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APPLICATION OF EQUIVALENT SOURCES TO THE DETERMINATION OF THE SOUND RADIATION FROM FLAMES

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Abstract
Equivalent sources have been successfully used to calculate the sound radiation and the sound scattering from solid bodies lying in a homogeneous medium without flow. For the field determination an acoustic boundary condition at the body surface must be known. In an earlier work, the application of this method to compute the sound radiation of open turbulent flames was investigated in order to extend the range of use of this basic method to aero-thermoacoustic problems. It was assumed that outside a region surrounding the flame, the flow and temperature gradient had strongly decayed and approximate homogeneous conditions existed. The necessary data at a control surface (Kirchhoff surface) surrounding the combustion zone was delivered by an incompressible Large Eddy Simulation (LES). Measurements carried out of two simulated flame configurations showed that while the spectrum of one flame was well reproduced, the spectrum of the second flame was satisfactorily matched only in some positions.
In the present work, additional calculations are made trying to explain and reduce these differences, for example, calculations using different control surfaces, using open surfaces and including a constant background flow. The results obtained are presented and discussed.

INTRODUCTION

The use of hybrid methods to predict the noise originating from turbulent flows and its interaction with solid structures has become a usual practice in the field of computational aeroacoustics. Sound generating mechanisms and sound propagation are separately treated to resolve their characteristic time and spatial scales efficiently. Recently, the application of these hybrid methods is being extended to solve aero-thermoacoustic problems, since although the relevant sound sources involved in combustion processes are usually of a different nature than the sources in non-reactive turbulent flows, the acoustic perturbations of the physical quantities are obtained by solving similar conservation equations.

In previous works [1]-[3], the sound radiation of open turbulent diffusion flames was determined by using a hybrid method that couples an incompressible Large Eddy Simulation (LES) with a Kirchhoff method. Our particular hybrid approach has an advantage over other combined techniques: only one acoustic quantity at a surface surrounding the reactive region is needed, which implies a significant reduction in the amount of data that has to be processed. Details of the methods employed can be found in the above references. A comparison of the simulated results with the measured ones shows a very good agreement in one of the studied cases and differences in the second one. In the present paper the results from subsequent calculations trying to explain and reduce the deviations are presented.

REVIEW OF THE RESULTS

Two turbulent H_2/N_2 jet flames, referred to as “H3” and “HD” flames, were simulated with an incompressible LES. The values of the velocity field at cylindrical surfaces surrounding the flames were used as input data for a Kirchhoff method to determine the radiated sound. A hybrid approach that involves the use of a Kirchhoff method and particularly the Kirchhoff integral, usually takes the data at the control surface from compressible CFD codes, where pressure and density are functionally related. In the LES code that provides the data for this calculation, pressure and density are not related to each other directly, but density fluctuations, which are considerably high in the combustion zone, are admitted, For the low Mach numbers of the fuel, this approximation allows saving computational costs and should give a satisfactory representation not only of the flow mean quantities, but also of the chemical characteristics. Measurements on these flames, especially the H3 flame, have shown that this LES code was able to properly simulate their flow and chemical mean values [2]. This constitutes a very important issue since, to consistently validate a numerical procedure with experimental results, the simulated object must correspond to the measured one. The next step is to see if the acoustical properties can also be predicted.

Due to the numerical implementation of the LES, the pressure was not appropriate as a boundary condition for the acoustic computation. Therefore the velocity was selected as coupling quantity. The most important assumption in the development of this particular hybrid method is that the velocity field obtained by the LES carries acoustical information along with other non-acoustical components, but these spurious terms decay at some distance from the source terms, so that the velocity can be used as a boundary condition for the further computation of the sound field.

