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Modelling of combustion noise with the Boundary Element Method and Equivalent Source Method

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Abstract [546] The research project "Combustion Noise" concentrates on the development of methods for the prediction and minimisation of the noise generation by combustion in general and for aircraft engines in particular. In the present subproject the application of the acoustical Boundary Element Method (BEM) and Equivalent Source Method (ESM) for the prediction of noise from a free diffusion flame is investigated. These acoustical methods have been coupled with a Computational Fluid Dynamics-technique to describe the noise from the combustion process. The coupling of the BEM/ESM and the CFD–Simulation is realised on a Kirchhoff–surface. As coupling variables the normal velocity on the Kirchhoff–surface is used. The coupling was realised on different cylindrical surfaces with increasing radii around the centre of the flame. The results for the radiated sound power of the diffusion flame depending on the distance of the surfaces from the flame centre is discussed.

1 INTRODUCTION

The subject of interest, an open diffusion jet flame, is characterised by turbulent flow-fields, chemical reactions, heat transfer and the interaction of these processes. The governing equations of the combustion process are solved by a Large Eddy Simulation (LES), a powerful numerical technique from Computational Fluid Dynamics. The fluctuations of physical quantities that act as sound sources are calculated in a small computational domain around the flame with high time and spatial resolution. The sound field generated by those sources, in particular at large distances, can be computed in a faster and more efficient way by using the calculated fluctuations as input data for acoustical methods. The acoustic analogy (AA) or the linearized Euler equations (LEE) are often used as the coupling procedure to determine the sound field [3]. In the present work, the CFD domain is coupled to the radiation zone by a control surface, the Kirchhoff–surface, which must enclose all acoustical sources of the flame and has to be located in an homogeneous environment free of flow and temperature gradient. On this Kirchhoff–surface the normal velocity as Neumann boundary condition for the acoustic radiation problem is obtained from the LES calculation. This coupling is referred to as the Kirchhoff–method. The advantage of the Kirchhoff-Method is that only the surface integral on the control surface has to be evaluated to calculate the radiated sound field in the radiation zone, its possible drawback is the requirement of no flow and no temperature gradients outside the control surface. Hence, the positioning of the control surface and the exact description of the acoustic quantities on this surface are the sensitive points of the Kirchhoff–method.

In order to examine the influence of the position of the control surface, the sound radiation of different control surfaces with varying distance from the flame centre was studied. Since flow and temperature gradient decline with increasing distance to the flame the sound radiation should converge to the true value with increasing radius of the control surface.

2 THE ACOUSTIC METHODS

While the BEM solves the Helmholtz–Integral–Equation for exterior field problems on the control surface of the structure, the ESM replaces the original sound source with a system of acoustical elementary sources inside this control surface which satisfy the wave equation and radiation condition in the ambient medium and fulfil the boundary conditions on the surface. Detailed descriptions of these acoustical methods can be found e.g. in [8], [12]. Both methods are well approved for the calculation of the sound radiation from structure–borne sound. Up to now there are only few attempts to apply these methods in the field of thermo– or flowacoustics [3].

3 COMPUTATIONAL MODEL

3.1 Flame model

The flame model is a turbulent hydrogen jet diffusion flame, combusting a highly diluted mixture of H_2 and N_2 at the volume ratio of $23 : 77$. The stoichiometric mixture fraction is $f_{stoic} = 0.583$. The fuel was diluted in order to slow down the chemical reactions, i.e. to stabilise the numerical simulation. Due to the high dilution the flame burns close to its blow-off limit. 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. The corresponding Reynolds-number is 16000. The flame was numerically and experimentally investigated in detail at the Technical University of Darmstadt [4],[5].

