Numerical Sound Prediction of Open Rotors: Methods, Results and Perspectives

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Introduction

The numerical noise prediction of open rotors underlies special requirements due to the complexity of their geometry and flow. No standardized, entirely numerical prediciton method has been established so far. Presently within the field of Computational Aero-Acoustics (CAA) there are several methods available. Basically these extract unsteady acoustic sources out of a flow computation and proceed with the computation of the acoustical wave propagation through a fluid. Applying such a method to subsonic open rotors a combination of unsteady computations (ie. Large Eddy Simulation (LES)) together with a form of Acoustic Analogy, preferably Ffowcs Williams and Hawkings Analogy (FWHA), does not only produce reasonable results but also shows appropriate but nevertheless feasible demand of computing resources.

Within this presentation a brief overview of the acoustic module implemented in the in-house CFD solver using FWHA will be shown. There will be presented 3 case studies, realized by using LES and the FWHA, including a flow around a circular cylinder, a flow around a combination of a cylinder and an airfoil and through a simple, subsonic propeller. The configurations follow experimantal settings in order to compare numerical and experimental results and validate this approach.

Acoustic Analogy

The rotor flow as well as the noise generating mechanisms of rotating machinery were studied intensely over the last decades (e.g. [1]). The noise sources were identified and categorized according to their origin and contribution to tonal and broadband noise. Analytical studies as well as numerical applications show that the Ffowcs Williams-Hawkings Acoustic Analogy (FWHA) [2] is well suited for the prediction of both sub- and supersonic open rotor noise [3], [4]. The noise sources occurring in the flow due to flow turbulence, surface pressure fluctuations and displacement effects by moving bodies are included. These sources proved to be the most important ones concerning open rotors. In this contribution the far field approximation of the FWHA (see eq. 1) is used, since the acoustical observer of technical interest typically resides far outside the noise generating region.

The acoustic density fluctuations ρ' can be obtained by extracting the acoustic sources out of an unsteady flow calculation. The 1^{st} term of the integral eq. 1 represents the quadrupole or turbulent volume sources with the Lighthill tensor T_{ij} as described in [4], the 2^{nd} term contains the dipole sources f_i (mainly hydrodynamic pressure fluctations on surfaces), the 3^{rd} and the 4^{th} term represent sources due to body thickness and replacement of volume by body movement. Other quantities appearing are: the speed of sound c_0, Doppler factor D, body surface s, flow volume ν, body volume ν_c, volume element $d\xi$, retarded time variable τ and retarded emission time τ_e, fluid density ρ_0, acceleration a, flow velocity v, position of volume or surface element r with the space indices i, j, using Einstein summation.

$$\begin{aligned}\rho' &\approx \frac{1}{4\pi c_0^4}\int_{\nu(\tau)}\left[\frac{r_i r_j}{r^3 D}\frac{\partial}{\partial\tau}\frac{1}{D}\frac{\partial}{\partial\tau}\frac{T_{ij}}{|D|}\right]_{\tau_e} d\xi \\ &+ \frac{1}{4\pi c_0^3}\int_{s(\tau)}\left[\frac{r_i}{r^2 D}\frac{\partial}{\partial\tau}\frac{f_i}{|D|}\right]_{\tau_e} ds(\xi) \\ &+ \frac{1}{4\pi c_0^3}\int_{\nu_c(\tau)}\left[\frac{r_j}{r^2 D}\frac{\partial}{\partial\tau}\frac{\rho_0 a_j}{|D|}\right]_{\tau_e} d\xi \\ &+ \frac{1}{4\pi c_0^4}\int_{\nu_c(\tau)}\left[\frac{r_i r_j}{r^3 D}\frac{\partial}{\partial\tau}\frac{1}{D}\frac{\partial}{\partial\tau}\frac{\rho_0 v_i v_j}{|D|}\right]_{\tau_e} d\xi. \quad (1)\end{aligned}$$

Flow Calculations and Solver

For all calculations the in-house developed CFD solver is used. The relevant noise sources are extracted out of the flow calculation and the acoustic density fluctuations are computed within the implemented acoustic module according to the FWHA eq. 1. The flow calculation must contain the unsteady noise sources. In the past this was realized by superposing a steady-state calculation with an unsteady statistic/stochastic modelling for the reason of sparing computing resources. Today, unsteady Reynolds Averaged Navier-Stokes (URANS) or Large Eddy Simulation (LES) could be used [5]. However, only LES proved to lead to acceptable acoustical results [6]. URANS calculations resolve only limited, distinct frequencies, LES resolve a broad spectrum of flow frequencies due to their nature of resolving a broad range of turbulent flow structures. With URANS most of the turbulent energy appears in few structures and their frequencies. Additionally URANS calculations do not develop significant structures in the 3^{rd} dimension as it is the case applying LES (see fig. 1). This leads to a systematic over-estimation of the main acoustic frequency peaks related to the frequencies of the flow [5], [6]. On the contrary, with a sufficently fine LES the SPL (sound pressure level) spectrum becomes acceptable. Details of the applied solver and the available models can be found in [7], [8]. Here, all calculations are 3-dimensional and unsteady due to the nature of LES and have been configured according to experimental setups in order to compare them with suitable measurements.