In Fig.1, the curves of the sound power density for both flames are compared. The better agreement of the results of the HD flame can be clearly seen. For the H3 flame, the overestimation of the power level is noticeable and the decay of the curve at high frequencies is only partially reproduced (up to approx. 2 kHz)

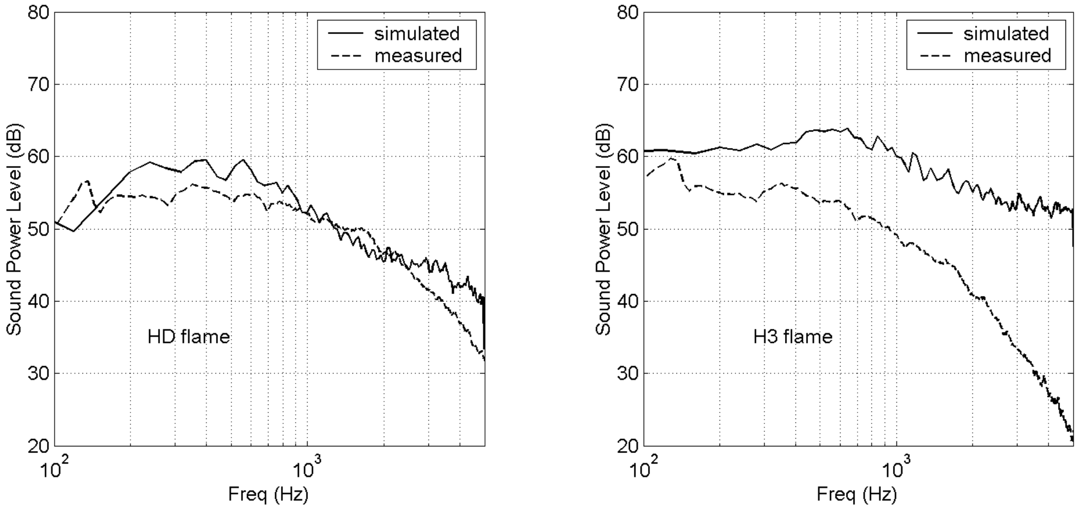

Figure 1: Comparison of the simulated sound power density for the two flame configurations with the experimental results

SEARCH FOR THE ERROR SOURCE

To determine the factor which produces this big difference, a local comparison of the simulated and measured sound field was made. The spectra of the measured normal sound intensity were compared to the simulated intensity spectra in seven points around the flame (Fig. 2).

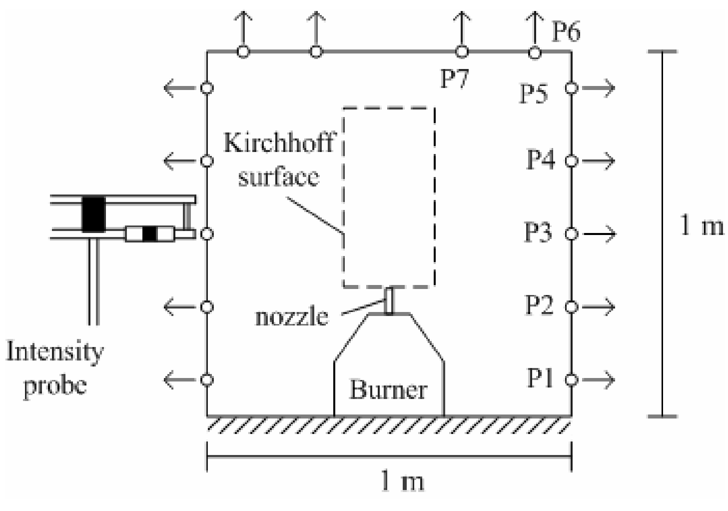

Figure 2: Localization of the measurement points

In Fig. 3 it can be seen that the difference in the intensity spectra is not the same at all points. Actually there is a good agreement between simulation and measurement at the points which are farther away from the upper cap of the cylindrical control surface. The overestimation of the intensity level, especially in the higher frequency range, increases as the field points lie closer to the upper cap. This suggests that the velocity at this part of the control surface has an important influence on the radiated sound field. This effect is confirmed when the portion of the sound power produced by the upper cap and that of the rest of the cylindrical surface are calculated separately (Fig. 4)

