Prediction of the Sound Radiated from Open Flames by Coupling a Large Eddy Simulation and a Kirchhoff-Method

Haike Brick, Rafael Piscoya
Technical University Dresden, Institute for Acoustics and Speech Communication, 01062 Dresden, Germany, e-mail: **{brick, piscoya}@tfh-berlin.de**,

Martin Ochmann
TFH Berlin, FB II, Luxemburger Str. 10, 13353 Berlin, Germany, e-mail: **ochmann@tfh-berlin.de**,

Peter Költzsch
Technical University Dresden, Institute for Acoustics and Speech Communication, 01062 Dresden, Germany,
e-mail: **Peter.Koeltzsch@ias.et.tu-dresden.de**

Hybrid methods, coupling CFD codes and acoustic methods like the acoustic analogy, the linearised Euler equations and the Kirchhoff-Method are being used to predict the sound produced by turbulent combustion, since the present computational power only allows an accurate estimation of the physical quantities, in a reasonable computational time, near the source. This means that the acoustic far field cannot be determined by a direct simulation. This research attempts to show that the Equivalent Source Method (ESM) and the Boundary Element Method (BEM), which are considered as Kirchhoff-Methods, can also be used to determine the sound generated by combustion. These two methods have the advantage that only one acoustic variable must be known at a surface surrounding the source zone and that the far field can be directly computed. The sound power generated from two open diffusion flames have been calculated with both the ESM and the BEM, using the velocity distribution over cylindrical control surfaces computed with a Large Eddy Simulation. Results of the calculations are presented and compared with the measured sound power of the same flames. For one configuration good agreement between measurement and simulation at low and middle frequencies is obtained. Possible reasons for the differences for the other configuration will be discussed.

1 Introduction

In the German basic research project "Combustion noise" prediction tools for reduction of combustion noise are under development, [1]. This is an extremely complex task taking into account that it involves both the noise generation due to the processes in the reactive zone (i.e. turbulent flow and combustion) as well as the transport/radiation of noise through turbulent area to the surrounding. Due to its complexity a direct numerical simulation (DNS) is not possible and hybrid methods have to be applied. This means that the source region (reactive zone) is modelled typically with Computational Fluid Dynamic (CFD) codes, while the propagation is handled by standard acoustic methods such as the Kirchhoff-Integral or the linearized Euler equations. In this paper an approach is chosen where data are provided from incompressible Large Eddy Simulations on a defined surface around the flame. These data are then the input to a Boundary Element Model (BEM).

In the following the approach is described in detail. The results from the BEM are compared with results from the Equivalent Source Method (ESM) and measurements, which were carried out for two different flames. Additional measurements as the determination of the sound power levels of the isothermal flow as well as for varying Reynolds numbers have been made and will be also presented and discussed in this paper.

2 Numerical Approach

The numerical approach consists of three parts,

- the model of the flame which describes the processes in the source region,
- the Kirchhoff method which couples the source region to the surrounding medium and
- a BEM approach (and ESM approach respectively) predicting the radiated sound field.

These three parts are described in the following.

2.1 The flame model

The flames studied in this paper are open, non-premixed jet flames, whose properties were investigated thoroughly and documented [4, 5]. They are referred to as the HD and H3 flame. Details of the two flames can be found in Table 1. Both flames are very similar aside from different hydrogen/nitrogen ratios. To give an impression of the studied flames, Fig. 1 shows the flame front of the H3 flame, indicated by the OH-mass fraction.

The turbulent flow field and the chemical processes in the source region are simulated by Large Eddy Simulation (LES). The low mach number of the jet flames allows an incompressible formulation of the LES, which is very efficient. These simulations were done by F. Flemming from the TU Darmstadt. Details of the used LES approach can be found in [3].