The Large-Eddy-Simulation (LES) of the flame was executed on a cylindrical computational domain of 48 nozzle diameters D length and radius $30D$. The numerical grid consisted of 257 x 32 x 60 (axial x circumferential x radial) cells. The simulation based on the steady Flamelet model and the presumed-pdf method. The used numerical method assumes density to be independent of pressure (incompressibility), which is a widespread approximation within the methods of computational fluid dynamics for the considered low Mach number flow. The LES-code was developed at the Technical University Darmstadt, Institute for Energy and Powerplant Technology. More detailed information about the used LES-model for turbulent diffusion flames can be found in publications of this institute [4], [11]. For the acoustic calculations, velocity samples at spatial points on ten cylindrical surfaces with radii varying from $R = [6.7, 7.3, 7.9, 8.6, 9.3, 10.0, 10.8, 11.7, 12.6, 13.6]D$ and constant length $L = 47.8D$ were excerpted from the LES calculation within a timeframe of $0.17 \cdot 10^{-1}s$ with a sampling rate of approximately 10000 Hz. The time series of the velocity were transformed into the frequency domain by means of the Fourier transform before serving as input data for the BEM or ESM.

3.2 Acoustic model

From the point distribution given by the LES surface meshes of ten cylindrical control surfaces were generated. To save computing time and memory the number of axial points was much

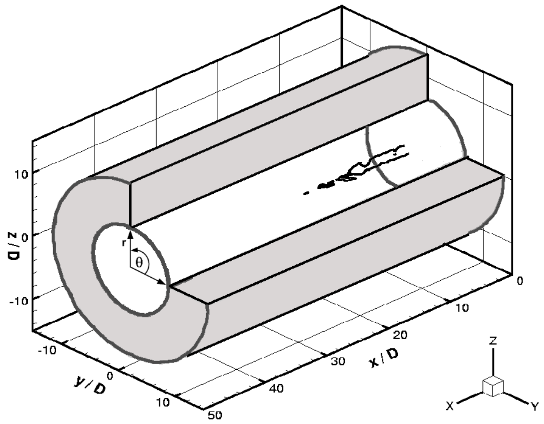

Figure 1: *Domain of the LES velocity samples at cylindrical surfaces around the flame (gray area). The black line indicates the contour of the stoichiometric mixture fraction of the flame.*

reduced to build the surface meshes, i.e. the grid of the cylindrical area was reduced to 33 x 32 points for the smallest cylinder with $R_1 = 6.7D$ and 19 x 32 points for the biggest cylinder with $R_{10} = 13.6D$. The surface mesh for the cylinder of largest radius fulfills the requirement of six grid points per wavelength up to a frequency of $f_{max} = 3000$ Hz.

BEM

The BEM for the calculation of the sound radiation of the presented Neumann problem does not have an unique solution at the characteristic eigenfrequencies of the associated interior Dirichlet problem. The CHIEF method was chosen to remedy the non-uniqueness at these eigenfrequencies. A brief description of the CHIEF method can be found in [12]. Tests showed, that ten equidistant CHIEF points at the axis of the cylinders provide satisfactory results at the occurring characteristic eigenfrequencies. More details of the used BEM application and test procedure are described in a former paper [1].

ESM

An ESM model is characterised by the distribution of acoustical elementary sources inside the control surface. For the presented problem three different distributions of the source positions were tested: a) 20 sources along the cylinder axis, b) 32 sources in parallel rings and c) 30 sources in random positions over a smaller cylindrical shell of radius $0.5R$ and length $0.6L$ (see Fig. 2). In each position, sources of zeroth, first and second order were considered, which correspond to monopoles, dipoles and quadrupoles. The results presented in this paper correspond to configuration a) in Fig. 2. The results obtained by the other configuration do not differ notably from this configuration.

