Sweep-angle effect on low-order acoustic prediction for low-speed fans

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Abstract. The low-speed fans that are used for automotive engine cooling contribute to a significant part of the global noise emitted by the vehicle. Automotive engine cooling manufacturers are therefore interested in developing low-order noise prediction methodologies that include the radiated sound in pre-design optimization cycles. Two among the most influential broadband noise mechanisms characterizing the automotive axial cooling-fans spectra in operating conditions are the turbulence-impingement noise and the trailing-edge noise. We modelled them through the application of a semi-analytical method called Amiet’s airfoil theory, appropriately adapted via a strip-theory approach, in order to take the rotating motion into account. In modern fan designs, the fan blades are strongly forward-swept, meaning that the blade edges are not always perpendicular to the tangential-to-rotation velocity vector. This is particularly true at the tip of the blades where the sweep angle often reaches its maximum value, and where most of the noise is expected. Sweep was shown to reduce the noise emitted by isolated airfoils, but its effect on rotating machines is not yet well understood. Its prediction requires an extension to the classical Amiet’s theory, which has been implemented in this work, permitting to assess the importance of varying sweep on the acoustic far-field radiation. Amiet’s theory is therefore applied for the two noise mechanisms mentioned above, starting from steady CFD simulations, reproducing the ventilator geometry operating at its maximum-efficiency condition. In contrast with the classical unswept formulation, the predicted results considering the sweep variation along the blade span better compare with the experimental measured ones in the VKI anechoic chamber, especially for high frequencies.

1. Introduction

Several industrial fields, such as the aeronautical, automotive, and wind turbines sector are concerned with the acoustic radiations of rotational machinery [1, 2, 3]. Manufacturing ventilators with swept blades is considered as a classical technique in order to mitigate the far-field emissions, as well as to enhance the aerodynamic efficiency [4]. In the automotive field, low-speed cooling fans [5] are used to cool down the engines of the cars by extracting hot air out of heat exchangers. Several noise generating mechanisms of tonal and broadband nature occur in this application [6] where backward-swept and forward-swept propellers are often employed [7]. Among the most influencing sound source mechanisms, one distinguishes the turbulence-interaction or leading-edge one and the trailing-edge or self-noise mechanism [8]. Following the semi-analytical works carried out in [9, 10, 11, 12] for the previous two broadband mechanisms, the aim of this study is to implement semi-analytical methods, based on Amiet’s airfoil noise theory [13, 14], able to take into account the effect of having fan blades with varying swept leading- and trailing-edges. Although these methodologies have already proven to accurately model the noise emitted by isolated swept airfoils, to the authors knowledge, no application to low-speed rotating blades has been carried out so far including sweep, in order
to predict the overall broadband emitted sound. Nevertheless, the work of Roger et al. [11] aimed at modelling tonal noise emissions by Contra-Rotating Open Rotors (CRORs) and was instrumental in deriving the set of equations hereafter adapted to model the leading-edge noise for low-speed cooling fans.

In the recent work [15], the authors implemented a low-order prediction methodology that was only including the trailing-edge noise modelling neglecting the acoustic influence of blades with varying sweep angle. The following study is intended to be a continuation of the just mentioned one and thus, the same experimental measurements and CFD simulation are considered.

Hereafter, the leading-edge noise prediction has been included in the low-order acoustic methodology and both the trailing- and leading-edge noise formulations are now considering the presence of a radius-dependent sweep angle.