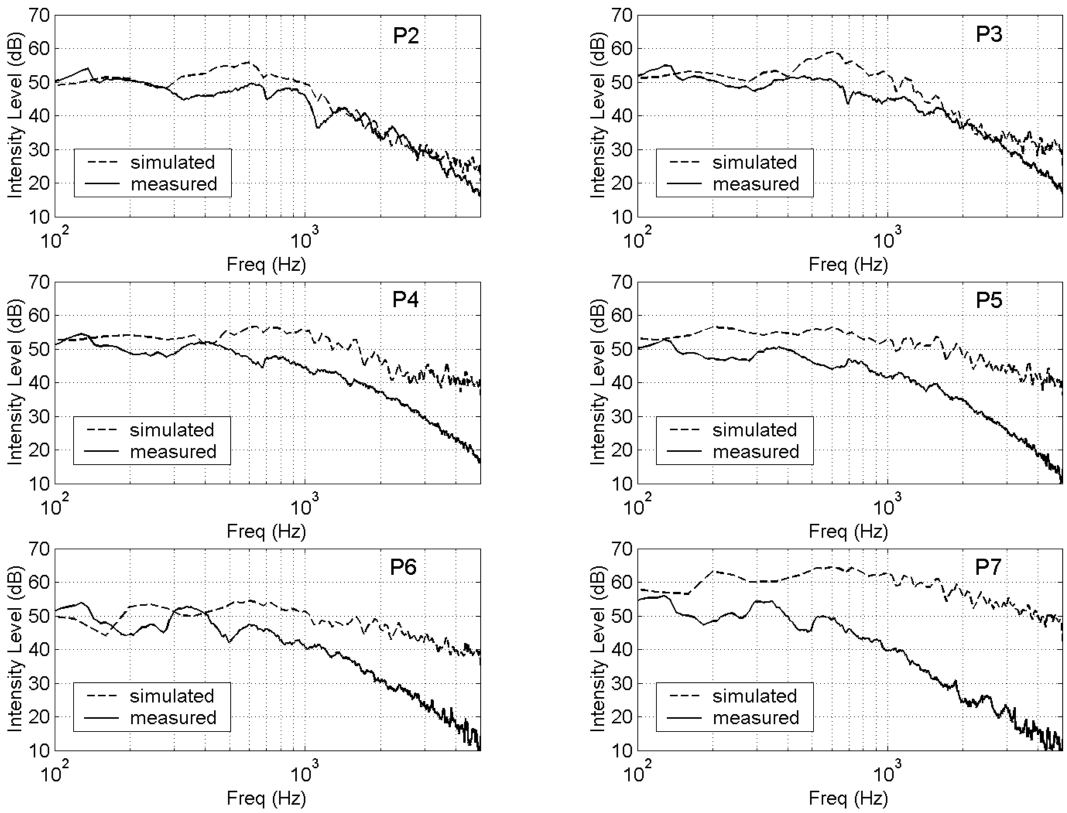

Figure 3: Comparison of simulated and measured intensity spectra

ACCOUNTING FOR EFFECTS OF THE UPPER CAP

Since the data at the upper cap of the cylinder affects the accuracy of the predicted sound field, ways of avoiding or reducing its disturbing effect have been examined.

Use of Open Surfaces

In the work of Freund [4], the use of open Kirchhoff surfaces for the determination of the sound field of turbulent jets was discussed. It was shown that calculations using the Kirchhoff integral over open control surfaces can approximately predict the sound field at a specific set of points. The line connecting these field points with the sound sources must intersect the surface. Under these circumstances, the sound power cannot be determined since the sound field is not accurately computed at all points. Following this idea, a new calculation was made excluding the data of the upper cap, so that the strength of the equivalent sources was determined reproducing the velocity only at the side surface of the cylinder.

