ICSV14
Cairns • Australia
9-12 July, 2007

14th International Congress on Sound & Vibration

TWO- AND THREE-DIMENSIONAL COUPLING IN THE NOISE PREDICTION OF THE EDGE TONE

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Abstract

The reduction of noise in our everyday life requires the understanding of its generation and propagation. Aeroacoustic sources are among the most complicated noise sources and their simulation still presents a challenge.
In this paper recent results of the developed numerical aero-acoustic simulation algorithm are presented. A commercial CFD code was used to carry out high precision unsteady flow simulations in 2D for the well known low Mach number edge tone flow field. Adopting Lighthill's analogy, noise sources were calculated from the flow field and then an in-house acoustic code was used to compute the acoustic field. The acoustic calculations were performed in the frequency domain. Several kinds of coupling of the two codes were tried: 2D flow - 2D acoustics, 2D flow - 3D acoustics and 3D flow - 3D acoustics simulations. Comparisons of the various couplings are presented, as well as comparisons with recent time domain simulations.

1. INTRODUCTION

Much of the noise disturbing our everyday life is generated by flows (e.g. vehicle aerodynamics, air conditioning systems). In order to reduce this noise it is essential to understand the physics of its generation. The main difficulty is the several orders of magnitude difference between the acoustic pressure and the pressure fluctuations in the flow.
The price of the computational resources fell dramatically in the last few decades giving justification to the computational aero-acoustical methods (CAA). CAA methods make the connection between the flow field calculation and the sound propagation calculation. They can be categorized in two main groups: the direct and the hybrid methods [1].

The direct methods calculate the pressure fluctuations of the flow so accurately that they can resolve even acoustic pressures. To achieve this they need a very fine spatial resolution in the whole aero-acoustic domain, and high order numerical schemes. Because of these the computational cost of these methods are enormously high (~ Re^3 because of the flow, and ~

Ma^{-4} because of the acoustics [2]) yielding the direct methods to be a research tool for simple flows with rather small acoustical domains. One solution can be the usage of turbulence models for the flow calculations and since they cannot resolve the acoustical pressure waves any more, hybrid models for the acoustic side.

Hybrid methods use a different approach to resolve the magnitude-difference problem. They separate the acoustic field from the flow field. The flow field is calculated with a suitable computational fluid dynamics (CFD) method (even incompressible solvers) for the near field of the aero-acoustical configuration. Then an acoustical analogy (e.g. Lighthill's [3,4] or Ffowcs Williams and Hawkings's [5]) is used to calculate the acoustical sources from the flow field. Hybrid methods can be discrete integral methods, calculating the acoustic pressure only in a predefined point with an integral formula, or they can be field methods, calculating the sound propagation for a complete domain. For the field methods the acoustical domain can be significantly larger than the fluid domain. A fundamental assumption of these methods is that the sound generated by the flow does not affect the flow itself.

The algorithm used in this paper is the following: commercial software (ANSYS CFX [6]) is used to calculate the flow field. After that an in-house code is used to calculate the sound sources using the Lighthill's analogy. These sound sources are then interpolated onto the acoustic grid with a commercial code (MpCCI [7]), and the sound propagation is calculated using CFS++ [8], an in-house code of the Department of Sensor Technology, University of Erlangen-Nuremberg. CFS++ is able to calculate the sound propagation both in time and frequency domain.

This method is applied to the well known, low Mach number edge-tone flow which is one of the simplest aero-acoustical configurations. This is a two dimensional flow, where a wedge shaped object (traditionally called edge) is placed opposite to a plane free jet. Despite the steady boundary conditions, under certain circumstances the jet starts to oscillate around the wedge. The oscillation of the jet creates a periodic force on the wedge leading to a dipole like sound radiation.

There are several configuration parameters affecting the qualitative appearance of the edge-tone. The width of the jet, the nozzle-wedge distance and the mean exit velocity profile are the main parameters, and there are some secondary parameters also, such as the exit velocity profile of the jet, the shape of the nozzle and the wedge. Depending on the parameters, edge-tone flow structure can occur in qualitatively different shapes, which are called the stages (or hydrodynamic modes). In each stage the frequency is proportional with the mean exit velocity of the jet, and inversely proportional with the nozzle-wedge distance. Detailed information about the edge-tone configuration and flow field can be found in [9].