2. Experimental Setup and CFD Computation

The experimental campaign and the CFD study carried out at the von Karman Institute for Fluid Dynamics in [15] are used as a base to investigate the sweep-angle effect inclusion within the proposed analytical formulation and in order to compare it with a real application. In the ACOVES anechoic chamber, the cooling module has been mounted in an open-rotor configuration as depicted in Fig. 1 (a) and its far-field sound spectrum has been measured for the fan maximum-efficiency working condition. The laboratory has been designed by Bilka et al. [16] to have low turbulence level at the inlet and an acoustic cut-off frequency of 150 Hz. The chosen fan has 7-almost-equally-spaced blades that are forward skewed, with high sweep-angle values particularly at the tip of the blades, which are found to be the most influenced regions by the sweep. A 3D modelling of the fan has been employed and is shown in Fig. 1 (b). Steady Reynolds-Averaged Navier-Stokes simulations (RANS), coupled with $K-\omega$ SST turbulence model [17] are chosen as a fair compromise between the computational cost and the simulation accuracy in describing the near-field flow characteristics. The aim of the simulation is to collect the leading-edge upstream local flow information (turbulence kinetic energy $k_t$, specific rate of dissipation $\omega_t$, and mean relative velocity $U_0$) as well as to reconstruct the velocity profiles around the blade trailing edge in order to model the wall-pressure spectrum with semi-empirical methods [18]. In Fig. 2 (a), an iso-radial cut is carried out at the blade region. The seven blades present similar aeraulic properties, where in the tip the highest values of velocities and turbulence kinetic energy are achieved. More details are given in [15].

Figure 1: (a) ACOVES anechoic chamber: upstream room with B&K microphones and open-rotor configuration from [15]. (b) Suction-side 3D CAD model of the Valeo fan employed in the simulation.
not shown in here for sake of conciseness, was carried out to clarify the dependency of the acoustic results on the extraction points at the leading-edge upstream and at the trailing-edge boundary layer. Especially at the tip region it is not trivial to define the correct locations where to extract this information. As shown by an unsteady RANS computation of the same fan in Fig. 2 (b), the Q-criterion technique depicts a complex vortical structure developing all around the rotating ring. This suggests the presence of large coherent eddies that are not captured by steady calculations and that are probably responsible for the typical sub-harmonic humps characterizing the low-frequency spectrum, as discussed in [19]. Higher-order methods could be considered if one is interested in including these coherent structures in the noise prediction.

Figure 2: (a) An iso-radius cut is carried out at the blade tip region where the turbulent kinetic energy is shown. (b) The relative velocity is plotted on the iso-surface obtained with the Q-criterion technique. Large vortical structures are depicted in particular close to the ring and in the trailing-edge recirculating region.

3. Theoretical Background

An extension of Amiet’s theory to rotating blades, initially developed by Schlinker and Amiet [20] and subsequently by Rozenberg et al. [12], is firstly proposed in order to take into account leading-edge and trailing-edge noise mechanisms. Although the two models present consistent similarities, a distinction will be made when implementing the sweep-angle formulations for the two different noise mechanisms.

3.1. Noise Emitted by Rotating Blades

To deal with spanwise-varying conditions, the fan blade is subdivided into strips (or segments) through iso-radial cuts such that each strip encounters its own flow condition. The overall radiated fan noise is calculated as the summation of the sound individually emitted by each strip to which the single-airfoil theory is applied, assuming that the circular motion can be approximated by an equivalent local translation. The relative motion between the listener and the source is afterwards considered by including a Doppler factor and taking into account all the azimuthal blade locations as shown in Fig. 3 (a) and expressed by Eq. (1). For a given angular frequency \( \omega \), the fan radiated noise is calculated as:

\[
S_{pp}(\vec{x}, \omega) = \frac{B}{2\pi} \int_0^{2\pi} \left( \frac{\omega_e(\Psi)}{\omega} \right)^2 S_{pp}^\Psi(y, \omega_e) \, d\Psi,
\]

where \( \vec{x} \) is the vectorial listener’s position, whereas \( y \) is the source location; \( B \) represents the blades number, \( \omega_e(\Psi) \) is the source emitted frequency for a certain azimuthal position expressed
Figure 3: (a) From [12], the rotating local airfoil reference frame is denoted. The fixed reference frame $\vec{x} = (X, Y, Z)$ defines the observer’s position. (b) Sweep-angle definition over the leading edge of the fan blade; the rotated local reference frame $(x', y', z)$ is determined.

by the angle $\Psi = \Omega t$, as depicted in Fig. 3 (a). The Doppler factor has to be squared as proven by Sinayoko et al. [21] and for low-Mach number is given by the relation:

$$\frac{\omega_e(\Psi)}{\omega} = 1 + M_r \sin \Psi \sin \Theta,$$

in which $M_r$ is the Mach number of the source relative to the fluid. The term $S^{\Psi}_{pp}(\bar{y}, \omega_e)$ of Eq. (1) is obtained from the single-airfoil theory as the sum of the trailing-edge and leading-edge noise contributions such that $S^{\Psi}_{pp} = S^{TE}_{pp} + S^{LE}_{pp}$, discussed in the next paragraphs.