Circular Cylinder with Airfoil

A combination of an airfoil in the wake of a cylinder (fig. 2) is computed as measured in [9]. The extension of the numerical grid in the third direction was of the order of the flow correlation length and as such much smaller than in [9] in order to reduce the computing demands. However, the acoustical data then must be corrected with a suitable correction formula to match the measurements [6]. Therefore calculations of the cylinder without the airfoil were performed and a suitable correction was chosen and consequently applied to the cylinder-airfoil case.

The computations are performed with the following data: Mach number 0.2, Reynolds number (airfoil related) 480,000, time step $2 \cdot 10^{-5}$ s, turbulence level of 1%, grid resolution of $7.2 \cdot 10^6$ control volumes, fine wall resolution of $y^+ = 1$. The acoustical observer is positioned at a distance of 1.85 m over the airfoil midpoint (half of its span and cross length). The applied sub-grid scale model of the LES is an adaptive k-τ model. The computed fundamental acoustic frequencies (fig. 3 and 4) agree well with the measurements. However, the peak height of the SPL in the cylinder-airfoil case differs substantially, although the correction formula calibrated with the cylinder only case was applied. Other corrections show better results but differ in the cylinder only case.

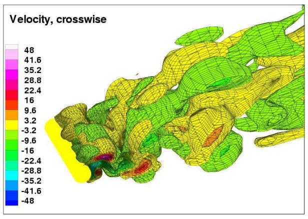

Figure 1: LES cylinder, developed crosswise velocity structures

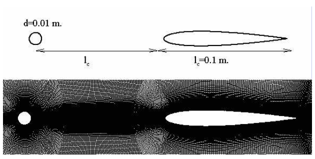

Figure 2: Scetch (top) and numerical grid (bottom) of cylinder-airfoil case

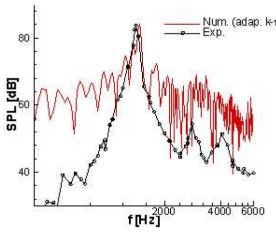

Figure 3: SPL spectrum cylinder only (Numerics red)

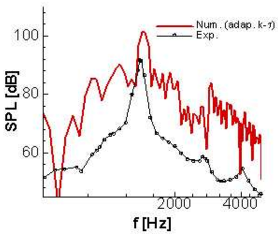

Figure 4: SPL spectrum cylinder-airfoil (Num. red)

Propeller

A generic propeller with 2 unprofiled, flat blades (length x width x depth: 100 mm x 40 mm x 4 mm) was computed. The blades were measured with different angles of inclination, here the computation and measurements of an angle of 45° are compared. The blade tip Mach number is 0.14, the blade Reynolds number 130,000, the rotational velocity 2950 rpm, which leads to a blade passing frequency of 98.33 Hz. The acoustical observer is placed at the position of the measurement microphone 1 (see fig. 5). All microphones are at a distance of 1.8 m from the rotor hub tip according to DIN EN ISO 3744. The numerical C-form grid of 1.3 Mio. control volumes covers 1.4 m from the hub tip in each direction, y^+ is kept at 1, the time step is 10^{-4} s. The applied sub-grid scale model of the LES is the Smagorinsky-Lilley model. The computed SPL narrow band spectrum is transformed into a 1/12 octave spectrum for a better comparison with the measurements. Both curves show satisfactory agreement in the frequency postitions although the numerical peak heights are still over-estimated. This indicates a slightly too coarse grid resolution for the LES of the flow.

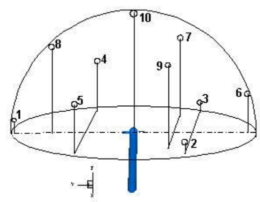

Figure 5: Microphone positions around propeller (blue)

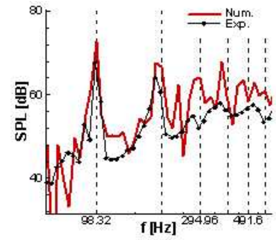

Figure 6: SPL spectrum propeller, microphone 1

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