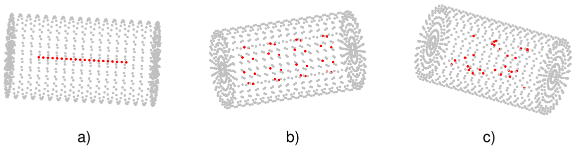

Figure 2: *The three different distributions of source positions inside the mesh of the cylindrical control surface.*

4 RESULTS

Starting from the given normal velocity distributions at the ten cylindrical surfaces as the results of the LES, the pressure distributions at the same surfaces were calculated by the BEM and the ESM for a set of frequencies. The sound power is then computed by integrating the acoustic intensity over the control surfaces. Fig. 3 shows the radiated sound power P calculated by the BEM for each cylinder. But the curves of the sound power are hardly plausible. The expected convergence of the radiated sound power with increasing radii of the control surface can not be observed. Also, the distinctive peaks in the higher frequency range are not assumed from a real flame. Diffusion flames as the present flame should show an intense sound radiation in the lower frequency range declining with the frequency [6], [7], [9], [10]. A closer examination revealed, that the sound power radiation depends mainly on the velocity spectrum of the centre of the inflow plane. Fig. 4 shows the velocity spectrum of the centre in comparison with other points of the inflow plane. Only the spectrum of the centre point has considerable high

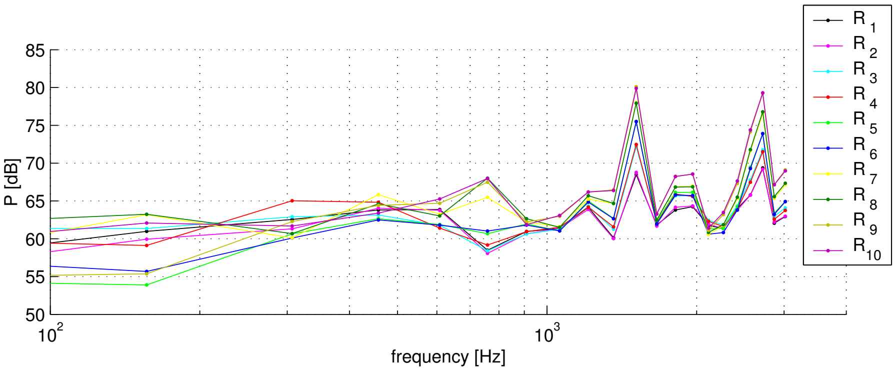

Figure 3: *Sound power radiated by the ten control surfaces around the flame*

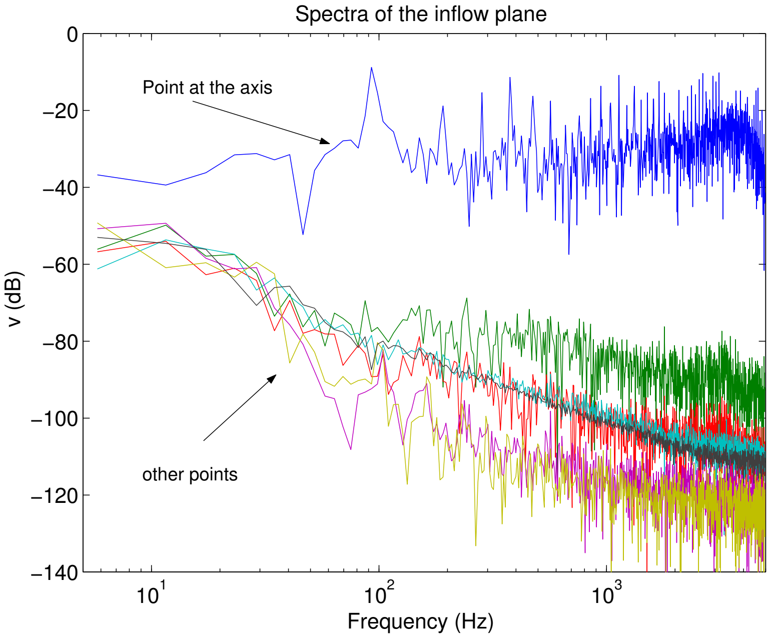

Figure 4: *Velocity spectrum of the centre and other points of the inflow plane of the cylindrical control surface*