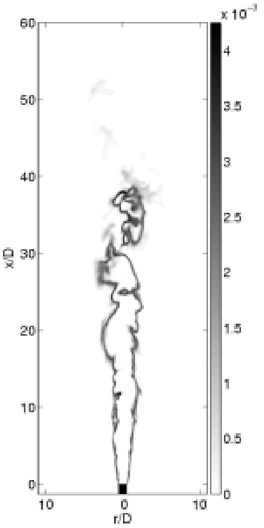

Figure 1: A snapshot of the OH-mass fraction indicating the flame front of the H3 flame, which is one of the studied jet flames

Table 1: Parameters of the studied jet flames

	HD	H3
fuel [vol%]	23/77 H_2/N_2	50/50 H_2/N_2
D [mm]	8 mm	8 mm
U_{bulk} [m/s]	36,3 m/s	34,8 m/s
U_{coflow}[m/s]	0,2 m/s	0,2 m/s
Re	16000	10000
f_{stoic}	0,583	0,310

fuel: hydrogen/nitrogen ratio, D: nozzle diameter, U_{bulk}: flow velocity, U_{coflow}: cowflow velocity, Re : Reynolds number, f_{stoic}: stoichiometric mixture fraction

As output from the model only the velocity field on the Kirchhoff-surface can be used. Due to the incompressible formulation of the LES pressure data could not be obtained.

2.2 The Kirchhoff-Method

The Kirchhoff-Method is based on the coupling of a nonlinear source region and a homogeneous acoustical radiation zone via a control surface. The control surface has to enclose all acoustical sources. Beside this, the medium in the acoustical radiation zone has to be sufficiently free of flow and temperature gradient as required by the homogeneous acoustical wave equation.

From the LES velocity data at sampled time steps are obtained on the control surface. These velocity distributions serve as input data for a boundary element method, which yields the pressure at the control surface. Once velocity and pressure at the control surface are known, the radiated sound power as well as the sound pressure at field points in the radiation zone can be evaluated.

Another Kirchhoff-approach is discussed in [2], where the equivalent source method is applied to the velocity data of the LES. In the present paper the results of the two approaches will be compared without giving a detailed description of the ESM approach.

2.2.1 Coupling LES and BEM

As acoustical data, samples of the flow velocity in a cylindrical domain around the flame were gathered at every s during the LES run. From the spatial distribution of the sampling positions cylindrical surface meshes with increasing radii from 6.7D to 13.6D could be formed. For the HD-Flame a total number of 1717 velocity samples at every spatial point where collected, for the H3 Flame even longer time signals of 2619 samples for every spatial point where generated. The time signals where transformed into the frequency domain by Fast Fourier Transformation.

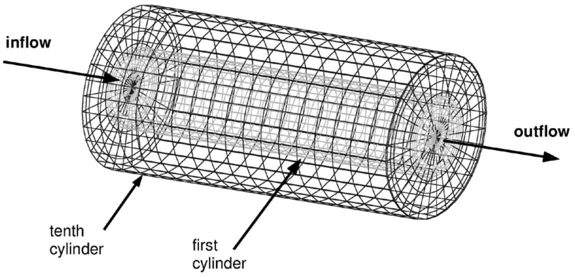

Figure 2: Meshes of the cylindrical Kirchhoff-surface, where the velocity data of the LES were sampled

The complex spectra of the normal velocity at each surface point are the input data for the BE model.

2.3 The BE model

The BE approach is a direct BEM, which solves the Helmholtz-Integral-Equation for exterior problems on the control surface. The surface elements are regarded to be constant.

Since the BEM for the presented Neumann problem does not have a unique solution at the characteristic eigenfrequencies of the associated interior Dirichlet problem, the CHIEF method was applied to remedy the nonuniqueness at these eigenfrequencies. Ten equidistant CHIEF points at the axis of the cylinders were chosen and tests showed that thus a satisfactory regularisation of the occurring irregular frequencies in the considered frequency range could be achieved. The test method is described in [6, 7].

3 Acoustic measurement

To validate the numerical results, the acoustical sound power of the flames was measured. The radiated sound power was obtained by measuring with an intensity probe around the flames along the surface of a cube with dimensions 1m × 1m × 1m. The intensity was then integrated over all sides.

3.1 Radiated sound power

Beside the sound power of the burning flames also the sound power of the isothermal flow was quantified. The measured sound power levels are shown in Fig. 3. The characteristics of the sound radiation of both flames do not differ much due to the high similarity of the flames. One can conclude that in a wide frequency range the combustion noise level is much higher than the level due to flow noise only. While the flow noise shows some distinct peaks, the reactive flow emits broadband noise, decreasing towards the higher frequency range.