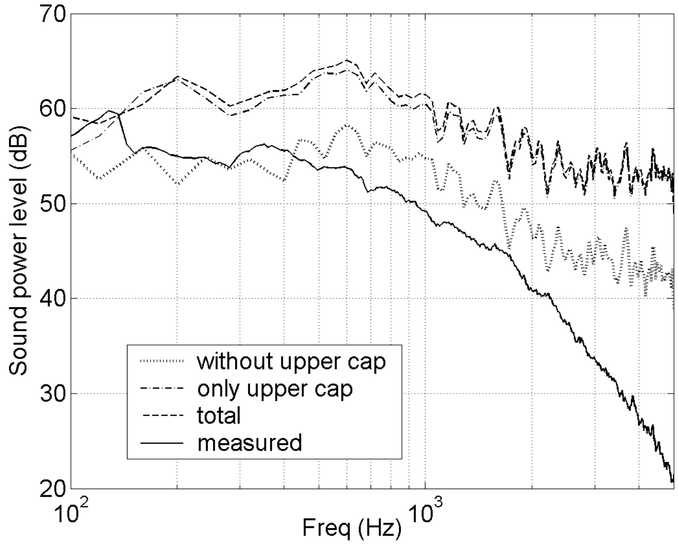

Figure 4: Contribution to the sound power from the upper cap and the rest of the cylindrical control surface

The spectra obtained with the open surface were compared to those computed with the closed surface (see Fig. 5) The agreement of the new calculation with the measured spectra is not better, on the contrary, the differences at low frequencies are bigger. These results show that the contribution of the upper cap should not be totally excluded, but it has to be in some way weighted to avoid the overestimation of the levels without loss of the spectral information.

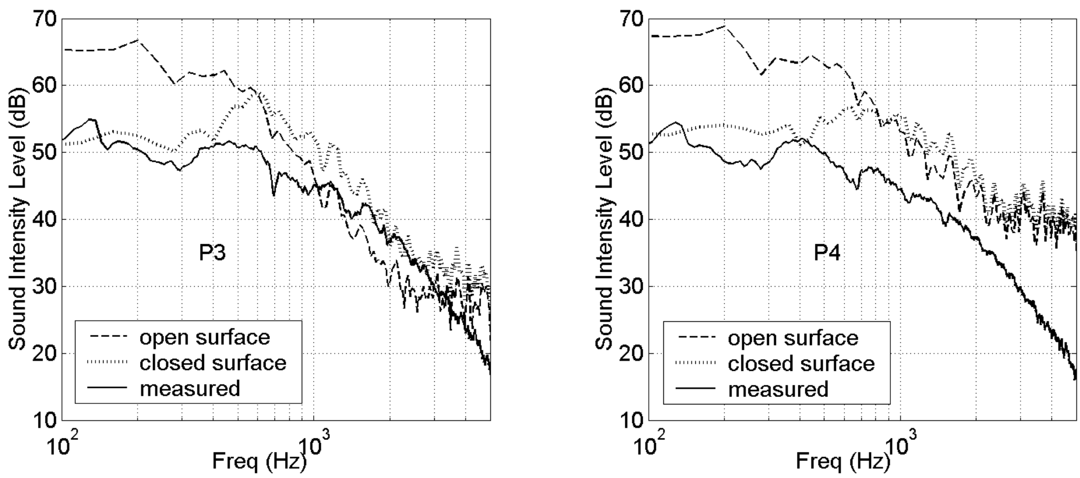

Figure 5: Sound intensity calculated with open and closed control surface

Processing of the input data

It has been assumed that the nonlinear components of the velocity decay strongly with distance and could be neglected at positions far away from the source. The results of the previous calculations suggest that in the flow axis, these components may still have to be accounted for. A procedure to filter out the disturbing components, the Principal Component Analysis (PCA), was considered.

