A Hybrid Approach to Analyze the Acoustic Field Based on Aerothermodynamic Effects

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Abstract

A hybrid LES/CAA approach to simulate sound fields generated by aeroacoustic and thermoacoustic effects will be presented. Acoustic perturbation equations are used, which are capable to describe acoustic wave propagation in a non-uniform mean flow such that the computational domain of the flow simulation has to comprise only the significant acoustic source region. The input data to evaluate the acoustic source terms are generated by an LES computation in a flow region that contains all major acoustic sources. Special emphasis is put on combustion noise for which a sound field of an unbounded flame is simulated. A fourth-order DRP-Scheme (Dispersion Relation Preserving) [4] for spatial discretization and an LDDRK-Scheme (Low Dissipation and Low Dispersion Runge Kutta) for time integration are used. Since the sound radiation is simulated for an unbounded domain the sponge layer technique is used to avoid unphysical numerical reflections.

Introduction

This research project focuses on numerical methods which enable an efficient analysis of the mechanism and propagation of combustion noise. Combustion generated noise could also be carried out by a direct numerical simulation (DNS). By applying a hybrid LES / CAA approach, however, the required computational costs can be reduced dramatically. The hybrid approach investigated in this paper predicts the acoustic field using a two-step procedure. Fig. 1 shows a sketch of the different computational domains (LES / CAA) and the required boundary conditions (BC) such as non-reflecting BCs using the sponge layer formulation. The CAA grid resolution can be chosen much lower than that of the LES grid due to the large disparity between the characteristic fluid mechanical and acoustical length scales.

Governing Equations

A set of acoustic perturbation equations (APE) has been derived in [2] to compute acoustic sound fields in compressible or incompressible flow problems. It is shown in [1, 2] that the excitation of instabilities in global unstable mean flows is prevented due to the properties of the APE system. The APE system for the perturbation variables $(\rho^{'}, \boldsymbol{u}^{'}, p^{'})$, which corresponds to the APE-4 version in [2], reads

$$\frac{\partial p^{'}}{\partial t} + \bar{c}^2 \nabla \cdot \left(\bar{\rho} \boldsymbol{u}^{'} + \bar{\boldsymbol{u}} \frac{p^{'}}{\bar{c}^2} \right) = \bar{c}^2 q_c \qquad (1)$$

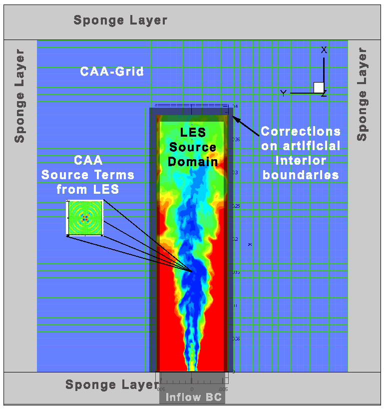

Figure 1: Sketch of the computational LES and CAA domains to determine combustion noise of an unbounded flame.

$$\frac{\partial \boldsymbol{u}^{'}}{\partial t} + \nabla \left(\bar{\boldsymbol{u}} \cdot \boldsymbol{u}^{'} \right) + \nabla \left(\frac{p^{'}}{\bar{\rho}} \right) = \boldsymbol{q}_m \qquad (2)$$

with the right-hand side sources

$$q_c = -\nabla \cdot \left(\rho^{'} \boldsymbol{u}^{'} \right) + \underbrace{\frac{\bar{\rho}}{c_p} \frac{\overline{D} s^{'}}{Dt}}_{I} \qquad (3)$$

$$\boldsymbol{q}_m = -\left(\nabla \frac{(\boldsymbol{u}^{'})^2}{2} \right) + \left(\frac{\nabla \cdot \underline{\tau}}{\rho} \right) - \underbrace{(\boldsymbol{\omega} \times \boldsymbol{u})^{'}}_{III} + \underbrace{T^{'} \nabla \bar{s} - s^{'} \nabla \overline{T}}_{II} \qquad (4)$$

The left-hand side of this system describes wave propagation in a non-uniform mean flow field $\bar{\boldsymbol{u}}$.
When combustion flows are considered the terms (I), (II) are assumed the major contributions besides the Lamb vector (III). The term (I) is directly related to the perturbed heat release per unit volume via

$$\frac{\bar{\rho}}{c_p} \frac{\partial s^{'}}{\partial t} = \frac{(\gamma - 1)}{\bar{c}^2} \frac{\partial Q^{'}}{\partial t}. \qquad (5)$$

