Experimental Investigation of the Acoustic Radiation of an Oscillating Airfoil

David Raus, Benjamin Cotté, Romain Monchaux, Baptiste Lafoux, Emmanuel Jondeau, Pascal Souchotte, Michel Roger

EXPERIMENTAL INVESTIGATION OF THE ACOUSTIC RADIATION OF AN OSCILLATING AIRFOIL

David Raus[1] **Benjamin Cotté**[1] **Romain Monchaux**[1] **Baptiste Lafoux**[1]
Emmanuel Jondeau[2] **Pascal Souchotte**[2] **Michel Roger**[2]
[1] IMSIA, ENSTA Paris, CNRS, CEA, EDF, Institut Polytechnique Paris,
828 Boulevard des Maréchaux, 91120 Palaiseau, France
[2] École Centrale de Lyon, 36 avenue Guy de Collonge, 69131 Écully, France
david.raus@ensta-paris.fr, benjamin.cotte@ensta-paris.fr

In open rotor applications, such as wind turbines and propellers, the angle of attack of a blade can vary during its rotation, due to an inhomogeneous or unsteady inflow. This causes a variation of the broadband noise radiated by the blades, which is a possible explanation for the amplitude modulations of wind turbine noise that can be measured *in situ*. The noise generation mechanisms for an oscillating airfoil are not fully understood [1]. The goal of this experiment is to characterize the broadband airfoil noise in static (fixed angle of attack) and dynamic (oscillating airfoil) configurations.

The experiments were performed in the anechoic wind tunnel of Ecole Centrale de Lyon (ECL). This wind tunnel consists of an open-jet with a rectangular 0.4 m $\times 0.3$ m nozzle exit, enclosed in an anechoic chamber of dimensions 8 m $\times$ 9 m $\times$ 10 m. Two horizontal end-plates were installed downstream of the nozzle exit in order to guide the incoming flow, as shown in Figure 1a. Measurements were conducted on a vertical NACA0012 airfoil of chord $c = 0.12$ m and of span $s = 0.30$ m. The rotation and pitching motion of the airfoil is driven by a motor placed under the lower end-plate. The airfoil was subjected to a flow of free-stream velocity $U = 25$ m/s, corresponding to a Reynolds number based on the chord $Re_c = 2.1 \times 10^5$.

Measurements of the steady and unsteady wall pressure on the airfoil were performed using 16 steady pressure taps (sampling frequency $f_s = 1.1$ kHz) and 4 remote-microphone probes ($f_s = 51.2$ kHz), installed mid-span, along the chord of the airfoil (see Figure 1b). The far-field noise was investigated using 4 microphones placed in the mid-span plane, 2 meters away from the airfoil center-chord, at different angles with the incoming flow (see Figure 1b). In the following, directivity of the airfoil noise is not studied and only the microphone perpendicular to the incoming flow is analyzed.

The airfoil was subjected to a sinusoidal motion of mean angle of attack α_0, amplitude α_1 and reduced frequency $k = \pi f c/U$, with f the frequency of the oscillation. In this paper, $\alpha_0 = \alpha_1 = 15°$ and $k = 0.005$.

In an open-jet wind tunnel, the flow deviates from the nozzle axis because of the presence of the airfoil, reducing the effective angle of attack of the airfoil. Brooks *et al.* [2] incidence corrections are commonly used to estimate the effective angle of attack for a static configuration, but these corrections cannot be straightforwardly applied to an oscillating airfoil. Geometric angles of attack α_g are thus used in the following.

