This highlight refers to the PhD Thesis by Fernanda Leticia dos Santos (2023, Cum Laude)

Broadband flow-induced noise for airfoils: inflow turbulence distortion effect on leading-edge noise generation and prediction

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Background

Many marine animals have developed an excellent sensory perception of sound, strongly relying on acoustic communication to navigate, locate prey, avoid predators, and reproduce. Unwanted sound, i.e., noise, dramatically affects these animals. The propeller of marine vessels significantly contributes to underwater noise. When propeller cavitation occurs, cavitation noise is the dominant noise source; thus, avoiding cavitation inception is important, as reflected in the guidelines of the International Maritime Organization. In addition, cavitation must be avoided due to strict noise requirements for certain vessels, such as fishery research ships, oceanography research ships, and naval vessels. In the PhD thesis, noise sources for noncavitating propellers, specifically flow-induced broadband noise sources, are studied.

The primary sources of broadband noise for a propeller blade section are leading- and trailing-edge noise. Leading-edge (LE) noise is generated by the impingement of the hull wake in the propeller LE. This noise is usually dominant in the low- and mid-frequency ranges, whereas trailing edge noise is dominant for high frequencies. Low-frequency sound waves are of great interest for marine applications because the noise generated by vessels is dominant in this frequency range and these waves propagate for long distances due to the high speed of sound in water and the low dissipation. Therefore, LE noise is one of the most relevant broadband sources for noncavitating marine vessels. Accurate LE noise prediction is paramount to designing silent propellers. One of the most used prediction methods is Amiet's theory. This theory neglects the blade section geometrical effect on the near-field and radiated noise. This results in inaccurate noise predictions for foils in the mid- and high-frequency ranges. This inaccuracy is attributed to the distortion of the turbulent inflow as it approaches the foil LE. Hence, to improve LE noise prediction, the turbulence distortion phenomenon should be understood and quantified so that it can be accounted for in Amiet's LE noise prediction model. This project aims to investigate the turbulence distortion phenomenon with the objective of enhancing LE noise predictions.

Trailing-edge (TE) noise is generated by the interaction of the TE region of the blade with the boundary layer and the near wake flow and strongly depends on the boundary layer at the foil TE. In scaled tests, tripping devices are installed on the model surface to hasten the laminar-turbulent transition due to the relatively low Reynolds numbers in these tests. As these devices affect the boundary layer development and, thereby, the source of TE noise, a better understanding of the influence of tripping devices on the TE noise source and radiated noise is needed.

Method

Experiments were performed in the Aeroacoustic Wind Tunnel at the University of Twente, where a turbulent inflow was generated by a grid and a rod, and it interacted with different airfoil geometries, named NACA 0008 (N08), NACA 0012 (N12), NACA 0018 (N18), and NACA 63018 (N63018). The turbulence distortion phenomenon was investigated based on hot-wire anemometry measurements performed at the stagnation line of the airfoils and on wall-pressure fluctuation (WPF) measurements at the surface of the airfoils. The noise generated by the interaction of the turbulent inflow with the airfoils was measured by a microphone array located in the far field. Based on the hot-wire and WPF measurements, it was possible to analyze the turbulent inflow behavior near the airfoil LE, which is the noise source for the LE noise, giving insights into the physics of how the turbulence distorts (changes) in the near field, i.e., near the airfoil surface. The far-field noise measurements were used to investigate the noise generated by different airfoils when submitted to the same turbulent inflow, giving insights into the effect of the turbulence distortion on the far-field radiated noise. These measurements also allowed us to analyze the capability of Amiet’s LE noise prediction method to estimate this noise source. Furthermore, numerical simulations were performed and validated with the experimental results, which resulted in new insights regarding the distortion of the turbulent inflow.

Boundary layer measurements using hot-wire anemometry, WPF measurements, and radiated far-field noise were also performed for a NACA 0012 airfoil subjected to a non-turbulent, uniform inflow. These measurements were conducted using different tripping devices to trigger an earlier boundary layer transition. Two tripping device geometries were tested: a zigzag strip and grits distributed randomly along the span.

Results

Based on the experimental results, we observed that the turbulence distortion affects the near field of the LE noise, i.e., the turbulent inflow near the LE (see Figure 1), the spanwise correlation length, and the WPFs in the LE region, consequently also impacting the far-field radiated LE noise (see Figure 2). Lower LE noise levels are observed for mid and high frequencies at most directivity angles for thicker airfoils.

Empirical formulations were proposed to model the integral length scale and the streamwise velocity fluctuations at the stagnation line of an airfoil as a function of the relevant airfoil geometrical parameter for the turbulence distortion, i.e., airfoil maximum thickness. These formulations are essential because more accurate LE noise predictions are obtained when the turbulence parameters used as input to Amiet's model are extracted near the airfoil LE, as shown in this research. Furthermore, the turbulence spectrum near the LE has a high-frequency decay different from the prediction of the rapid distortion theory (RDT). Based on the experiments, a new formulation is developed for the turbulence spectrum. A much better agreement between experimental and predicted LE noise is observed when this new turbulence spectrum formulation is used with as input the turbulence parameters obtained near the airfoil LE (see Figure 3). This leads to a new approach to account for turbulence distortion in Amiet's LE noise model.

