Modelling of the combustion noise by means of the equivalent source method (ESM)

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Introduction

To predict the noise generated by combustion, the equations governing the movement of the fluids, chemical reactions and sound propagation have to be solved. The differences in characteristic time and length scales between combustion and sound propagation make it necessary to use hybrid methods that can handle the different processes in an optimal way. The most common hybrid approaches compute the fluctuations of the physical quantities in the reaction zone by means of unsteady Computational Fluid Dynamics (CFD), and use them as input data for acoustic methods like the acoustic analogy, the Kirchhoff method or the linearized Euler equations [1]. The methods based on the Kirchhoff integral equation show an advantage over the two other methods, since only a surface integral has to be evaluated. The possible limitation of this method is the assumption that outside the integration surface, there must be no flow and no temperature gradients. This means, special care should be taken to the choice and positioning of the control surface. Then, the accuracy of the results of the Kirchhoff method depends basically on two factors: a) where the surface is placed, and b) how good the acoustic perturbations are described at the control surface.

The equivalent sources method (ESM) was used to compute the sound radiation of an open flame from data of the velocity fluctuations obtained with a CFD code by means of a Large Eddy Simulation (LES). We thank Prof. Janicka and Mr. Flemming from the TU-Darmstadt for putting the data to our disposal. The results are compared with those obtained by a BEM program with the same input data. This work is integrated in the Research Project "Combustion Noise", supported by the German Research Foundation (DFG) [2].

The Method

The equivalent sources method is a well known general tool to compute the sound radiation or scattering from complex-shaped structures into the three-dimensional space. Instead of solving the Kirchhoff integral equation, like the BEM, the ESM uses a system of acoustical elementary sources which satisfy the differential equation and the radiation condition to replace the real sound source. These sources are placed inside a certain surface (control surface) and must fulfil any boundary conditions demanded on it. A detailed description of the method can be found in [3].

Calculations

An open turbulent non-premixed flame was simulated with a LES code. The fuel was a mixture of 23% H_2 and 77% N_2. The circular nozzle diameter is D = 8 mm and the fuel discharges with a bulk velocity of U_{bulk}=36.3 m/s into air co-flowing at U_{coflow} = 0.2 m/s. The simulation was executed on a cylindrical computational domain of length 48D and radius 15D. For the acoustic calculations, velocity samples at spatial points on 10 cylindrical surfaces with radii varying from R_1=6.7D to R_{10}=13.6D and constant length L = 47.8D were generated. The data was Fourier transformed and served as input data for the ESM and BEM programs.

The sound power and radiation patterns were calculated using each cylinder as control surface, so that the dependence of the results with the position of the control surface could be analyzed. Three different distributions of the source positions were tested: a) 20 points along the cylinder axis, b) 32 points in parallel rings and c) 30 points in random positions over a smaller cylindrical shell of radius 0.5R and length 0.6L (see Figure 1). In each position, sources of zeroth, first and second order were considered, which correspond to monopoles, dipoles and quadrupoles.

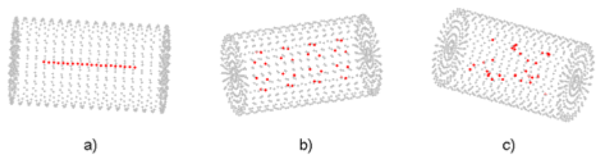

Figure 1: The three different distributions of source positions inside the control surface.

Results

Given the velocity distributions at the cylindrical surfaces, the pressure distributions at the same surfaces were calculated. The sound power is then computed by integrating the acoustic intensity over the surface. The velocity data have been sampled at approximately 10000 Hz, but according to the dimensions of the mesh cells, the requirement of six grid points per wavelength is fulfilled up to only 3000 Hz. Figure 2 shows the curves of the radiated sound power for each cylinder computed with the sources located at the cylinder axis. The other source distributions give similar results.

As already mentioned, the control surface must be placed outside the combustion zone to agree with the condition of a homogeneous outer medium. A convergence of the sound power to its true value with increasing distance between the source and the control surface would be expected. That convergence can not be identified in the results of Figure 2, instead, a growth of the sound power with increasing radius at high frequencies can be seen.

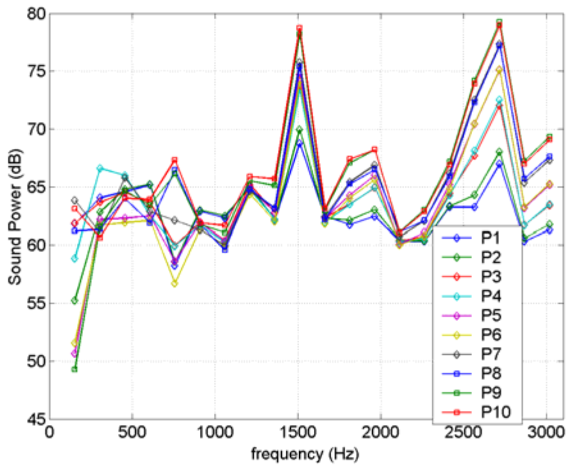

Figure 2: Sound power curves calculated with the velocity distributions of the ten cylindrical control surfaces.