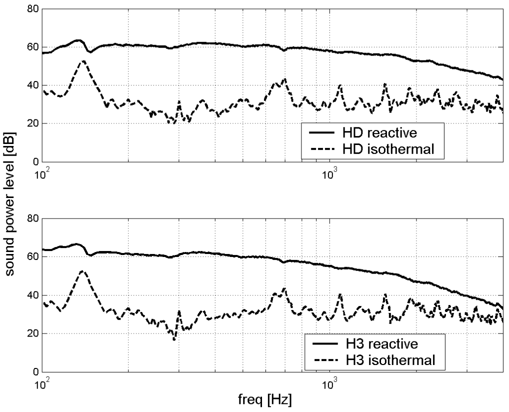

Figure 3: Measured sound power levels of HD and H3 flame for the isothermal and the reactive flow, respectively

3.2 Influence of the Reynolds number

For the H3-flame the flow velocity, which is proportional to the Reynolds number, was varied additionally to have a closer look on the noise generating mechanisms. Fig. 4 shows the respective sound power levels. Assuming an aerodynamical monopole source, the sound power should scale with $\mathrm{U}_{\mathrm{flow}}^4$ or Re^4, respectively. In Fig. 5 the same sound power levels are plotted after normalizing the sound power with respect to the reference Reynolds number of Re=10000,

$$Lp_{norm} = Lp - 40 \log_{10}(\mathrm{Re}/10000). \qquad (1)$$

The results obtained in this way confirm the assumption of monopole characteristics quite well, despite for the lowest Reynolds number where the noise due to the flame is in the order or lower than the noise due to the flow. In this case the tonal parts are especially dominant at higher frequencies.

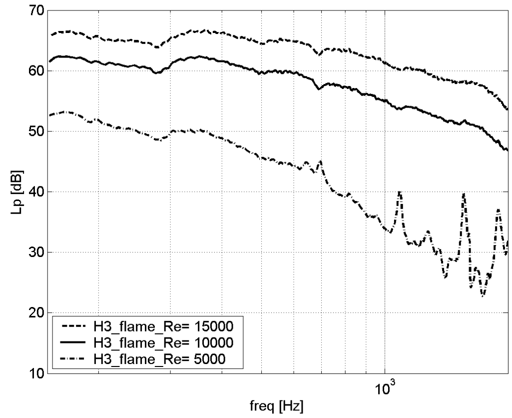

Figure 4: Sound power level of the H3 flame for varying Reynolds numbers

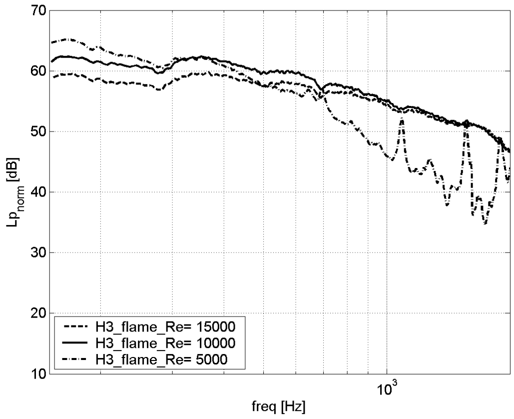

Figure 5: Sound power level of the H3-flame, normalized with respect to 40log10(Re/10000)

A more closely determination of the noise generating mechanisms is beyond the scope of this paper. An attempt to find corresponding equivalent acoustical sources to describe the sound generation of the flames can be found in [2].

4 Simulation results

After obtaining the BEM solution for the pressure distribution p on the control surface, the radiated sound power P of the flames was calculated from this pressure distribution p and the normal velocity v_n, integrated over the control surface S,

$$P = \frac{1}{2}\int_S \mathfrak{Re}\{pv_n^*\}dS. \qquad (2)$$

In Fig. 6 and 7 the calculated and measured spectra of sound power level are shown for the two flames. Beside the resulting sound power of the BEM simulation also the results for the sound power calculated with the ESM approach (see [2]) are plotted. Firstly it can be recognized, that both approaches give very similar results. Only in the lower frequency range the deviations can be detected for the HD flame, which may be caused by instabilities of the ESM in this frequency range.