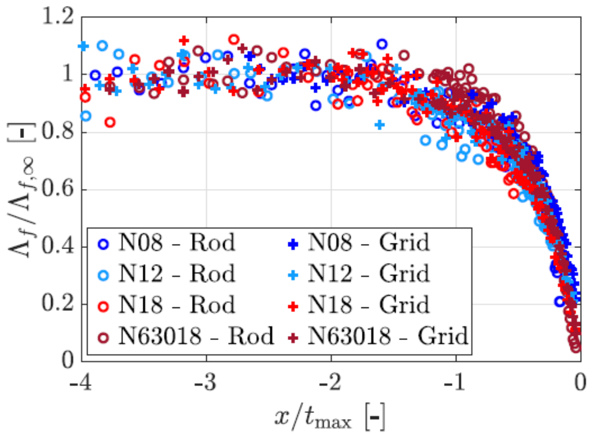

Figure 1: Integral length scale (Λ_f) of the turbulent inflow normalized by its free-stream value ($\Lambda_{f,\infty}$) along the streamwise direction (x) normalized by the airfoil maximum thickness (t_{max}) at the airfoil stagnation line. Turbulent inflow generated by the grid and rod for the different airfoil geometries.

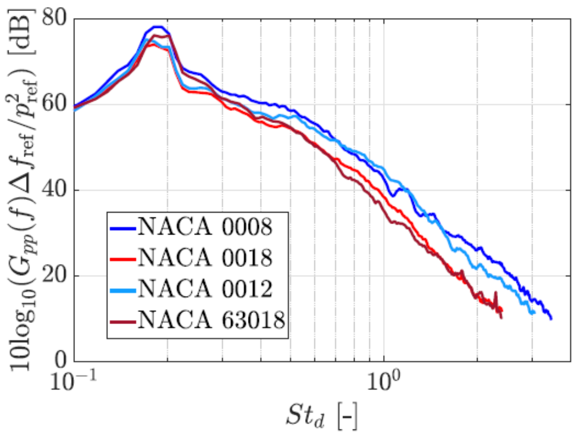

Figure 2: Power-spectral density of the measured radiated far-field noise for the different airfoils tested.

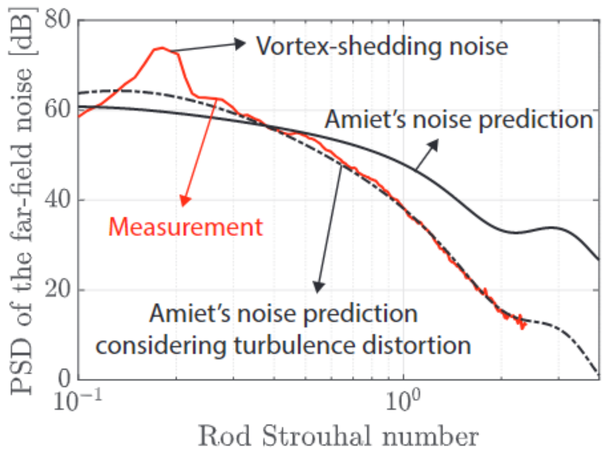

Figure 3: Power-spectral density (PSD) of the radiated far-field noise measured compared with Amiet's prediction and with Amiet's prediction considering the turbulence distortion effect.

As the turbulence distortion also impacts the WPFs in the airfoil LE region, poor estimations of the WPF spectrum using Amiet's model are observed. Also here, a better agreement between experimental and predicted WPF spectra is observed when the turbulence parameters used as input to Amiet's model are extracted near the airfoil LE. This shows the importance of accounting for the turbulence distortion in Amiet's model for LE noise and WPF spectrum in order to obtain accurate predictions.

The implications of incorporating the turbulence distortion in Amiet's LE noise prediction were also analyzed for propeller blade sections (see Figure 4). The predicted LE noise levels for the propeller blade sections are lower when turbulence distortion is accounted for (see Figure 5). However, this noise mechanism is dominant in the low- and mid-frequency ranges. The frequency at which the dominant noise source shifts from the LE to the TE reduces when turbulence distortion is considered (see Figure 5. The analysis also shows that the observed frequency range in which the turbulence distortion affects the LE noise is within the range where noise generated by a noncavitating marine application is relevant. This demonstrates the relevance of the results for the design of silent noncavitating propellers.

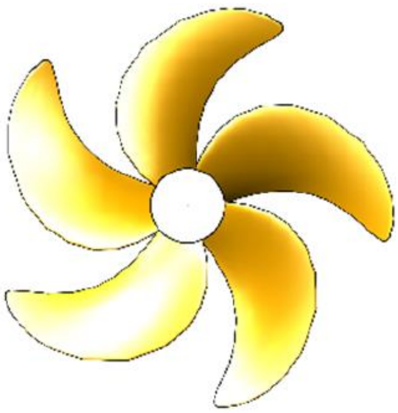

Figure 4: Propeller geometry used to estimate the LE and TE noise for blade sections located at 70% and 90% of the propeller radius.

