is the peak 1/3rd octave band level, K is an empirical constant, $Ma = U/a$ is the Mach number, δ^* the displacement thickness at the TE, L the length of the trailing edge, r the distance to the observer. However, use of their model assumes similar airfoils to those used to develop their data, i.e. NACA 0012. Fig. 1 shows a recent application of their method to a small fan with NACA 4509 profiles by SCHNEIDER et al. [11]. Assuming an angle of attack to the NACA 0012 airfoil, which results in the same lift coefficient as with the cambered NACA 4509 blade in the fan, the agreement of the prediction with measurements is reasonable.

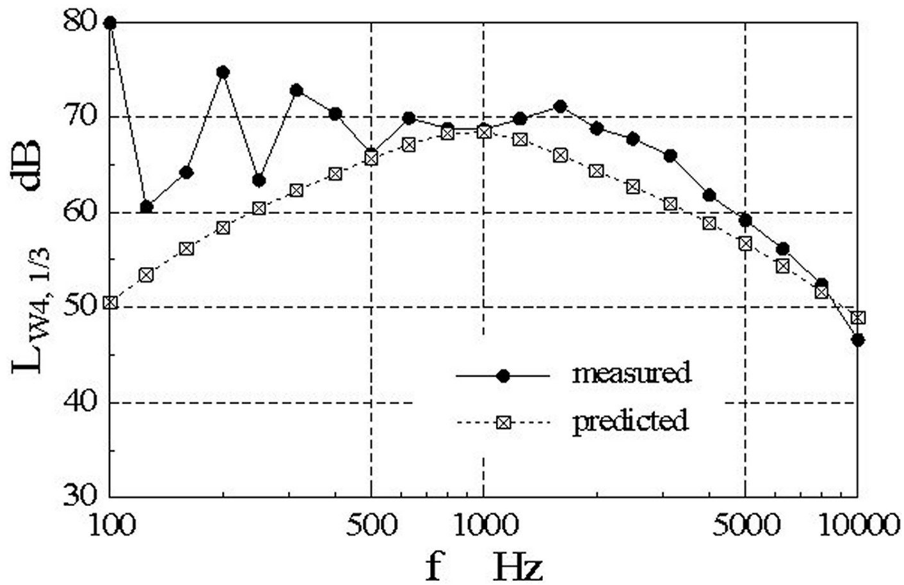

Figure 1: Computed ([10]) and measured noise spectrum of an axial fan.

3.5 - Methods used for windturbine noise prediction

Elements from wind turbine prediction methods also might be useful in fan noise prediction. As examples two schemes are mentioned. GROSVELD [12] considers TI, TBTE and the wake due to a blunt trailing edge. His method is partly empirical and based on acoustic measurements of large wind turbines and airfoil models. LOWSON's method [13] again takes TI and TBTE into account. With the turbulent intensity, the free field velocity and the boundary layer displacement thickness as aerodynamic input parameters both methods yield sound pressure spectra in the far field of a free rotor.

4 - BLADE SWEEP AND SKEW

Blade sweep (fig. 2) and skew has becoming more and more popular in axial fan design. It has an affect on both, discrete frequency and broad band noise.

FFOWCS WILLIAMS et al. [14] gave a quantitative model which allows to predict the reduction of sound pressure due to TBTE on an oblique TE. Considering only the field points which are many wave lengths away from both the turbulent region and the edge, and assuming that the turbulent eddies are well within a wave length of the edge and smaller than the wave length, the farfield sound pressure becomes $\overline{p^2} \propto \sin^2\vartheta^*$.

BROWN [15] and HAYDEN [16] name TBTE and Von Karman type vortex streets springing from the trailing edges collectively vortex shedding phenomena. They hypothesised that the velocity significant to vortex shedding is the component U_N in a direction normal to the trailing edge of the blade. As for an aerodynamic dipole mechanism it then follows

$$\overline{p^2} \propto U_N^6 \cdot L \propto \cos^6\vartheta \cdot \frac{1}{\cos\vartheta} = \cos^5\vartheta$$

A fundamental analysis of the noise generation by a finite span swept airfoil due to TI was given by KERSCHEN et al. [17]. They considered high frequency gusts, for which the noise generation is concentrated at the airfoil leading edge. For the case of infinite span airfoils, airfoil sweep results in a cut-off phenomenon due to destructive interference between acoustic pressures generated at different locations on the airfoil. According to their model fairly small sweep angles ϑ are sufficient at low flow Mach numbers. In fans, however, the effectiveness of sweep with respect to this mechanism is affected by end

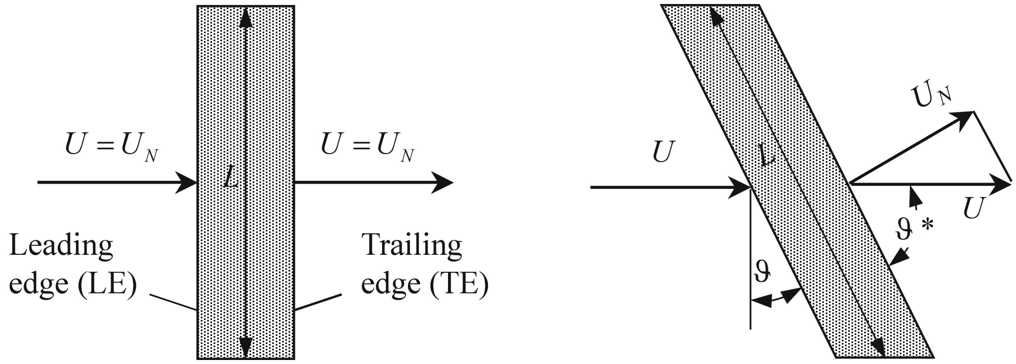

Figure 2: Angles and velocities for unswept and swept blades.

effects due to finite span and misalignments of the gusts. In a comparatively random field of disturbances sweep angles will have to exceed the ideal considerabely ([18]).

5 - CONCLUSIONS

To the knowledge of the authors none of the more advanced noise prediction methods are used routinely in fan design. A reason might be that the required inputs parameters as inflow and boundary layer parameters are not known in a traditional aerodynamic design procedure. It is hoped, however, that at least boundary layer parameters such as the velocity distribution and boundary layer displacement thickness will become increasingly available as computational fluid dynamic methods are used routinely. Thus, based on a larger data base, the various noise prediction methods then should be validated and improved.

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