3.2. Leading-Edge Noise Formulation

Based on the classical Amiet’s analytical gust-airfoil interaction noise model [13], Roger et al. in [11] extended the formulation to account for swept blades in order to predict tonal noise emitted by CRORs. In the following work, these developments are used to predict broadband sound sources as carried out for an isolated airfoil in the work of Giez et al. [22]. The sweep angle is defined as the angle between the fan radius line and the line locally tangent to the edge of the blade, as depicted in Fig. 3 (b). The chord $c$ and span $L$ of the blade segment are indicated in the same figure. A local reference frame $(x, y, z)$ is defined, with the $x$ axis parallel to the flow direction $U_0 = \Omega R$ (with the fan angular rotation $\Omega$), the $z$ axis perpendicular to the blade-strip plane and the $y$ axis orthogonal to the previous two. A second local reference frame $(x', y', z)$ is obtained by rotating around the $z$ axis by the sweep angle $\Psi$; the $y'$ axis is now laying on the leading edge of the blade segment. It is worth noticing that in the latest figure, the sweep angle has been defined for the leading edge, but its definition is going to be equivalent for the trailing-edge case as long as the reference frames are centered on the trailing-edge of the blade.

To have further information about the following formulation, the interested reader can refer to [1, 23, 11]. We define the acoustic wavenumber $k_a = \frac{\omega}{c_0}$ and the observer corrected distance $S_0$ to take into account the convection effects as:

$$S_0^2 = \beta_y^2 X^2 + \beta_y^2 Y^2 + \beta_0^2 Z^2,$$

where $\beta_{y,x,0} = \sqrt{1 - \left(\frac{U_{y,x,0}}{c_0}\right)^2}$.
Hence, the velocity component $U_x = \frac{U_0}{\cos \psi}$ perpendicular to the swept leading edge and the one parallel to it $U_y = \frac{U_0}{\sin \psi}$ are determined. The turbulence is assumed as isotropic, frozen, and expanded into harmonics gusts. We write the power spectral density (PSD) of the far-field acoustic pressure for a fluid with the speed of sound $c_0$ and the density $\rho_0$, with the assumption of large aspect ratio. This choice has been done in order to have a simpler mathematical expression of the PSD reported in Eq. (4):

$$S_{pp}^{LE} (\vec{x}, \omega) = \left( \frac{\rho_0 k_a c_0 \cos \psi Z}{2 S_0^2} \right)^2 \pi U_x \frac{L_2}{2} \Phi_{ww} \left( K'_x, K'_y \right) \left| L^{LE} \left( X, K'_x, K'_y \right) \right|^2,$$  \hspace{1cm} (4)

where $K'_y$ is the only involved gust, which is always supercritical [1] and is expressed as [10, 22]:

$$K'_y = \frac{k_a}{\beta_2} \left( \frac{\beta_2^2 Y}{S_0} - \frac{U_y}{c_0} \right),$$  \hspace{1cm} (5)

Given the dispersion equation $U_0 \cdot \mathbf{K} = U_x K'_x + U_y K'_y$, the $x'$-wavenumber is defined as:

$$K'_x = \frac{\omega - K'_y U_y}{U_x}.$$  \hspace{1cm} (6)

The mathematically-derived aeroacoustic wavenumber term $L^{LE}$ does not consider the contribution of the trailing-edge back-scattering derived in [24], which is typically much smaller if compared to the main contribution shown in Eq. (7).

$$L^{LE} = -e^{-i \Theta_2} \frac{2}{\pi} \sqrt{\left( K'_x + K'_y \right)^2 E[2 \Theta_1]},$$  \hspace{1cm} (7)

We define the parameter $\kappa$ as:

$$\kappa^2 = \frac{\tilde{K}_x^2 U_x^2}{\beta_2^4} - \frac{\tilde{K}_y^2}{\beta_2^2},$$

where $\tilde{K}_x'$ and $\tilde{K}_y'$ are the dimensionless wavenumbers; $E[\cdot]$ is the Fresnel integral, whereas the expressions of $\Theta_1$ and $\Theta_2$ can be found for instance in [22, 11, 23].