Two dimensional aero-acoustical simulations were carried out for the different stages of the edge tone calculating the acoustical field both in the time and in the frequency domain. In spite of the two dimensionality of the flow, algorithm to couple 2D flow with 3D acoustic simulation and 3D flow with 3D acoustic simulation has also been developed. This was done in order to be able to compare the results of the 2D coupled simulation with real 3D measurements in the future.

2. 2D-2D COUPLING

2.1 2D CFD Simulations

The CFD simulations were performed in ANSYS CFX which is a commercial CFD code. ANSYS ICEM was used for the geometry and mesh generation. The width of the jet was 1 mm, the nozzle-wedge distance was 10 mm. The fluid domain was large enough (97.5 mm x

151 mm) to avoid unwanted effects of the boundaries and the nozzle was shifted somewhat inside of the domain for the same reason.

Although the flow is two dimensional the geometry and mesh had to be made in three dimensions by extruding the two dimensional mesh in the third direction, because CFX is a three dimensional solver. Since the geometry is very simple a block-structured hexagonal mesh with only one layer in the third direction could be used. A careful parameter study was carried out to determine the optimum mesh for the simulations which contained 36300 hexahedra. No turbulence model was used since the flow is laminar. Second order discretisations were used both in time and space. Details on the mesh, boundary and initial conditions and other CFD parameters can be found in [9].

For this configuration it was found, that the jet starts to oscillate around the wedge in the first stage at Re = 100 (Reynolds number based on width of the orifice, speed of the jet and the kinematical viscosity of the air). At Re = 250 the second stage occurs, and the third stage appears around Re = 1000. Unlike in [10] where the inlet velocity profile is parabolic, the different stages coexist superposed on each other. It was found that if the inlet velocity profile is changed to parabolic, then with increasing Reynolds number the lower stages disappear when a higher stage appears. All the simulations in this paper were performed with uniform exit velocity profile. Figure 1. shows a typical picture of streamlines of the edge tone in Stage II.. From these simulations, qualitatively different ones were picked out to perform aero-acoustical simulations with them.

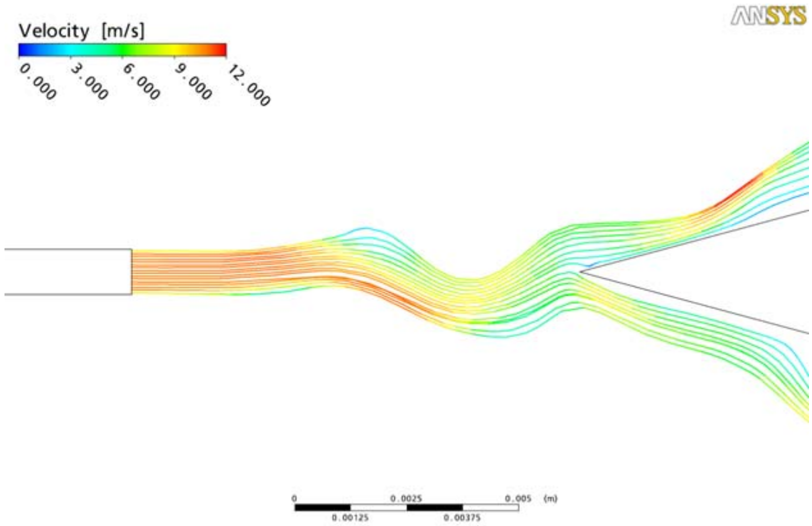

Figure 1. Streamlines of stage II. edge tone flow, Re = 700

2.2 2D Acoustical Simulations

Although most of the acoustical simulations presented in this paper were performed in frequency domain, it has to be mentioned that previously several coupled simulations were carried out in the time domain [11]. From those simulations a quite obvious result was confirmed that the frequency of the flow oscillation (and thus that of the periodic force acting on the wedge) is equal to the frequency of the sound generated by the edge tone configuration. This fact justifies the decision to calculate the acoustic field in the frequency domain only for some specific frequency, and thus shorten the CPU time needed for the simulation. In the time domain simulations, the used first order absorbing boundary conditions exhibit partial reflections, especially at the corners of the boundary. Thus the acoustic domain had to be quite large, so that the reflections from the domain boundaries do not disturb the region of interest during the simulation time. In the frequency domain a so-called perfectly matched layer (PML) technique [12] ensures a perfectly absorbing boundary condition. The acoustic domain can thus be as large as the area of interest and is then extended by the PML damping layer, which is chosen to be about one third of the wavelength.

