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A HYBRID LES-BEM METHOD FOR THE CALCULATION OF COMBUSTION NOISE ABOVE AN INFINITE PLANE

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ABSTRACT

The Boundary Element Method (BEM) is a well-established and efficient tool for the calculation of sound radiation from vibrating structures. Up to now few attempts have been made to enhance this method for the use in aero- and thermoacoustical simulations. In this presentation, the BE method is applied to the calculation of the sound radiation of an open, turbulent flame. The calculation is realised by coupling of a Large-Eddy-Simulation (LES) with the BEM. The LES calculates the velocity field in the close vicinity of the flame. Based on these data BEM is used to calculate the radiated sound field. The results are compared with measurements. To determine the directivity of the sound field, the reflections from the ground or floor have to be taken into account. As long as the impedance of the reflecting plane is infinite or zero, this can be easily achieved by including image sources. A new approach for solving a finite impedance problem will be discussed. In this approach the image sources are equipped with complex source points. The results for selected test cases as well as the effect on the directivity of the sound field of the flame will be presented.

1 INTRODUCTION

Within the German research group "Combustion Noise" the application of the Kirchhoff-Method for the simulation of the combustion noise of open, non-premixed, turbulent jet flames was investigated. The Kirchhoff-Method is a hybrid method. The governing, non-linear equations of the flow and chemical processes in the source region are solved with a method from the domain of Computational Fluid Dynamics and the obtained data for the velocity and pressure distribution are transferred via a control surface, which is referred to as the Kirchhoff-surface, to the methods of linear acoustics. In this project the Kirchhoff-method is realized by a coupling of an incompressible Large-Eddy-Simulation (LES) for the source region and the Boundary-Element-Method (BEM) or the Equivalent-Source-Method (ESM) for the acoustical domain respectively. A detailed description of results for two flame configurations HD and H3 and the methods can be found in former publications [2],[4],[8].

In the present work, the focus is not the hybrid strategy itself, but the consideration of the influence of reflections from the ground to the sound radiation of the flame.

2 REVIEW OF THE RESULTS

A short review of the results shall be given here. Fig. 1 shows the measurement setup for measuring the radiated sound power of the flames including the Kirchhoff-surface of the numerical model. The radiated sound power was determined by integrating the sound intensity over a closed measurement grid around the flame.

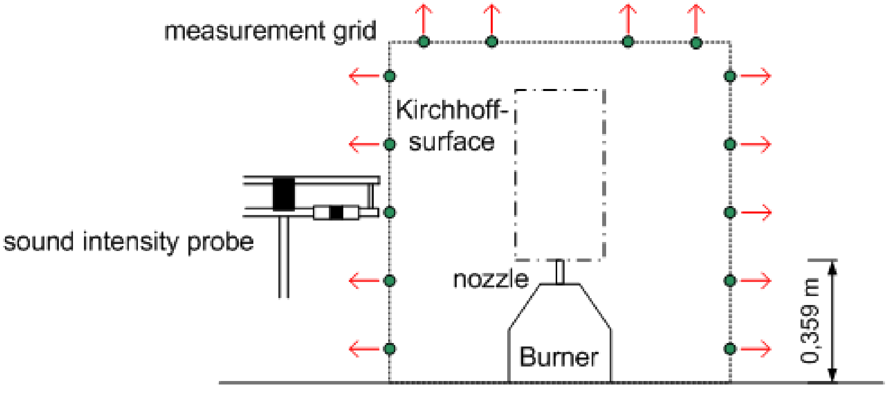

Fig. 1. Position of the burner, measurement grid and measuring points as well as the Kirchhoff-surface of the numerical model.

In Fig.2 a comparison of the calculated and measured sound power density for the HD- as well as for the H3-flame can be seen. The results differ much for the two configurations. In general the calculated sound power overestimates the measured sound power. In case of the HD-flame the overestimation is around 3-5 dB, whereas in case of the H3-flame the measured sound power is overestimated in the middle frequency range about 9 dB and this difference even further increases with frequency. Some approaches were made recently to improve the simulation results with respect to the coupling strategy or a preprocessing of the LES-data before transferring to the acoustical methods. A discussion of these approaches can be found in [9].