The von Karman turbulence model is used to calculate the two-wavenumber spectrum $\Phi_{ww}(K'_x, K'_y)$ analogously to what has been done by Christophe in [6, 25]. In fact, starting off from the steady RANS computation of section 2, we can write the two-wavenumber spectrum as:

$$\Phi_{ww} \left( K'_x, K'_y \right) = \frac{4 \bar{u}^2}{9 \pi k_e^2} \frac{\tilde{K}_x^2 + \tilde{K}_y^2}{\left( 1 + \tilde{K}_x^2 + \tilde{K}_y^2 \right)^{7/3}},$$  \hspace{1cm} (8)

with $\bar{u}^2$ as the square of the r.m.s of the streamwise fluctuations, which is related to the RANS scalar turbulent kinetic energy $k_t$ as: $\bar{u}^2 = \frac{2}{3} k_t$.

The average wavenumber of the energy-containing eddies $k_e$ in Eq. (8) is defined as:

$$k_e = \frac{\sqrt{\pi} \Gamma(5/6)}{\Lambda_f \Gamma(1/3)},$$  \hspace{1cm} (9)

where $\Lambda_f$ is the streamwise integral scale of the turbulence, function of the RANS-output scalar specific dissipation ratio $\omega_l$ as:

$$\Lambda_f = \frac{B_l k_1^{1/2}}{\omega_l C_\mu},$$  \hspace{1cm} (10)

with the empirical constant $B_l = 0.4$ given in [26] and $C_\mu = 0.09$ given in [27].
3.3. Trailing-Edge Noise Formulation

According to the original derivation by Amiet [14], afterwards extended by Roger & Moreau [24], the inclusion of the sweep-angle effect for the trailing-edge noise modelling in this work followed the recent work of Grasso et al. [10]. The PSD of the far-field noise for the large aspect ratio is given as:

\[
S_{pp}^\text{TE}(\vec{x}, \omega) = \left( \frac{k_a c \cos \psi Z}{2S_0^2} \right)^2 \frac{L}{2\pi} \Phi_{pp}(\omega) l_y \left( \omega/U_c, K'_y \right) \left| \mathcal{L}^\text{TE} \left( K'_c, K'_y \right) \right|^2,
\]

(11)

consistently with the leading-edge formulation in the previous section, the main contribution of the aeroacoustic transfer function is written:

\[
\mathcal{L}^\text{TE} = -\frac{e^{2iC/cos\psi}}{iC} \left\{ (1 + i)e^{-2iC/cos\psi} \sqrt{\frac{2B}{cos\psi}} ES^* \left[ \frac{2(B - C)}{cos\psi} \right] - (1 + i)E^* \left[ \frac{2B}{cos\psi} \right] + 1 - e^{-2iC/cos\psi} \right\},
\]

(12)

where the mathematical expressions of the terms \(B\), \(C\), \(E^*[-]\) and \(ES[-]\) are given in [10].

The \(K'_y\) term is given by Eq. (5), whilst the rotated convective wavenumber is shown in Eq. (13), assuming the frozen turbulence hypothesis can be applied such that the convective velocity is determined as \(U_c = U_0/\alpha\), with \(\alpha = 1/0.7\).

\[
K'_c = \frac{\omega}{U_c \cos \psi} - K'_y \tan \psi.
\]

(13)

Rozenberg’s model [28], suited for airfoils generating boundary layers with relevant adverse-pressure gradients, has been employed to determine the wall-pressure spectrum \(\Phi_{pp}(\omega)\) in Eq. (11), by exploiting the trailing-edge boundary-layer information, as illustrated in [15]. The Generalized Corco’s model derived in [29] is used following Section IV of [10] to find the analytical expression of the spanwise correlation length \(l_y \left( \omega/U_c, K'_y \right)\).

