A Zonal Direct-Hybrid Aeroacoustic Simulation Framework Using a High-Order Discontinuous Galerkin Spectral Element Method

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Abstract: In this work, we present a zonal direct-hybrid aeroacoustic simulation framework using a high-order discontinuous Galerkin spectral element method. We combine a zonal RANS/LES approach with an acoustic propagation solver. We use the recycling rescaling anisotropic linear forcing method as turbulent inflow at the RANS/LES interface. This method relies upon provided turbulent statistics to generate turbulence. Based on a RANS simulation, we present a simple and robust method to model the required Reynolds stresses using the distribution of the turbulent kinetic energy obtained from the turbulence model. We follow a direct-hybrid simulation approach by simultaneously performing the zonal LES and acoustic propagation simulation. The acoustic sources are directly exchanged between the two solvers. To validate the framework, we present simulation results of a zonal direct-hybrid trailing edge simulation of a NACA 64418 airfoil at $Re = 10^6$.

Keywords: Hybrid RANS/LES Method, Aeroacoustics, High-Order Method.

Hybrid simulation methods are state of the art in computational aeroacoustics. The acoustic sources rely on an accurate prediction of the underlying hydrodynamic field, which is typically computed with the low-fidelity unsteady Reynolds-averaged Navier–Stokes (RANS) equations or detached eddy simulation. In complex flows, these approaches reach their limit. Thus, high-fidelity models like wall-resolved large eddy simulation (LES) are necessary. To close this gap between computational complexity and accuracy, our approach is to limit the LES domain to the region of physical relevance, which requires a method to generate the necessary inflow turbulence.

As a zonal LES approach, we use a combination of a recycling-rescaling and an anisotropic linear forcing to generate the inflow turbulence. This turbulent inflow method requires the time-averaged mean velocities and the full Reynolds stress tensor in the inflow region as input data. Usually, this data is not known beforehand. Therefore, we developed an approach to model the full Reynolds stress tensor based on a two-dimensional RANS simulation. The model is based on the findings of Bradshaw et al. [1] and models the Reynolds stresses by a constant scalar scaling of the turbulent kinetic energy k from a RANS simulation. We define a symmetric scaling tensor S_{ij} with an individual scaling scalar dedicated to each Reynolds stress component. To generalize the model, the sign of the Reynolds stresses approximated by Boussinesq's assumption is used to specify the sign of the Reynolds stresses. The model is described by Equation 1.

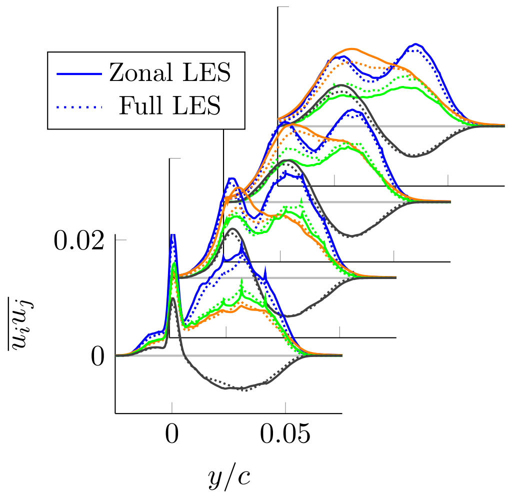

Figure 1: Velocity fluctuation distributions of the zonal LES in comparison to the full LES. Equidistantly staggered profiles in streamwise direction from the trailing edge up to 0.2 cord length into the wake region.

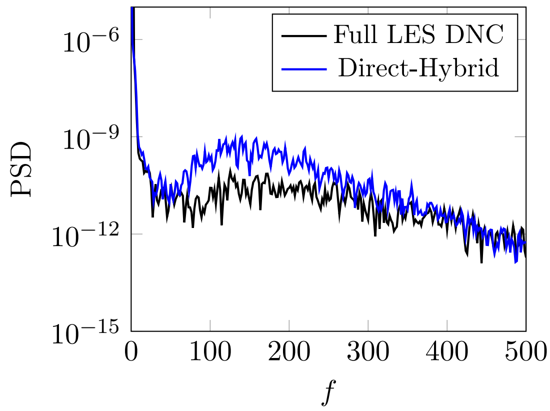

Figure 2: Dimensionless PSD of the pressure below the trailing edge. Comparison of the direct-hybrid simulation and the direct noise computation of the full airfoil.

$$\overline{u_i' u_j'} = sgn \left(-\nu_t \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) + \frac{2}{3} \delta_{ij} k \right) S_{ij} k \tag{1}$$

The acoustic propagation simulation is done by solving the APE-4 equation. We follow a direct-hybrid simulation approach to prevent the bottleneck of the available I/O bandwidth. The flow and acoustic propagation simulations are performed simultaneously, and the acoustic source, the perturbed Lamb vector, is communicated via MPI. This reduces the amount of data stored and makes the simulation suitable for high-performance computing. The imbalance between the acoustic and flow solver is taken into account by a static load balancing. To solve the compressible Navier-Stokes equations and the APE-4 equation system we use the discontinuous Galerkin spectral element method described in Krais et al. [2]. This high-order scheme is well suited for its beneficial dissipation and dispersion properties.

To validate the framework, we present simulation results of a zonal direct-hybrid trailing edge simulation of a NACA 64418 airfoil. The airfoil has an angle of attack of 6 degrees, which leads to a small separation close to the trailing edge, a free-stream Mach number of $Ma = 0.2$, and a Reynolds number of $Re = 10^6$. The turbulent fluctuations in the wake region of the zonal LES compared to a LES of the full airfoil are shown in Figure 1. The good agreement proves the proposed model approach for the Reynolds stresses combined with the turbulent inflow method to be suitable for hybrid acoustic simulations. In Figure 2 preliminary results of the direct-hybrid acoustic simulation are presented.

References

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