Large-Eddy Simulation of Rotor Turbulence-Ingestion Noise

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The noise produced by a rotor interacting with turbulent inflow, known as turbulence ingestion noise, is a significant concern for marine propellers as well as aeronautical, automotive and wind-energy applications. It is traditionally modeled in the framework of inviscid gust response theory for a thin flat-plate airfoil coupled with empirical models for the wavenumber spectra and correlation length scales of the approaching turbulence. The turbulence is often assumed to be homogeneous and isotropic. This type of semi-empirical model does not provide sufficiently accurate noise prediction in practical situations.

Realistic turbulent flows encountered by rotors often involve wakes of upstream bodies such as stators, grilles and control surfaces, and are inhomogeneous and complex. The wide range of spatial and temporal scales present in the flow causes broadband noise radiation in addition to tonal noise associated with blade rotation and possible coherent vortex shedding from the upstream bodies and blade trailing edges. The objectives of this study are to improve the ability to predict rotor turbulence-ingestion noise and clarify the physical mechanisms of noise generation using a combination of large-eddy simulation (LES) and Lighthill’s aeroacoustic theory.

A canonical flow configuration consisting of a modified, scaled-up Sevik rotor in the turbulent wake of a circular cylinder is considered as in the experiment of Alexander et al. [1] The ten-bladed rotor has a diameter of 457 mm. The cylinder, whose diameter is 1/9 of the rotor diameter, is located 20 cylinder diameters upstream of the rotor. The free-stream velocity is 20 m/s and the free-stream Mach number is 0.058. Numerical simulations are conducted for rotor advance ratios $\dot{J} = 1.44$ and 1.05, corresponding to a nominally zero-thrust rotor and a thrusting rotor, respectively. Because of the large separation distance between the cylinder and the rotor, the rotor simulation can be decoupled from the simulation of the cylinder wake. The turbulent wake is generated using LES of uniform flow over a circular cylinder with a long span that is 23.6 times the cylinder diameter. A time series of velocities in a plane ten diameters downstream of the cylinder center is saved as inflow data and later fed into the rotor LES, which is carried out in the rotor frame of reference. The simulations are performed using an energy-conservative, low-dissipative, finite-volume scheme for incompressible flow with the dynamic subgrid-scale model [2]. The noise is calculated based on the Ffowcs Williams-Hawkings integral formulation of the Lighthill equation [3] with the blade unsteady loading provided by the LES.

Figure 1a shows an instantaneous flow field in terms of iso-surfaces of the second invariant of velocity gradient tensor for the thrusting rotor ($\dot{J} = 1.05$) case. A wide range of vortical structures is seen to interact with rotor blades, causing unsteady loading and noise radiation. The mean velocity and turbulence intensity profiles in the rotor inlet plane obtained from the LES are in good agreement with experimental measurements. The computed sound pressure levels (SPLs) also agree well with experimental data as exemplified in figure 1b for a port-side observer location $r_o = 28.8R$, $\theta_o = 44^\circ$, where $R$ is the rotor radius and the coordinate origin is at the rotor center with $\theta_o$ measured counter-clockwise from the upstream direction. Similar agreement is observed at other measurement locations over a wide range of observer angles and
for both rotor advance ratios. The numerical results capture the broadband noise over three decades of frequencies, a strong tonal peak at the cylinder vortex-shedding frequency, and the blade-passing frequency (BPF) peak. By comparing the numerical SPLs with and without contributions from the cylinder, it can be concluded that turbulence ingestion by the rotor is the dominant noise source at frequencies higher than the cylinder vortex-shedding frequency, whereas the cylinder is the dominant source at frequencies around its shedding peak and lower. Consistent with experimental observations, the SPL increases as the rotor advance ratio is decreased at fixed free-stream velocity. An analysis of acoustic contributions from different blade regions indicates that the source strength increases with the radial distance to the hub. The acoustic field is dominated by axial dipole radiation, although radiation in the other two directions is also significant.

Additional results to be discussed include phase-averaged turbulence statistics around the rotor, blade-to-blade correlations and coherence of acoustic dipole sources, the effect of turbulence distortion by the rotor, and an assessment of the accuracy of the Sears theory for rotor noise prediction based on the LES data.

References