4. Acoustic Far-Field Results

The implementation of the single-airfoil Amiet’s analytical formulations including the sweep-angle effect has been compared and validated with the work of Giez et al. [22] for the leading-edge noise case and with the work of Grasso et al. [10] for the trailing-edge noise case. For example, in the latest case, the strip-theory approach can be visualized in Fig. 4 (a), where 4 blade planes have been generated together with their local reference frames at the trailing edge. An improvement taking into account the sweep angle is shown in Fig. 4 (b), where the trailing-edges of the blade planes are now locally parallel to the forward-skewed curvature of the blade. Similar blade segments are defined but not illustrated for the leading-edge noise formulation. For the two noise mechanisms, the unswept classical Amiet’s formulations [13, 14] are retrieved as a limit case where \(\psi = 0\). The acoustic far-field results are plotted in Fig. 5 for the fan maximum-efficiency operational condition. The measured experimental overall noise presents tonal contributions, particularly at the blade-passing frequency (around 400 Hz) and its harmonics, not accounted for in the prediction methodology. When including the sweep contribution (SW), the leading-edge noise mechanism appears to be relevant at low-frequency, whereas the trailing-edge at higher frequency [6]. This behaviour is fairly similar to the one encountered in the work of Sanjose & Moreau [9] and with the beamforming study carried out by Herold et al. [7]. As in their beamforming experiments, also in this noise prediction, most of the noise is emitted by the blade segments approximating the tip of the blade, where the relative velocities reach the highest values and where the sweep angle is at its maximum along the blade span. For both the noise mechanisms, the effect of the sweep is to reduce the emitted noise, especially from medium to high frequencies. The sum of the trailing-edge (TE) and leading-edge (LE) noise mechanisms
Figure 4: For the trailing-edge case, the blade is divided into 4 segments: in (a), a classical unswept trailing-edge formulation can be used; in (b), the effect of the sweep is evaluated with blade strips which have locally parallel trailing-edges, following the blade forward-skewed curvature.

...in the swept case results to be in fairly good agreement with the experimental case, especially at high frequencies. The unswept case instead, results to over-predict the radiated noise in this frequency range. In the two cases, the methodology is not suited to model the sound spectrum for low-frequencies; in this region in fact, most of the radiated sound is expected to be generated by sub-harmonic coherent vortical structures convected upstream within the gap between the fan shroud and the rotating ring [30, 19]. Secondary flows with more broadband behaviour as well as recirculation bubbles under the trailing-edge pressure-side of the blade can also take place in the tip region [31], but their modelling would require higher-order CFD inputs to feed in semi-analytical methods.

Figure 5: PSD of the far-field emitted sound by the fan at its maximum-efficiency operational point: the solid red line representing the summation of trailing-edge (TE) and leading-edge (LE) noise contributions for the swept case (SW) is in fairly good agreement with the experimental curve in solid blue, especially at high frequency, resulting into a better description of the noise emission with respect to the unswept (UN) classical Amiet’s formulation shown in dashed line.

5. Conclusions
The aim of the present work was to extend the low-order noise prediction methodology developed in [15], exploiting the same near-field steady RANS computation and experimentally measured sound emitted by an automotive fan. We implemented a semi-analytical methodology, based...
on Amiet’s theory, to predict the leading-edge noise and the trailing-edge noise mechanisms for a fan with forward skewed blades. These have been divided into strips through iso-radius cuts where the single-airfoil Amiet’s theory has been calculated, taking into account the local sweep angles for the leading and trailing edges separately. The overall effect of considering swept blades with respect to the classical Amiet’s formulations, is a reduction of the predicted noise for both the sound mechanisms that is in good agreement with the experimental measurements acquired in the ALCOVES anechoic chamber of the von Karman Institute for Fluid Dynamics. Although the tip region of the blade is the most influenced by the sweep-sound mitigation, yet it remains the one radiating most of the noise due to the highest relative velocities. The trailing-edge noise appears to be dominant at high frequency, in agreement with [9]. The under-prediction of the far-field noise can be justified, especially for low-frequencies, by the typical presence of large turbulence structures and secondary flows, hardly detectable by steady RANS. This motivates further investigations and developments to include these noise mechanisms in the prediction methodology.

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