For the HD flame the simulated and the measured sound power are in relative good agreement. The measured sound power is slightly overestimated by the simulations with 3-5 dB. In the higher frequency range above 2000 Hz, the simulated curves do not follow the further decrease of the measured sound power level. In case of the H3 flame this good agreement cannot be found (Fig. 7). The frequency response of the measured and simulated sound power level deviates much and the measured level is highly overestimated with at least 9 dB. For a further investigation of this deviation the intensity level was calculated at some selected measuring points and compared to the measured intensity level at these points. Fig. 8 shows the position of the measuring points P3, P6 and P7; the arrows indicate the direction of the intensity vector. The dashed box represents the location of the Kirchhoff-surface in this setting. In Fig. 9 the measured and simulated sound intensity level at these points are plotted. Both curves match well for P3 (upper plot). Point P3 has the largest distance from the flame axis as well as the largest distance from the outflow plane of the Kirchhoff-surface. The measured and simulated sound intensity levels at the other two points differ strongly. The difference at point P7, which is located more close to the flame axis, is higher than at point P6. From these evaluations it can be concluded that the velocity field of the outflow plane of the Kirchhoff-surface disturbs the acoustical simulations, especially near the flame axis.

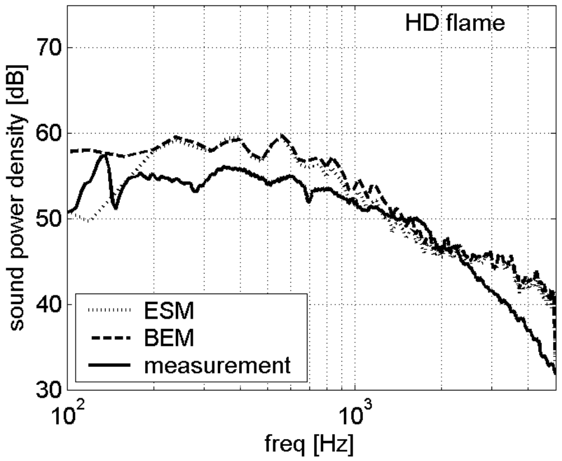

Figure 6: Simulated and measured sound power density level of the HD flame

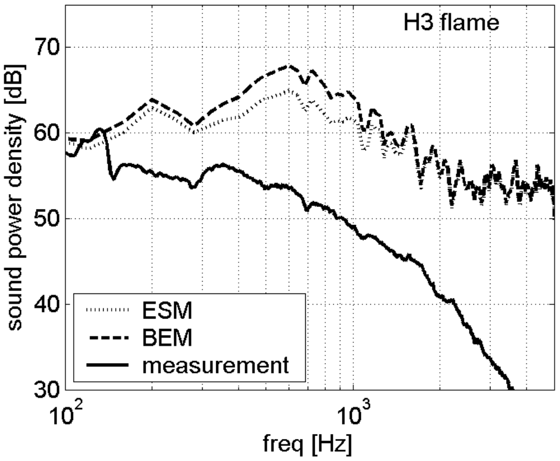

Figure 7: Simulated and measured sound power density level of the H3 flame

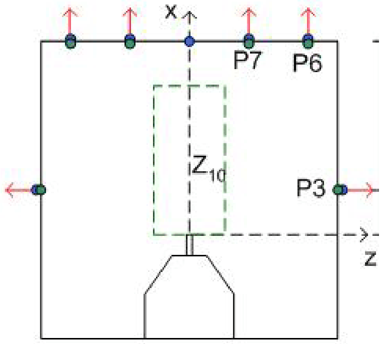

Figure 8: Position of the measuring points P3, P6 and P7

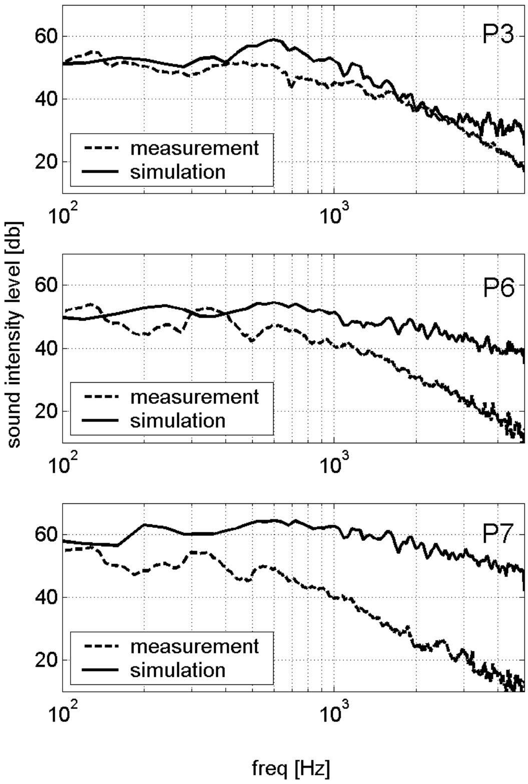

Figure 9: measured and simulated sound intensity level of the H3 flame at the measuring points P3, P6 and P7

5 Conclusions

It could be shown, that the Kirchhoff-method, here realised as a coupling of a incompressible Large Eddy Simulation and a Boundary Element Method, is a powerful tool for the simulation of the noise, generated by open, non-premixed jet flames.

Two different flames were investigated, which differ mainly with respect to their fuel ratio. Regarding the obtained results for the two flames, it can be concluded that for one case (HD) the presented approach is able to predict the sound radiation of open, non-premixed jet flames with high quality. Here, the agreement between calculations and measurement is good over a wide frequency range.