frequency components, all other points show a strong decay with the frequency. The Large Eddy Simulation defines at this point an artificial turbulence as boundary condition. This artificial turbulence with extreme high amplitudes over the whole frequency range is an unphysical value, which obviously disturbs the acoustic approach. Fig. 5 show the sound intensity radiated by the tenth control surface in the x,z–plane at the frequency = 1511 Hz (first peak of the radiated sound power, see Fig. 3). The centre point of the inflow plane is clearly identifiable as the main sound source. In order to remedy this numerical perturbation from the inflow condition of the LES model the normal velocity of the inflow plane was set at zero. As it can be seen in Fig. 6 the unfamiliar peaks of the radiated sound power disappear, the differences between the sound power of the different control surfaces are reduced and the radiated sound power decays with the frequency for all surfaces. Altogether, the sound power spectra in Fig. 6 seem to be a more reasonable representation of the sound radiation from an open flame than these in Fig. 3. In Fig. 7 the radiated sound intensity is plotted which results from the new condition. Here the sound is radiated mainly in direction of the flow.

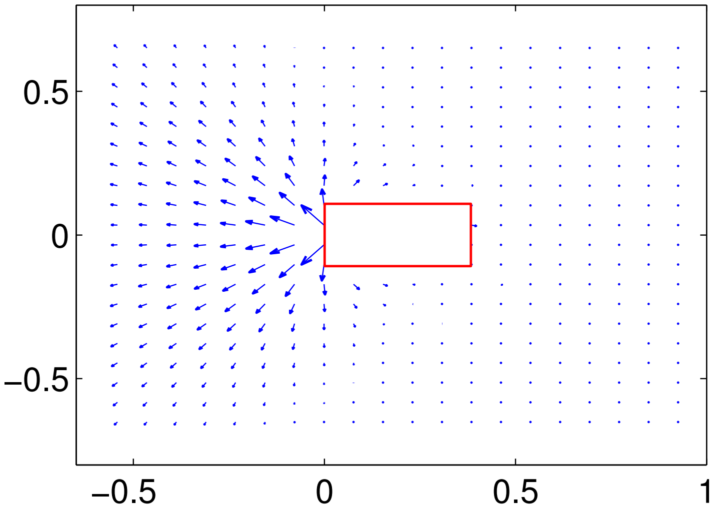

Figure 5: *Sound intensity radiated by the tenth control surface at a frequency = 2700 Hz. The centre of the inflow plane appears as main source of the sound radiation.*

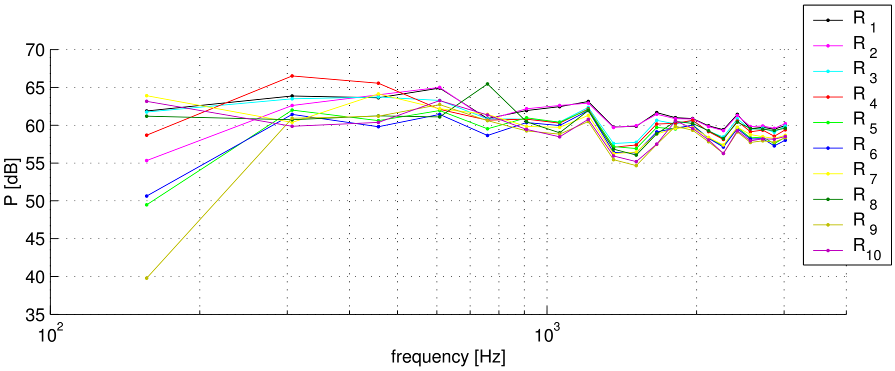

Figure 6: *Radiated sound power of the ten control surfaces with the normal velocity on the inflow plane set at zero*