A very detailed mesh study was made for the 2D-2D coupling in order to determine the optimum mesh for the acoustic simulation at Reynolds number 225. The mesh size used in the far field was found to have only a weak influence, while the discretization of the near field region shows a strong influence on the result. Figure 2a. shows the acoustic pressure amplitude at a distance of 2 m from the wedge at 90°, and Figure 2b. displays the directivity maps for discretizations with 10, 20 and 80 finite elements per wavelength. Just a deviation of the blue line (10 finite elements per wavelength) from the green and red ones can be observed, so that we have chosen 20 finite elements per wavelength for all subsequent simulations.

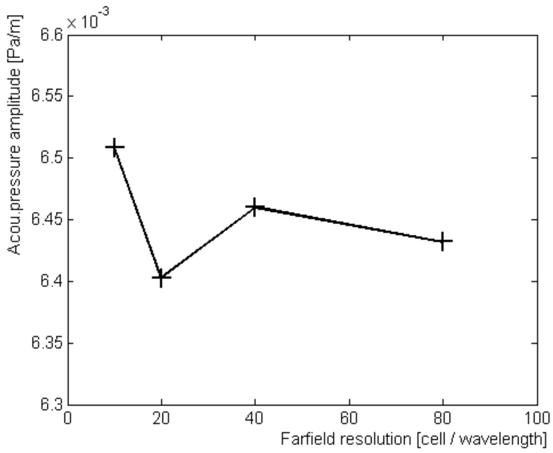

Figure 2a. Result dependence on the far field mesh resolution, acoustic pressure amplitudes at (r,φ) = (2 m, 90°)

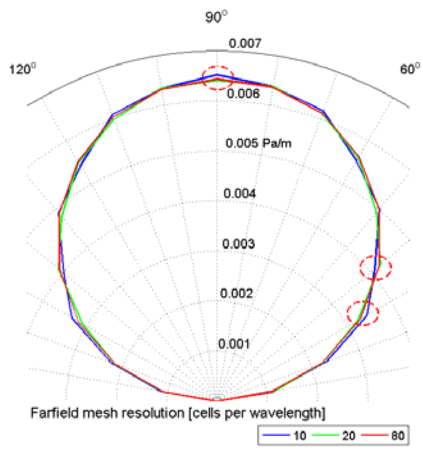

Figure 2b. Result dependence on the far field mesh resolution, directivity maps between 0 < α < 180°

The resolution of the acoustic mesh in the coupling region was found to be rather important. If the mesh was not able to capture the acoustic sources at the tip of the wedge the amplitude of the acoustic pressure dropped dramatically. It was because conservative interpolation added neighbouring “positive” and “negative” sources into “zero” source what jointly decreased the sound generation.

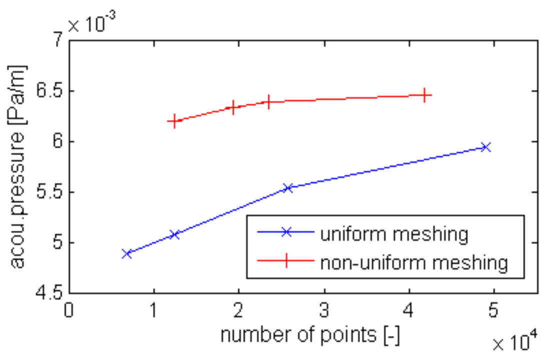

Figure 3. Result dependence on the coupling region mesh resolution

The computational time for the conservative interpolation of the acoustic sources using MpCCI increased linearly with the number of coupled nodes till a certain limit (around 50000 nodes), but beyond this limit the computational time increased dramatically, making the calculations almost impossible to carry out. In the coupling region first block-uniform meshing was used. After reaching the mentioned limit, the mesh study showed that the mesh in the coupling region is still not fine enough, so that a new meshing strategy was needed. The mesh was only refined near the tip of the wedge. With this new non-uniform mesh, the desired mesh convergence was reached with 23565 nodes and 7700 elements in the coupling region (See figure 3.). It also has to be mentioned that, although the quantitative result depend very much on the mesh resolution, qualitatively they all showed the same dipole characteristic. In the coupling region the same mesh was used for all simulations, only the far field region was changed depending on the minimum wavelength. The total number of elements in the acoustic mesh was between 55000 and 100000.