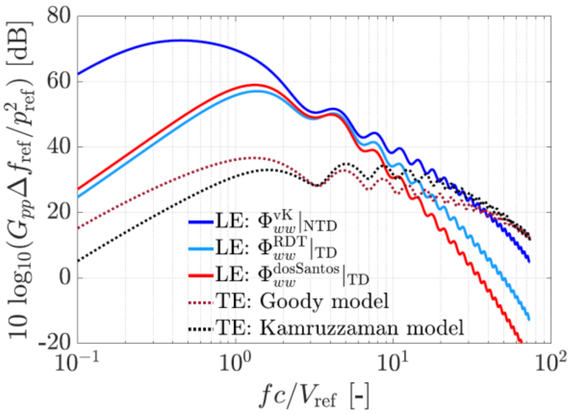

Figure 5: Power-spectral density of the predicted LE and TE noise using Amiet's theory. Different cases are considered for LE noise: NTD – no turbulence distortion effect considered, TD – turbulence distortion effect considered with different formulations for the turbulence spectrum (Φ_{ww}). TE noise is predicted for different WPF models.

In the thesis, it is also shown that tripping devices affect the transition process from a laminar to a turbulent boundary layer and the characteristics of the boundary layer developed at the TE, such as the WPFs (see Figure 6). When the trip height increases, the spectral level of the WPFs increases in the low-frequency range, resulting in an increase of TE far-field noise, reaching up to 4 dB (see Figure 7).

Conclusion

The results contribute to a better understanding of the turbulence distortion mechanism for airfoils and its effect on LE noise. The proposed approach to account for the turbulence distortion effect on Amiet's LE noise prediction can be used to obtain more accurate noise estimations for airfoils and to consider the airfoil shape effect on LE noise during the design phase of a propeller blade, for example. This improves the ability to design more silent, noncavitating propellers and other lift-generating surfaces, thus positively contributing to the well-being of both humans and animals affected by noise pollution. In addition, the discussion on the influence of tripping devices on the turbulent boundary layer developed at the TE and on the radiated TE noise can be used as a first guideline to determine the appropriate trip height for aeroacoustic measurements and to understand the uncertainty introduced by the tripping device on the determination of the boundary layer parameters and on the measured noise.

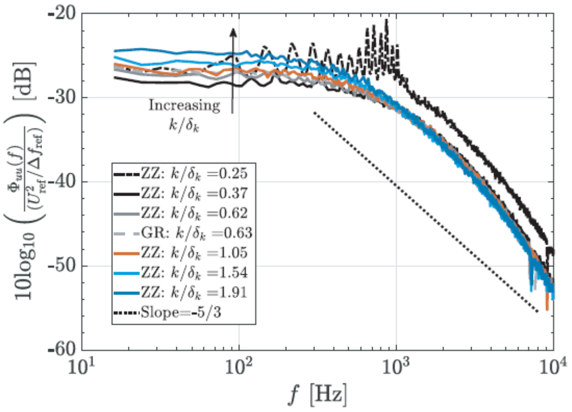

Figure 6: Power-spectral density of the velocity for different tripping devices height (k). Velocity measured in the boundary layer at 30% of the boundary layer thickness and at 95% of the chord length of a NACA 0012 airfoil at a Reynolds number of 270,000. ZZ – zigzag strip geometry, and GR – grit type of tripping device.

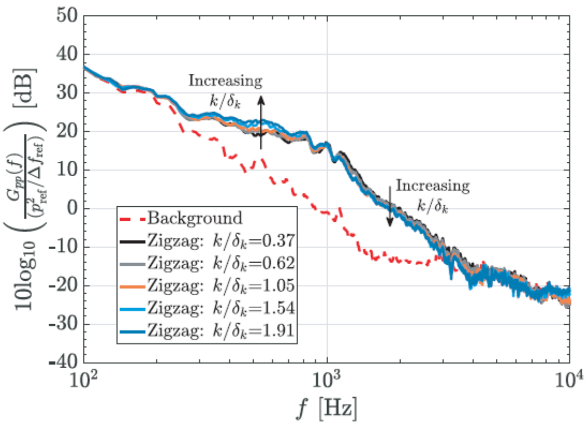

Figure 7: Power-spectral density of the TE radiated far-field noise for different tripping devices height (k). Velocity measured in the boundary layer at 30% of the boundary layer thickness and at 95% of the chord length of a NACA 0012 airfoil at Reynolds number of 270,000.

Acknowledgement

This work was part of the PANPA project, which was in collaboration with TNO and MARIN.

Reference

Fernanda Leticia Dos Santos, 2023. Broadband flow-induced noise for airfoils: Inflow turbulence distortion effect on leading-edge noise generation and prediction, PhD Thesis, University of Twente.