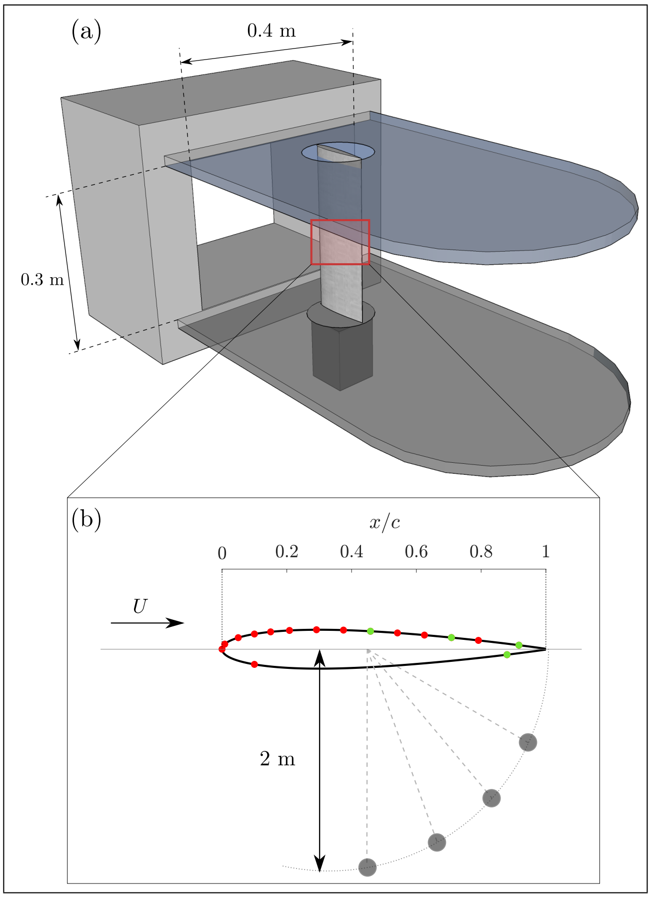

Figure 1. (a) Schematics of the nozzle exit and end-plates. (b) Position of the pressure taps. Red dots are the positions where only the steady pressure is measured. Green dots are the positions where both the steady pressure and dynamic pressure are measured. Grey dots are the positions of the 4 far-field microphones.

In order to investigate the acoustic radiation of an oscillating airfoil, the broadband noise of a static airfoil is first studied. Figure 2 shows the evolution of the airfoil self-noise against its static angle of attack $\alpha_{s,g}$. For $\alpha_{s,g} = 3°$,

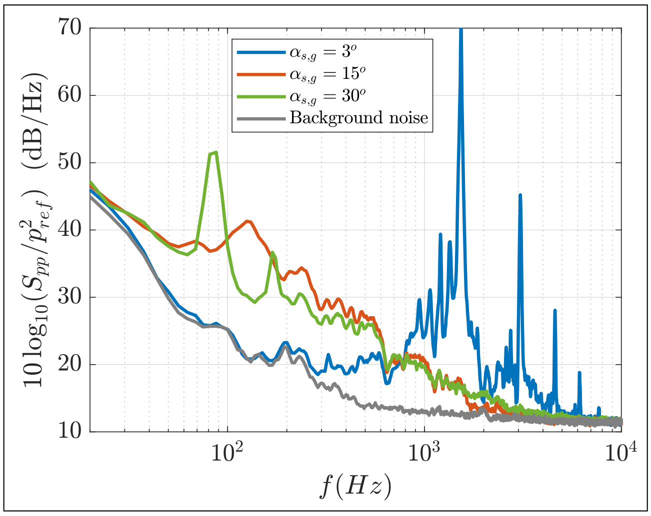

Figure 2. Power spectral density of the airfoil self-noise for various static angles of attack.

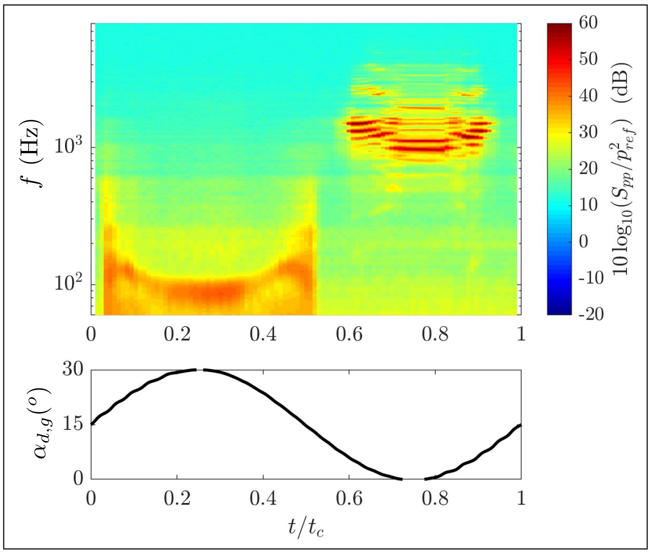

Figure 3. Evolution of the phase-averaged power spectral density of the airfoil self-noise during its oscillation. The phase-averaging is done on 90 oscillation cycles, $t_c = 1/f$ the period of one cycle.