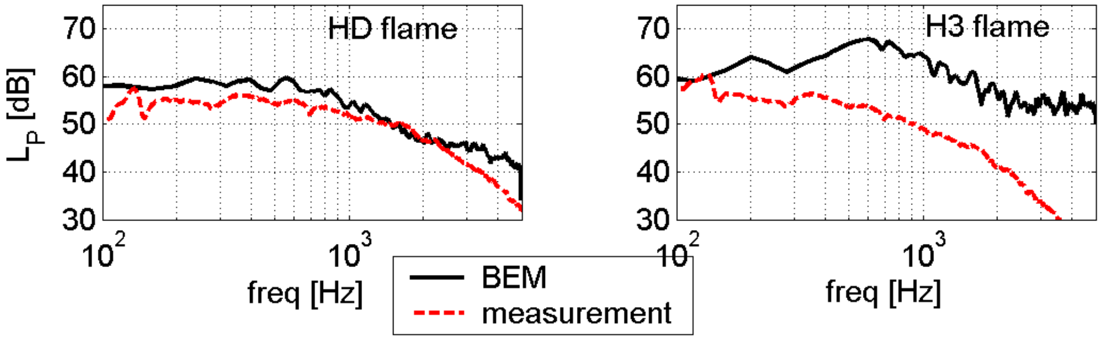

Fig. 2. Measured and simulated sound power density level for the HD- and the H3-flame. The simulated sound power was obtained by a LES-BEM coupling.

3 INFLUENCE OF THE GROUND

The flames are not located in free space. The measuring setup was placed in a large experimental laboratory on an experimental table. This environment can be approximately described as a half-space. There will be reflections from the ground, but also absorption and transmission of sound energy.

The reflections of the ground influence particularly the directivity of the sound field, because of the interferences of the incident sound field, radiated from the burning flame, and the reflected sound field, while the absorption of the ground will diminish the strength of the sound field in general.

Up to now the ground effects are not included in the simulation, i.e. the acoustical methods assume a sound radiation in the unbounded 3D-domain.

3.1 Including a rigid ground in the simulation

Starting point of the BEM calculation is the Helmholtz integral equation for exterior field problems,

$$\iint_s [p(\mathbf{y})\frac{\partial g(\mathbf{x},\mathbf{y})}{\partial n(\mathbf{y})}-\frac{\partial p(\mathbf{y})}{\partial n(\mathbf{y})}g(\mathbf{x},\mathbf{y})]ds=C(\mathbf{x})p(\mathbf{x}), \tag{1}$$

where

$$g(\mathbf{x},\mathbf{y})=\frac{e^{-jkr}}{4\pi r} \text{ with } r=r(\mathbf{x},\mathbf{y})=\sqrt{(x-x_s)^2+(y-y_s)^2+(z-z_s)^2} \tag{2}$$

is the Green's function in the three dimensional free space, and $C(\mathbf{x})$ is 1 for $\mathbf{x}$ in the exterior domain, ½ for $\mathbf{x}$ on the surface of the radiating structure and 0 for $\mathbf{x}$ in the interior domain. $\mathbf{x}$ denotes the receiver position $\mathbf{x}=[x\ y\ z]$, $\mathbf{y}=[x_s\ y_s\ z_s]$ the source location and k the wavenumber. The time convention is $e^{j\omega t}$.

As long as the ground can be considered as perfectly rigid or soft its inclusion in the BEM-calculations can be easily achieved by adding an image source [11]. The Green's function for the three-dimensional half space, which takes the effect of a rigid or soft ground into account, reads

$$G(\mathbf{x},\mathbf{y})=g(\mathbf{x},\mathbf{y})+R\,g(\mathbf{x},\mathbf{y}'), \qquad (3)$$

where R is the reflection coefficient of the ground and $\mathbf{y}'$ is the reflected source point. $R=1$ represents a perfectly rigid ground and $R=-1$ a perfectly soft ground. A reflection coefficient $R=1$ corresponds to the ground impedance $Z\rightarrow\infty$ of an ideal rigid ground and $R=-1$ corresponds to an impedance $Z=0$ of an ideal soft ground.

In Fig. 3 the influence of a rigid ground on the directivity of the sound field is shown. With increasing frequency the directivity is characterized by the appearance of more and more side lobes in addition to the main lobe pointing perpendicular to the ground and in direction of the flow. In the lower frequency range the radiated sound power will be slightly increased by the reflections of the ground, but in the higher frequency range the sound power of the flame is not influenced by the ground. Fig. 4 shows the simulated sound power assuming an unbounded domain and a half space with rigid ground.