The time step for the acoustic simulations had to be the same as the time interval of the transient results of the CFD simulations, which were always somewhere between 20 and 40 steps per period. Coupled simulations were carried out for the three stages. Re = 100, 150, 225 for the 1st stage edge-tone oscillation, Re = 350, 500, 700 for the 2nd stage oscillation and Re = 1000 for the 3rd stage.

2.3 Results

The results of the 2D acoustical simulations are given in pressure per unit length [Pa/m]. This makes the results difficult to interpret, and that is why the results are given on a linear scale. However, what is important is the relative magnitude, not the absolute scale. For data analysis monitoring points on concentric circles around the tip of the wedge were defined at every 5°. The radii of these circles depend on the size of the acoustic domain. On each of these circles directivity maps have been computed. Perfect dipole directivity was found for all Reynolds numbers calculated just as for the time-domain simulations [11]. Figure 4. shows a usual directivity map of the edge tone field at Re = 150.

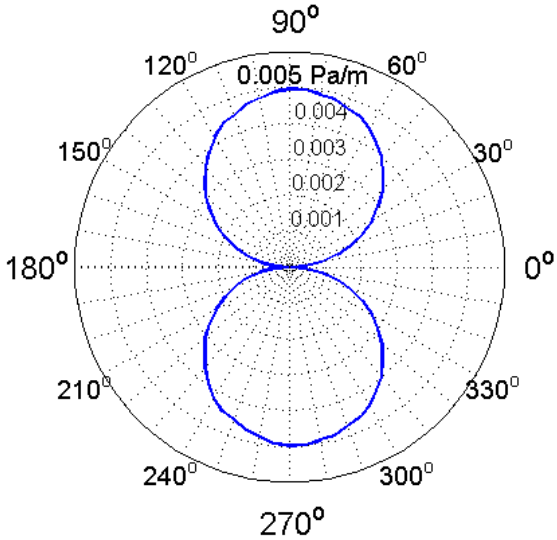

Figure 4. Directivity map of the sound propagation at 0.5 m from the tip of the wedge, Re = 150

Harmonic acoustical simulations were carried out only for the dominant frequencies, but for a few typical cases (once for each stage) harmonic acoustic simulations were carried out for the full spectrum. Figure 5. shows the case of Reynolds number 1000, where the 1st the 2nd and the 3rd stages are all present. The upper graph shows the spectrum of the force per unit length acting on the wedge from the CFD simulations and the lower shows the directivity of the sound generated by the flow at a distance of 0.25 m from the tip of the wedge. All three stages can clearly be observed.

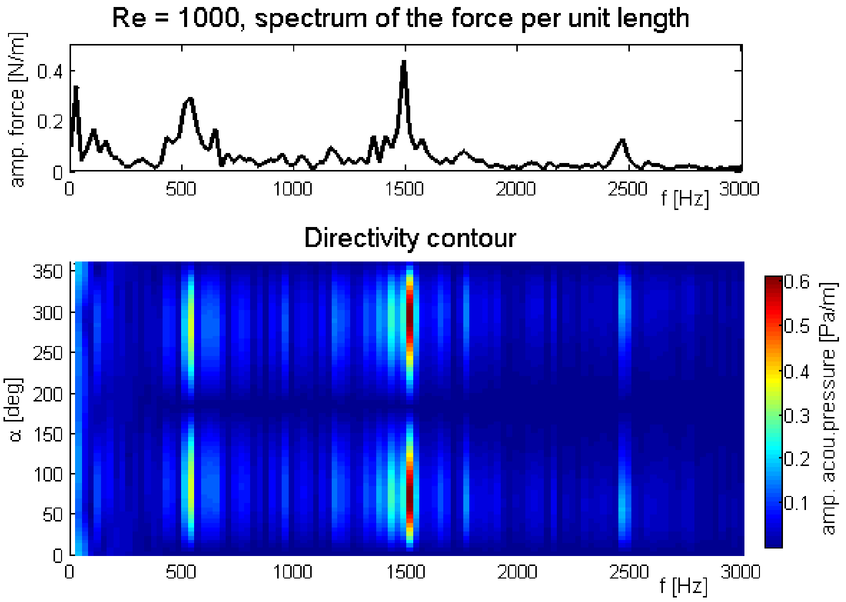

Figure 5. Re = 1000, Stage I., II. and III. oscillation; upper: Spectrum of the force acting on the wedge (CFD result); lower: directivity of the acoustic pressure (CAA result);