Also the maxima that appear at high frequencies, especially at 1511 Hz and 2716 Hz are not typical for an open flame. A comparison of the magnitudes of the velocity over the cylindrical surfaces shows that the contributions of both caps are significantly bigger than those of the sides, being those of the upper cap (outflow) more important at low frequencies and those of the lower cap (inflow), at high frequencies. The maxima in the sound power are caused by the velocities at the inflow cap, since a calculation of the sound power with the velocities at that cap set to zero, gives no maxima. The flame radiates the sound uniformly at low frequencies up to 600 Hz, for higher frequencies, the radiation shows not uniform spatial distributions like those of Figure 3.

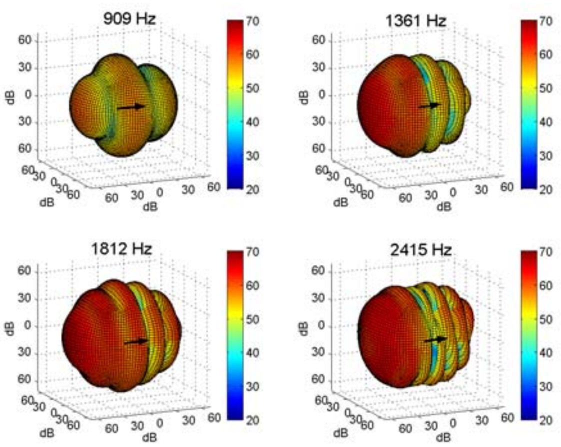

Figure 3: Three-dimensional radiation patterns of the flame at four frequencies calculated with the tenth cylinder. The arrow shows the direction of the flow.

The results of the sound power and radiation patterns, computed with the ESM, are in good agreement with the results of the BEM calculations. In Figure 4, the differences in sound power level, $\Delta L = L_{BEM} - L_{ESM}$ for the ten cylinders are shown. Practically, at all frequencies and for all cylinders, those differences lie within ±2 dB. Also the radiation patterns shown in Figure 5 are very similar.

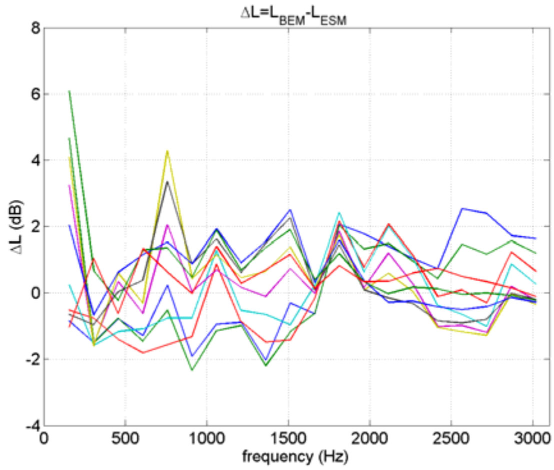

Figure 4: Difference in sound power levels of the ten cylinders between ESM and BEM calculations.

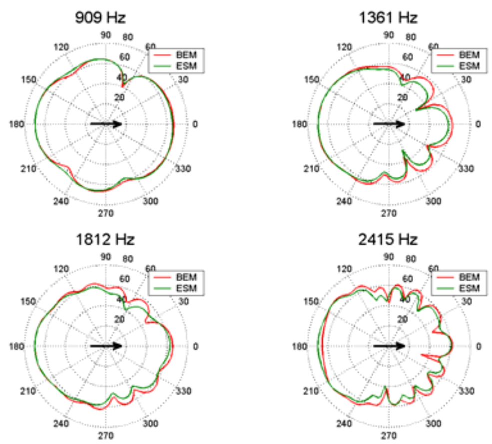

Figure 5: Comparison of radiation patterns calculated with the ESM and BEM. The arrow shows the direction of the flow.

Conclusion

The sound radiation of an open flame was computed by coupling a CFD code (LES) with two acoustic procedures (ESM and BEM) based on the Kirchhoff method. Nearly the same results are obtained for the sound power and radiation patterns, but the expected convergence in the sound power is not seen and strange maxima at high frequencies appear. The origin of these problems can likely be attributed to the assumption of incompressibility adopted by the LES and the use of artificial turbulence as inflow boundary condition. The effect of those assumptions on the acoustic calculations has to be reviewed.

References

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[3] Ochmann, M. “The Source Simulation Technique for Acoustic Radiation Problems”. Acustica 81, 512-527, 1995