Large Eddy Simulations of airfoils for improved trailing-edge noise reductions

Linear Stability and Resolvent Analysis for Prediction and Mitigation of Wind Turbine Trailing-edge Noise

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In Short

- Trailing-edge (TE) noise is one of the main sources of noise pollution from wind turbines
- Our aim is to generate a low-order model of the TE noise based on linear stability and resolvent analyses
- The model is built from compressible large eddy simulation data sets and compared with experiments

Wind turbines are widely used as power plants, providing a cheap, clean and sustainable source of energy. However, the noise pollution associated with turbine operation is a major limitation to the widespread use of onshore wind energy. Of the various noise sources, trailing edge (TE) noise is the most important and is caused by pressure fluctuations in the boundary layer scattered at the trailing edge of the rotor blade. Although it is known that the frequency and sound levels of TE noise are largely dependent on coherent eddy-like structures within the boundary layer, current strategies of trailing-edge noise reduction show contradictory results because their influence on these structures is neither sufficiently understood nor reliably modelled.

Fortunately, current investigations of turbulent free-shear and boundary-layer flow clearly show that linear stability and resolvent types of analyses of the mean flow can be used to systematically describe the formation and control of coherent structures. Therefore, it is the objective of the *LowNoise* DFG-project [1] to apply these novel methods to the flow field around an airfoil, in order to develop a low-order model describing the underlying physical mechanisms of trailing-edge noise.

A key part of the project consists of large-eddy simulations (LES) of the entire flow field around an airfoil, which will be carried out on the HLRN cluster. Results from these time-resolved simulations will be used in two ways: (i) the time-averaged flow will serve as base state to the stability and resolvent analyses; (ii) snapshots of the velocity and pressure fields will be used to extract coherent structures using data-driven methods and serve as a reference for the low-order model. Furthermore, the simulations will be compared with aero-acoustic experimental results obtained on the same airfoil in the *LowNoise* project, both in terms of the flow dynamics and acoustic fields.

The compressible LESs from this project will be carried out with the open-source PyFR library [3], which solves advection-diffusion types of problems, such as the ones governing the motion of fluids, using a high-order finite-element approach with flux reconstruction. This method allows to retain a high-numerical accuracy while tackling complex geometries using unstructured grids composed of various curved element types. PyFR is well fitted to run on heterogeneous cluster infrastructures thanks to a variety of available backends, and has already been used for aero-acoustic analyses in the literature [2].

An important characteristic of TE noise is that it can be either *tonal* or *broadband*. The former generally occurs at low Reynolds numbers and with a natural transition of the boundary layer to turbulence (un-tripped), causing the flow to behave as an excited oscillator at specific frequencies. The latter occurs at higher Reynolds numbers or when the transition to turbulence is forced (tripped), in which case the flow acts as an amplifier of disturbances over a wider range of frequencies. Full-scale wind turbines typically exhibit broadband TE noise.

In the framework of a collaboration with the FLOW group from KTH Royal Institute of Technology, the transitional flow around a NACA0012 airfoil at $Re = 50\,000$ (un-tripped) was obtained using the PyFR library. The methodology proposed in the *LowNoise* project was applied to this dataset, and allowed to successfully reproduce the *tonal* TE noise emitted by the airfoil for this configuration. An illustration of the instantaneous flow field is given in figure 1, and reference coherent structures were extracted from the dataset using spectral proper orthogonal decomposition (SPOD), as illustrated in figure 2. Finally, the low-order model, consisting of (i) the leading resolvent mode to capture the coherent structures in the boundary layer and (ii) Curle's acoustic analogy to associate the resulting pressure fluctuations on the airfoil surface with the radiated sound, proved successful in reproducing the acoustic spectrum from the LES, as shown in figure 3.