This statistical method transforms a number of dependent variables into a set of independent components, called principal components. The first principal component accounts for as much of the variability in the data as possible, and each succeeding component accounts for as much of the remaining variability as possible [5]. The velocity time series of both flames were disassembled in their principal components and the sound field was calculated keeping only the first components (Fig. 6). The decomposition of the input signals produces different results in the investigated flames. For the HD flame, the high frequencies are lowered too much generating a steeper slope in the decay of the sound power spectra. For the H3 flame, the sound power obtained with only the first component (pc1) is moved down about 12 dB. This provides a good agreement in the level and the form of the spectrum beyond 500 Hz but the values of the low frequencies are then much underestimated. Retaining more components practically displaces the curve upwards, as it can be seen in Fig. 6 (right), where the radiated sound power of the sum of the components 1 to 10 (pc 1-10) are also shown.

The calculated principal components seem to be not completely correlated to the coherent structures that are responsible for the sound radiation since in the two studied cases, different parts of the frequency range are not correctly estimated. A criterion to set the number of components that should be taken into account was not found. The method may not appear suitable for the filtering of our data but certainly more examples should be tested before discarding the use of this technique.

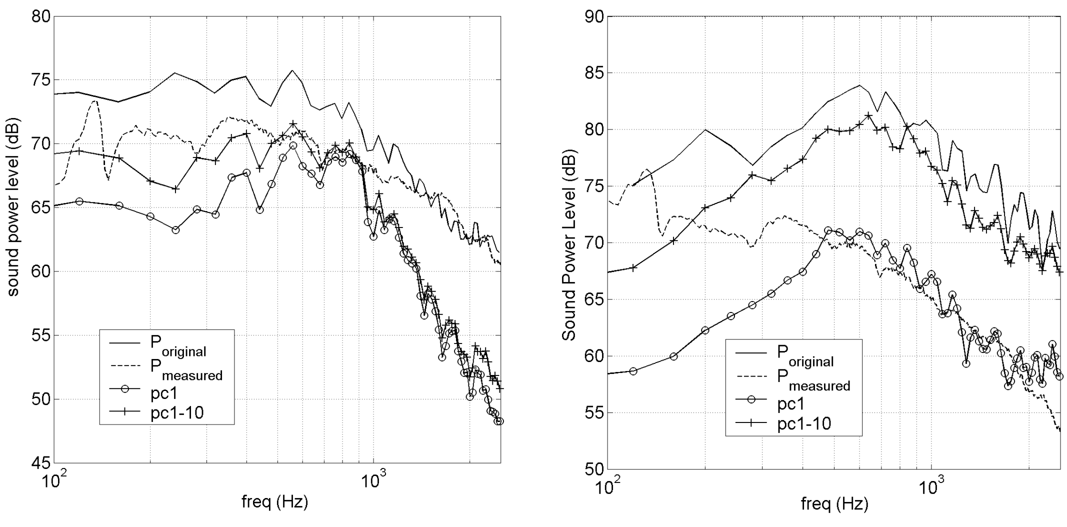

Figure 6: Sound power after application of the PCA to the velocity data

Inclusion of a Uniform Background Flow

The functions that describe the equivalent sources are solutions of the Helmholtz equation in a quiescent medium. To see if the movement of the medium affected the results, a calculation including the presence of a uniform constant background flow was performed. The source functions are then solutions of the convective Helmholtz equation. The assumption that for low Mach numbers the influence of a constant background flow can be neglected was confirmed. Only for Mach numbers above 0.5, the flow has to be considered. The studied flames have a Mach number of Ma=0.1.