For the second case (H3) the approach fails clearly for the medium and high frequency range. This seems to be mainly due the difference in the field at the outlet of the cylinder. There, the calculated intensity flow was much higher than the one through the sidewalls of the cylinder. This does not agree with measurements of the intensity, since the measured intensity flow through all surfaces is of similar magnitude.

A comparison of the mean density and temperature at the top of the Kirchhoff-surface between the two flames shows lesser variation from the room density and temperature for the HD flame than for the H3 flame. This suggests that the Kirchhoff-surface was probably not large enough for the H3 flame. A new calculation of the H3 flame with a longer cylinder is planned.

Various measurements have been carried out to determine the sound power level of the flames, but also the sound power level of the isothermal flow and for varying Reynolds numbers. Scaling with a typical Reynolds number leads to very similar results for flames with different Reynolds numbers Re, assuming that the sound generation is proportional to Re^4. This indicates that volume sources due to the combustion processes are responsible for the noise generation.

References

[1] Combustion Noise Initiative, URL: `http://www.combustion-noise.de`

[2] R. Piscoya et al., ’Numerical aspects of the Equivalent Source Method applied to combustion noise’, *Proc. ICSV12*, Lisbon, Portugal (2005)

[3] F. Flemming et al., ’A hybrid approach for the evaluation of the radiated noise from a turbulent non-premixed jet flame based on Large Eddy Simulation and equivalent source & boundary element methods’, *Proc. ICSV12*, Lisbon, Portugal (2005)

[4] R. Barlow (ed.), *Proceedings of the TNF Workshop*, Sandia National Laboratories, Livermore, CA, `www.ca.sandia.gov/TNF`

[5] M. Tacke, S. Linow, S. Geiss, E. Hassel, J. Janicka, J.-Y. Chen, ’Experimental and numerical study of a highly diluted turbulent diffusion flame close to blowout’, *Proc. Combust. Inst.*, 27, 1139-1148 (1998)

[6] H. Brick, M. Ochmann, E. Brenck, ’Simulation of the sound radiation from wheel-like structures using the boundary element method’, *Proc. Forum Acusticum*, Sevilla, (2002)

[7] M. Ochmann, A. Osetrov, ’Construction of analytical solutions for the error estimation of acoustical boundary element solvers’, *Proc. Forum Acusticum*, Sevilla, (2002)