# Strategies for Coupling Large-Eddy Simulations with Computational Aeroacoustics

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## Introduction

To describe the noise generation in turbulent combustion systems, it is important to capture the fluctuating density which acts as a volume source of sound. For small Mach numbers, the main source for the density fluctuations is the fluctuating heat release by the chemical reactions in the flamefront. Thus heat release can be related to the acoustical pressure fluctuations. For the presented case, these sources exceed the viscous sources by more than one order of magnitude. The main issue for flow simulations is then to get an accurate description of the fluctuating heat release.

There are several well known approaches in the field of Computational Fluid Dynamics (CFD) to simulate the flow field as shown in Figure 1 [1]. The stationary Reynolds Averaged Navier-Stokes (RANS) formulation is the most common one in todays applications. Its major drawback is the missing time dependency and therefore the missing frequency content. The Direct Numerical Simulation (DNS), resolving all time and length scales results in the highest frequency resolution with almost no modelling assumptions. Due to the enormous computational costs it is not feasible for todays applications. In order to reduce the cost while keeping the time dependency, Large-Eddy Simulation (LES) – appart from unsteady RANS – resolves all turbulent scales up to a certain cut-off frequency. This should lie well within the inertial range of the turbulent flow. In our case frequencies up to 3000 Hz can be extracted without any further modelling assumptions.

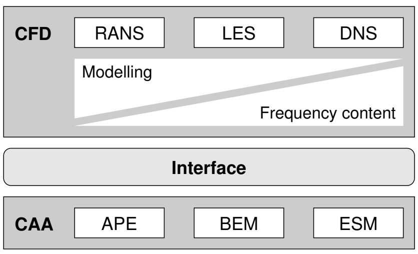


**Figure 1:** Coupling of CFD with CAA.

The sound propagation into the far field is usually evaluated using different Computational Aeroacoustic (CAA) techniques. The three approaches labeled in Figure 1 differ in the way, the information on the flow field obtained from the CFD is used. The Acoustic Pertubation Equations (APE) utilize the volumetric information of the CFD simulation to extract the sound sources [2]. The Boundary Element Method (BEM) computes the sound propagation by means of fluctuations on a defined control surface, outside the source region [3]. Finally, the Equivalent Source Method (ESM) arranges artificial noise sources inside a control surface in such a way, that their distribution of acoustic fluctuations on the control surface is equivalent to the results of the flow simulation [4].

For the investigation of combustion noise for small Mach numbers, a combined approach of LES including chemical reactions with CAA methods for the sound propagation into the far field is a promising technique. The problems of the interface, arising in such an approach shall be addressed in the following sections. The presented strategies are only intended for a "one way" coupling. No influence of the acoustic on the reactive flow is considered. The CAA techniques are used as a post-processing method for the LES results. To demonstrate the feasibility, a turbulent non-premixed jet flame has been used.

## CFD – Modelling and Configuration

The configuration used consists of a fuel jet of 23/77 vol% $H_2/N_2$ ejecting from a nozzle with $D = 8\,\mathrm{mm}$ at a bulk velocity of $36.3\,\mathrm{m/s}$ into a coaxial coflow of air with $0.2\,\mathrm{m/s}$ [5]. This yields a Reynolds number of Re $\approx$ 16,000. A sketch of the configuration is given in Figure 2(a). The mean axial inflow velocity profile is depicted by a dashed line.

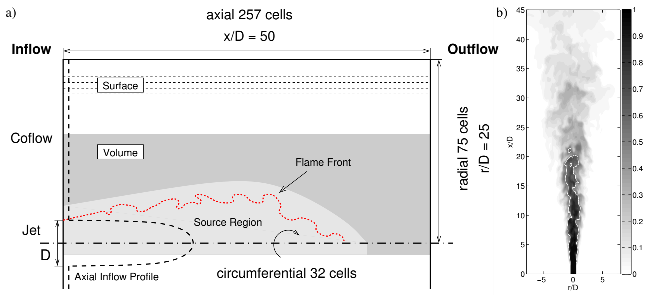


**Figure 2:** (a) Sketch of the configuration and the computational domain. (b) Instantaneous snapshot of the mixture fraction field.

The 3d LES code utilizes an incompressible approach on a staggered cylindrical grid with an explicit 3rd order Runge-Kutta Scheme in time and a 2nd order discretization in space. The sub-grid stresses are solved by means of the Smagorinsky model with the dynamic procedure proposed by Germano. The chemistry is modeled with a conserved scalar approach, relating the chemical state directly to the mixture of fuel and oxidizer [6]. An instantaneous snapshot of the mixture fraction field is given in Figure 2(b), showing the highly instationary character of the reactive flow.

## Coupling Strategies

Two main topics arise with regard to the coupling of CFD with CAA. First, the interface domain or surface needs to be defined. Since the CAA grid is usually much coarser than the CFD grid, the interpolation between the CFD grid and the CAA grid needs to be consistent. Second, the timestepping needs to be matched for the two different techniques. The two approaches need to resolve different time scales and have different numerical limitations for stability.