Extension of the Computational Domain

The positioning of the control surface plays an important role in the accuracy of the Kirchhoff method. Since the upper cap of the considered cylindrical control surface seemed to contain nonlinear components, a second calculation with a 16% longer LES computational domain (this time the ratio of stoichiometric flame length to computational length was equal to that of the HD flame) was performed. This small increment in dimensions caused a much bigger increment in calculation time. In order to evaluate the location of the Kirchhoff surface, five cylinders with the same radius but different lengths were used as boundary surfaces to compute the sound power. If all the cylinders lie in a homogeneous zone and enclose all acoustical sources, the sound power must be the same regardless with which cylinder it was calculated.

This second calculation provided two interesting results. Firstly, the sound power was not the same for all cylindrical surfaces, but increased with the length of the cylinders. This behaviour suggests that the cylinders do not enclose all the sound sources and probably a longer control surface would be necessary. Secondly, the sound power, calculated with the same cylinder of the first calculation, was different but agreed with the measurements better in form and level. A verification of the second LES calculation was made and it was found that the flow and chemical mean values were practically the same in both cases.

The LES calculations are validated by comparison of the mean values (profiles) of different quantities like velocity, density, temperature, mixture fraction, etc. with measured values. It is possible however that the turbulence that has to be injected into the LES calculation does not change the mean values significantly, but affects strongly the time fluctuations. Another explanation for the difference in the two calculations may lie in the effect of the boundary conditions. It is not really known, how far the boundary conditions distort the field in the inner calculation domain, so usually the values at several cells near the boundary are not considered. Probably, the cylinders that are some cells apart from the borders are less affected by the boundary conditions.

SUMMARY

A series of procedures and calculations have been examined aiming to reduce the errors of a hybrid method used to compute the sound radiation of open turbulent flames, but their application has not been quite successful. The region near the flame axis has been identified as the critical zone. It was seen that a weighting of the data in this region should improve the accuracy of the simulation more than excluding them from calculation. The application of correction terms accounting for the sources that are not enclosed by the Kirchhoff surface is an alternative that should be analyzed. The influence of the boundary conditions (also initial conditions) on the overall results and especially on the acoustic behaviour has to be investigated in more detail.

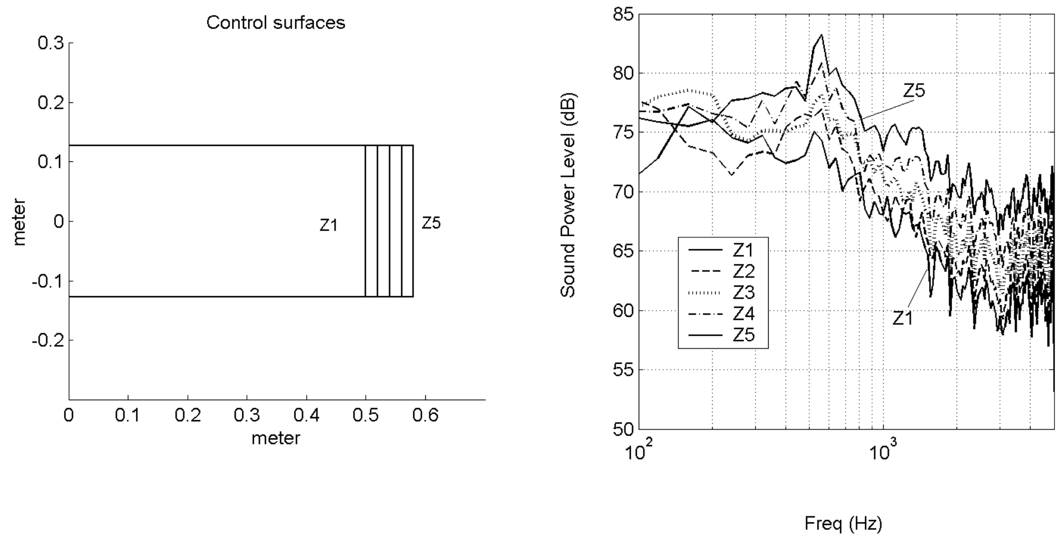

Figure 7: Sound power calculated with different control surfaces

ACKNOWLEDGEMENTS

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