Simulation of Combustion Noise

In the first step an unsteady flow field of an unbounded flame is simulated via a large eddy simulation (LES) the details of which are described in [5]. The source terms are evaluated on the LES grid and then interpolated onto the CAA grid using a trilinear interpolation algorithm. The acoustic simulations are then performed using the acoustic perturbation equations Eqs. (1) and (2).
As derived by Crighton et al. [3] term (I) is more dominant than the sound due to other source mechanisms in

unsteady combustion flows at low Mach numbers. Furthermore, the second source term (II) is composed of temperature and entropy gradients and as such it can be conjectured that this term also plays an important role in combustion noise investigations. If a cold jet is regarded it is well known from Lighthills jet noise theory that vortex induced sound (III) is the major contribution. In case of a reacting jet this sound source is also taken into account for comparison reasons.
To reduce the computational effort the acoustic source region is set to the first 40% of the LES domain. In addition, the time resolution of the source data is based on 240 time levels at a sampling rate of $20kHz$.
The whole procedure of data manipulation from the LES data to a CAA computation is shown in Fig. 2. If only incompressible flow data are available a pressure correction term needs to be inserted as was shown by Ewert et al. in the APE-2 version [2]. Since the jet Mach number is small ($Ma \leq 0.1$) a mean flow field with zero velocity was assumed for the CAA simulation. Additionally, a uniform density field was assumed. The errors due to this assumptions will be investigated in a subsequent analysis. The directivity is evaluated on a circle in the $z = 0$ plane. Due to the limited computational domain the maximum possible distance for directivity patterns is $r = 20D$, where D is the jet exit diameter. Note that this circle is not located in the far field. The major contribution to combustion noise, term (I), is of monopole type, which agrees with the predictions by Crighton et al. [3]. The directivity of term (II) showing a multipole behavior is quite different compared to term (I). The asymmetric directivity pattern obtained from term (II) appears be related to the limited number of source samples from the LES. As evidenced in Fig. 3 the major contributions to combustion noise are related to the sources (I) and (II). Comparing the magnitudes of the sources (I), (II) and (III) the impact of the vortex source term can be neglected since its magnitude is two orders smaller than that of terms (I) and (II).

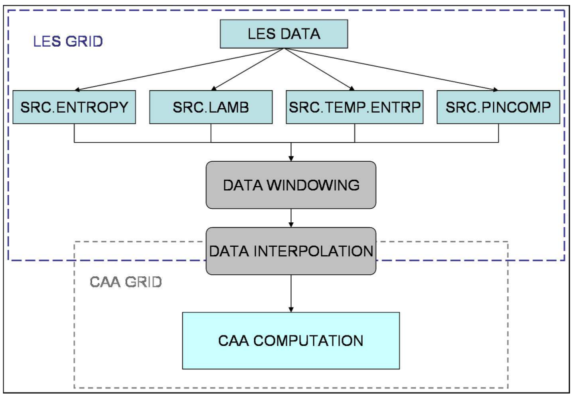

Figure 2: Data flow chart: From LES flow data to the induced acoustic field by source evaluation, data windowing, grid interpolation and CAA computation

Conclusion

From the present work the preliminary conclusions can be drawn.

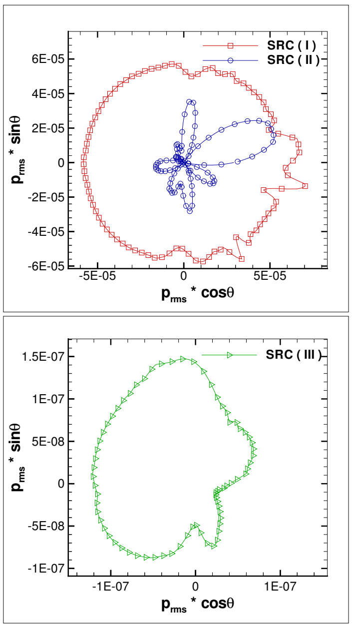

Figure 3: Directivity patterns for the source terms (I) and (II) (top), (III) (bottom) at $r = 20D$.

- The results show that this hybrid approach is capable of simulating an acoustic field based on combustion in a turbulent flame. Furthermore, the main combustion noise characteristic, the monopole nature, caused by the unsteady heat release could be verified.
- To analyze in detail the induced acoustic field and the sound generation mechanisms caused by a turbulent flame the CAA domain needs to be enlarged and the LES resolution has to be increased. In addition, more simulations will be done with an increased source term time resolution Δt_{src} and an enlarged sample interval T_{src}.

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