## CFD – CAA Interface

As mentioned before, the different CAA methods rely on instationary information within a given volume encapsulating all sources, e.g. APE, or on a surface enclosing the source region, e.g. BEM & ESM. These two interface domain types are presented in Figure 2(a) and 3. For the complete domain – volumetric or surface – all required quantities need to be transfered from the CFD solver into the CAA solver. Usually these quantities involve velocity $\vec{u}$, density $\rho$, as well as temperature $T$ and pressure $p$.

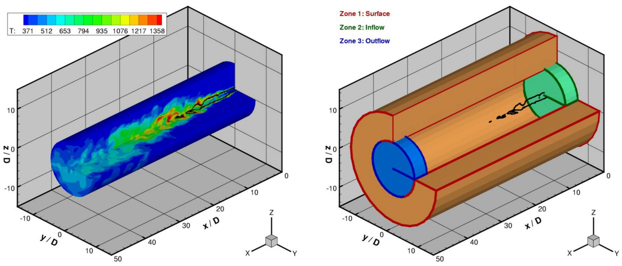


**Figure 3:** Interface domains for CAA methods. Left: Volumetric domain for APE, colorized by the instantaneous distribution of $T$ in Kelvin – Right: Surface domain for BEM & ESM.

For flow simulations with an explicit time integration scheme a limitation for the size of the timestep is the so called CFL condition $|\vec{u}|\Delta t_{LES}/\Delta x < \alpha$, where the CFL number $\alpha$ depends on the time discretation scheme – in this work $\alpha = 0.7$. A CFL number of unity corresponds to a fluid particle that is convected by the velocity $\vec{u}$ exactly from one cell center to the next ($\Delta x$) in one single LES timestep $\Delta t_{LES}$. In order to remain as efficient as possible, the CFL criterion is usually evaluated after every timestep during the LES to advance in time with the maximum timestep possible.

An acoustic method works best, if the timestep is kept constant, since every interpolation in time introduces artificial high frequencies. If the required acoustical timestep $\Delta t_{CAA}$ is clearly smaller than the minimum of the varying timestep of the LES, $\Delta t_{CAA} < \min(\Delta t_{LES})$, one can fix the timestep of the LES at a given point in time so that $\Delta t_{CAA} = \Delta t_{LES,cst} < \Delta t_{LES}$. From this point onwards an acoustic sample is generated every LES timestep. This allows a fast evolving LES to overcome the initialization effects of the simulation. Such a technique can be seen for the LES depicted by the solid line in Figure 4.

The second case, where the acoustical timestep is clearly larger than the LES timesteps, $\Delta t_{CAA} > \max(\Delta t_{LES})$, is shown by the dashed line in Figure 4. Here, a number $\Delta n$ of LES timesteps goes by for each acoustic sample (indicated by the dots in the figure). The accuracy of the acoustic timestepping increases with the number of non-constant LES timesteps inbetween two samples. The actual number of LES timesteps between two acoustic samples is not constant, whereas the acoustic timestep is almost constant. Problems arise, if the required acoustic timestep is of the same magnitude as the LES timesteps $\Delta t_{CAA} \approx \Delta t_{LES}$.

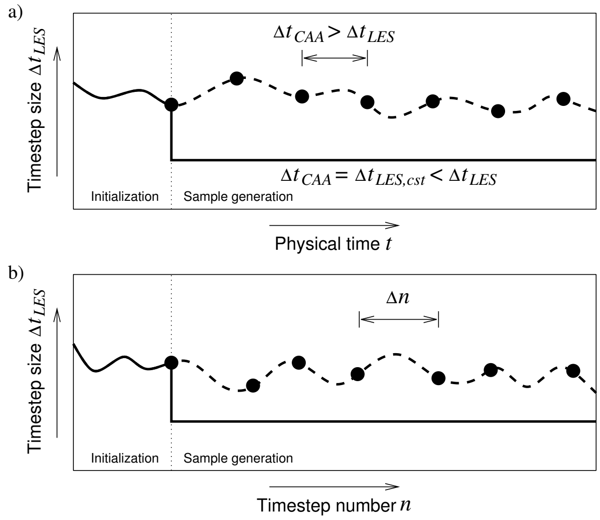


**Figure 4:** Timestep $\Delta t_{LES}$ as a function of physical time $t$ (a) and of timestep number $n$ (b) for two different coupling strategies.

## Incompressible vs. Compressible LES

The use of an incompressible approach for the flow simulation is valid, if the acoustic method uses volumetric information on the noise sources, as it is the case for the APE technique. For acoustic methods relying on the surface distribution of the fluctuations, the incompressible LES comprises problems. Here the acoustic information can not evolve from the sources onto the surface. Therefore, the coupling of the incompressible LES with methods like BEM or ESM has to be reviewed. For an expensive compressible LES, this transmission of acoustic waves is ensured for both cases [7].

## Summary and Conclusions

Different coupling strategies have been shown for a turbulent jet flame. The use of volumetric data, as well as surface data as input to the acoustic simulations has been discussed. Two cases to match the timesteps between the LES and CAA have been presented. The question of incompressible vs. compressible LES was addressed shortly. In conclusion, the one-way coupling of incompressible CFD with CAA is a promising approach because it combines the advantages of the two methods, while saving CPU time.

## Acknowledgements

The authors gratefully acknowledge the financial support by the German Research Council (DFG) through the Research Unit FOR 486 “Combustion Noise”.

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