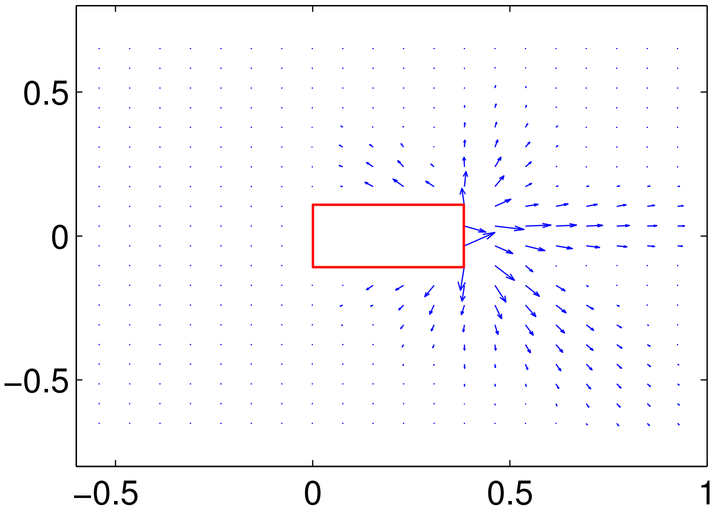

Figure 7: *Sound intensity radiated by the tenth control surface at a frequency = 2700 Hz. The normal velocity at the inflow plane* ($x = 0$) *is set at zero.*

Fig.8 shows the difference $\Delta L = L_{BEM} - L_{ESM}$ of the BEM and the ESM calculation in dB. Apart from the lowest frequencies the discrepancy of the results is marginal, though both methods follow a different approach. This result is very positive, especially in face of the future process, since both methods can approve themselves mutually.

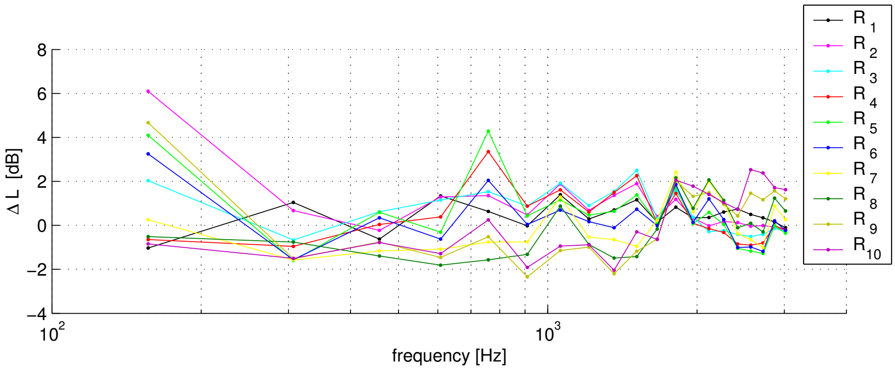

Figure 8: *Difference of the radiated sound power calculated by BEM and ESM,* $\Delta L = L_{BEM} - L_{ESM}$

5 CONCLUSIONS

The radiated sound power of an open diffusion jet flame was calculated by the Kirchhoff–method, which is characterised by the coupling of a Large Eddy Simulation with the Boundary Element Method or the Equivalent Source Method as acoustic methods based on the Helmholtz–equation. The BEM and the ESM calculations show nearly the same results. The influence of the position of the coupling surface was studied by varying the radius of the cylindrical surface around the centre of the flame. Beside the characteristics of the surface also the influence of the boundary conditions of the LES was examined. Especially the inflow boundary condition seems to disturb the acoustic calculations. Neglecting the velocity on the inflow plane by setting the values in this area at zero the assumed convergence of the radiated sound power for the different coupling surfaces could be shown. The transfer of boundary conditions from one model to another has to be reviewed carefully in the further progress of the research project. The small deviations originate possibly from the flow or temperature gradients in the ambient environment of the Kirchhoff–surface. The influence of the assumption of incompressibility, implied by the LES, on the acoustic calculations has not been studied yet.

The present work does not present the Kirchhoff–Method for the calculation of combustion noise as readily elaborated, but it discusses the possibilities and difficulties of this method. The planned experimental examination of the sound radiation from a diffusion flame will be an important step for the validation of the method.

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