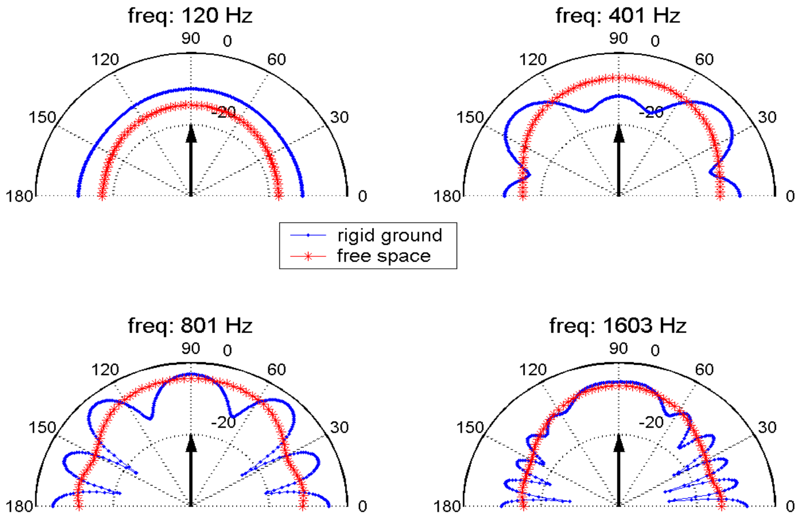

Fig.3: Influence of a rigid ground on the directivity of the sound field, the arrow indicates the flow direction of the flame.

3.2 Including a ground of finite impedance

With Green's function in eq.(3) it is not possible to include absorption effects or finite impedances of the ground in the simulation of the sound radiation. Exact solutions for the Green's function for the sound propagation above impedance ground were published by various authors in the past, e.g. [1],[5],[6],[10].

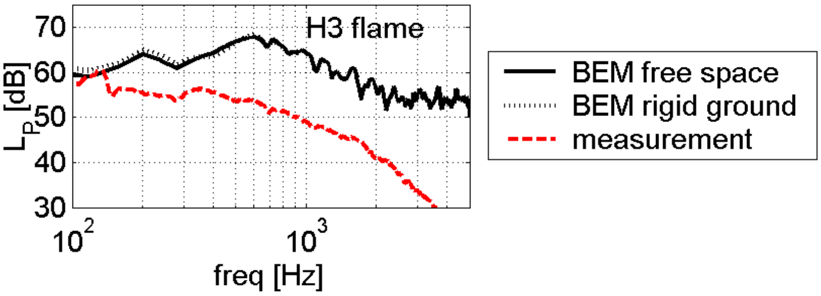

Fig.4: Level of the sound power density of the H3-flame calculated with a BEM free space model, a BEM half space model for rigid ground, compared to the measured sound power density.

But in a BEM formulation they are only suitable with restrictions. For configurations with a spring impedance of the ground a Hankel function can emerge, which becomes singular if the horizontal distance between **x** and **y** goes to zero. This leads to serious complications when solving the Helmholtz-Integral-Equation on the surface of the boundary element model. Also, a subsequent pressure evaluation at field points above and beneath the BE-model must be excluded. In [7], a Green's function for the sound propagation above impedance ground is presented, see eq.(4), which has a regular solution for any arbitrary impedance of the ground, mass impedance as well spring impedance independently of source and receiver point location:

$$G(\mathbf{x},\mathbf{y})=g(\mathbf{x},\mathbf{y})+g(\mathbf{x},\mathbf{y}')+\frac{j\gamma}{2\pi}\int_{-\infty}^{0}\frac{e^{-jk\sqrt{\rho^2+(z+z_s+j\varsigma)^2}}}{\sqrt{\rho^2+(z+z_s+j\varsigma)^2}}e^{-j\gamma\varsigma}\,d\varsigma\,, \tag{4}$$

with the horizontal distance $\rho=\sqrt{(x-x_s)^2+(y-y_s)^2}$ and the normalized admittance $\gamma=jkZ_0/Z\,,Z_0=\rho_0 c$. Here ρ_0 and c refer to the density and sound speed in the ambient medium, respectively. The only restriction pertains the grazing incidence; it is not possible that both the source and the receiver are located on the ground. The correction term for the influence of the finite impedance is realized by taking image sources with complex source positions into consideration. A detailed discussion concerning the implementation of eq.(4) in a boundary element code and its verification on the basis of representative test cases can be found in [3]. With a fast and stable evaluation of the integral in eq.(4) it is possible to include the reflection and absorption characteristics of a real ground in a simulation. With this improvement of the BEM calculation we expect improvements in the quality of the discussed simulation results concerning the sound radiation of flames, since this approach can represent a more exact approximation of the real measurement surrounding.

4 SUMMARY

Simulation results of the sound radiation of open, non-premixed jet-flames were briefly reconsidered. In a first step the BEM-model was modified in order to include the effects of a rigid ground into the simulation. The reflections of a rigid ground only affect the directivity of the sound field, apart from the lower frequency range, where the inclusion of a rigid ground leads to a slight increase of the radiated sound power. In the higher frequency range the radiated sound power of the flames does not differ in case of the assumption of an unbounded 3D-domain or a halfspace above rigid ground. For an incorporation of absorption effects of the ground, which could have effectively influenced the sound power measurements, it is necessary to integrate an appropriate Green's function in the BEM-model. A possible solution for this problem is outlined referring to a new Green's function, proposed recently for sound propagation above impedance ground.

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