the trailing-edge tonal noise described in Ref. [3] is observed, with a dominant discrete tone at 1530 Hz. For the stalled configurations, two regimes are visible, corresponding to the so-called ”light-stall” and ”deep-stall” regimes described in Ref. [4]. In the ”light-stall” regime ($\alpha_{s,g} = 15°$), a broadband noise is present between 40 Hz and 700 Hz, with a significant increase of the noise level at low frequencies (20 dB at 150 Hz, in comparison with $\alpha_{s,g} = 3°$). The ”deep-stall” regime ($\alpha_{s,g} = 30°$) is characterized by a narrow-band peak at 85 Hz and its first harmonic. These peaks could be explained by shear layer instabilities and large scale periodic vortex shedding [4]. It is noteworthy that, outside of these two peaks, the ”deep-stall” regime is less noisy than the ”light-stall” regime, in good agreement with [5].

The spectrogram of the noise radiated by the oscillating airfoil, phase-averaged on 90 oscillations periods, is shown on Figure 3. It shows a strong frequency and time dependence of the noise on the dynamic angle of attack of the airfoil $\alpha_{d,g}$, with two regimes appearing for low and high incidence angles. For low angles of attack, the trailing-edge tonal noise observed for static angles of attack is visible. The dominant discrete tone, weakly dependent on the angle of attack for static configurations, displays a more complex behavior here, with a frequency shift. For high angles of attack, a low frequency broadband noise is present, corresponding to the dynamic stall noise. Once again the noise displays a rich frequency content. At the stall onsets and when the flow reattaches, the noise presents a broadband content up until about 700 Hz. On the opposite, during the stalled phase the noise exhibits a narrow-band content whose center frequency shifts with the angle of attack. As for the ”deep-stall” static regime, the narrow-band peak is centered around the Strouhal number $St = fl_{app}/U = 0.21$ with l_{app} the apparent frontal width of the airfoil, as a sign of large scale periodic vortex shedding. It is interesting to note that this noise appears for $\alpha_{d,g} > 18°$ when the angle of attack increases, and disappears for $\alpha_{d,g} < 12.5°$ when the angle of attack decreases. This stall angle delay and hysteresis are commonly observed on airfoil dynamic lift coefficient curves [6].

The presence of the trailing-edge tonal noise and of the stall noise in the oscillating regime reflects the fact that the boundary layers on the airfoil are constantly adapting to its angle of attack. The noise generation mechanisms existing in a static configuration have enough time to develop in a dynamic configuration. For the oscillation parameters presented above, a quasi-static process is thus observed, the oscillation adding a time delay (or incidence delay) as well as a hysteresis to the presence of the two noise sources. In the future, the effect of the amplitude α_1 and the reduced frequency k on the oscillating airfoil noise will be studied, in order to understand how the hysteresis parameters depend on the angular velocity of the airfoil. Special attention will be paid to the effect of k on the frequency content of the dynamic stall noise. The influence of the inflow turbulence level on the static and dynamic stall noise and aerodynamics will be also studied.

[1] T. Zhou, Y. Sun, R. Fattah, X. Zhang, and X. Huang, “An experimental study of trailing edge noise from a pitching airfoil,” *The Journal of the Acoustical Society of America*, vol. 145, no. 4, pp. 2009–2021, 2019.

[2] T. Brooks, M. Marcolini, and D. Pope, “Airfoil trailing edge flow measurements and comparison with theory, incorporating open wind tunnel corrections,” in *9th Aeroacoustics Conference*, 1984.

[3] R. Paterson, P. Vogt, M. Fink, and C. L. Munch, “Vortex noise of isolated airfoils,” *Journal of Aircraft*, vol. 10, no. 5, pp. 296–302, 1973.

[4] S. Moreau, M. Roger, and J. Christophe, “Flow features and self-noise of airfoils near stall or in stall,”

in *15th AIAA/CEAS Aeroacoustics Conference (30th AIAA Aeroacoustics Conference)*, 2009.

[5] A. Laratro, M. Arjomandi, B. Cazzolato, and R. Kelso, "Self-noise and directivity of simple airfoils during stall: An experimental comparison," *Applied Acoustics*, vol. 127, pp. 133 – 146, 2017.

[6] K. McAlister, L. Carr, W. McCroskey, U. S. N. Aeronautics, and S. Administration, *Dynamic stall experiments on the NACA 0012 airfoil*. NASA technical paper, National Aeronautics and Space Administration, Scientific and Technical Information Office, 1978.