However, new simulations at higher Reynolds numbers are needed to understand the mechanism causing the *broadband* TE noise that characterises

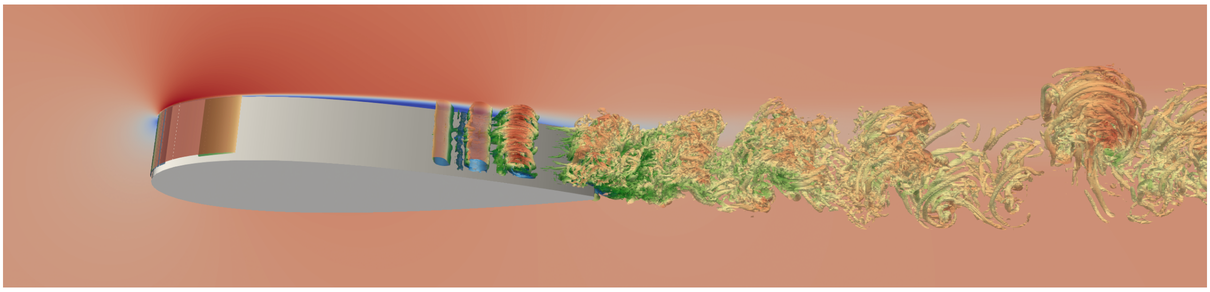

Figure 1: Snapshot of the turbulent structures (Q-criterion) developing around a NACA0012 airfoil at $Re = 50\,000$ without tripping of the boundary layer. The streamwise velocity contours are given in the background.

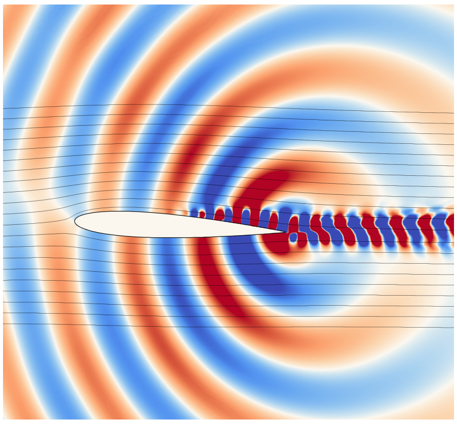

Figure 2: Pressure fluctuations from the leading SPOD mode of the flow around a NACA0012 airfoil at $Re = 50\,000$, revealing the coherent structures of the turbulent flow.

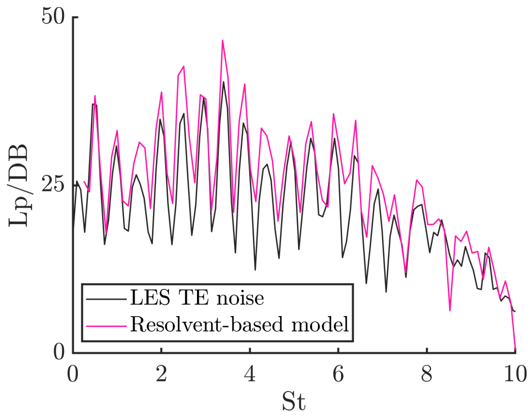

Figure 3: Comparison of the acoustic spectrum sampled near the trailing edge from the LES dataset and from the low-order model based on the leading resolvent mode of the flow.

full-scale wind turbine operation. In this project, compressible LESs of the flow around a NACA0012 airfoil are performed to investigate such cases. To obtain a fully turbulent flow at computationally tractable Reynolds numbers, the boundary layer is tripped near the leading edge. This is similar to what was done in the experiments of the LowNoise DFG project, which will also serve as reference. These simulations will allow us to answer the following questions: Is the resolvent analysis suitable for modelling the coherent structures that cause *broadband* TE noise for both pre- and post-stall conditions? What are the flow stability mechanisms that cause the formation of these structures? How can these mechanisms be controlled to develop the most efficient noise reduction techniques for wind turbines?

WWW

https://www.tu.berlin/en/flow/research/projects/modeling-of-trailing-edge-noise-on-the-rotor-blade-of-a-wind-turbine

More Information

[1] DFG project LowNoise: https://gepris.dfg.de/gepris/projekt/458062719?language=en

[2] Y. Hu, P. Zhang, Z. Wan, N. Liu, D. Sun, X. Lu, *Phys. Fluids* **34**, 105108 (2022). doi:10.1063/5.0108565

[3] PyFR library website: https://www.pyfr.org/

Project Partners

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