3. 2D-3D AND 3D-3D COUPLING

In reality the flow is always three-dimensional, but some flows can be approximated very well in 2D saving computational resources. This is the case for the edge-tone flow. As mentioned before, direct comparison between the 2D acoustical simulations and the measurements is difficult. Hence an intermediate step is taken on the way towards the full 3D-3D coupling. The results of the 2D simulation are extruded prismatically and this forms a 3D source region for a 3D acoustic field computation. Various extrusion lengths have been compared.

3.1 3D CFD Simulations

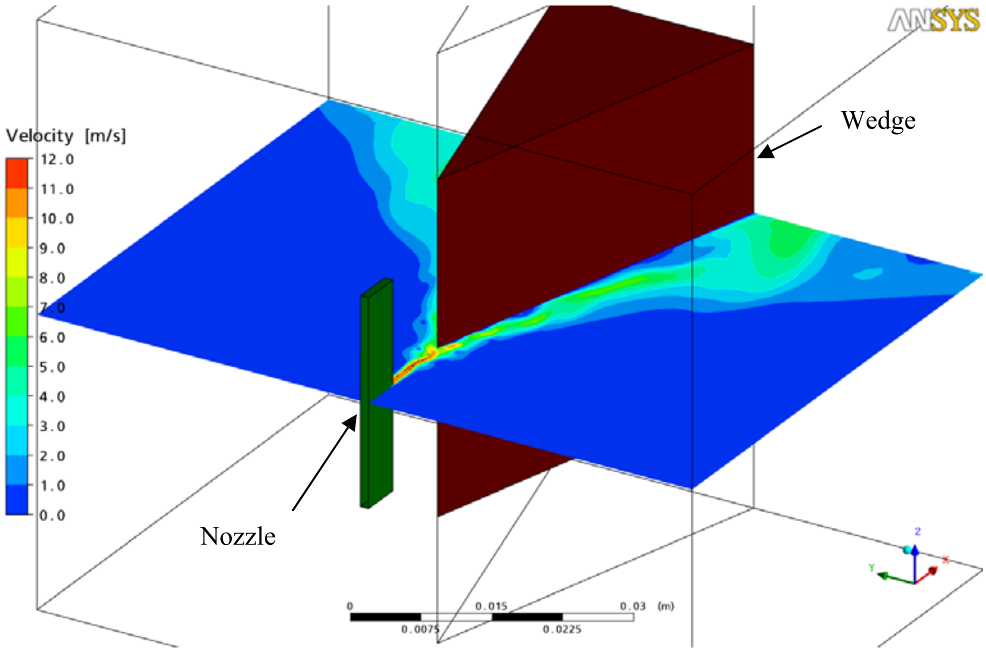

Figure 5. Re = 700, Stage II. Oscillation, Velocity contours in the central plane

For the full 3D-3D coupling 3D CFD simulations were carried out for several Reynolds numbers. In this case the geometry was somewhat more complex. The nozzle and the wedge had different heights, 25 mm and 40 mm respectively. This was done to allow the jet to spread in the z direction and to have the full effect on the wedge. The width of the jet and the nozzle wedge distance was the same as in the 2D simulations, but the size of the domain (60 mm x 81 mm x 70 mm) became somewhat smaller compared to the 2D case, in order to reduce the number of elements. Again block structured hexahedral mesh was used, in this case with 584438 elements. Detailed discussion of the 3D CFD simulation can be found in a forthcoming publication. Figure 6. shows the geometrical configuration and the velocity contour in the central plane for a Stage II. oscillation at Re = 700. It was found that in the middle x-y plane there are negligible disturbances in the z direction, so the assumption that the flow is two dimensional is correct. Comparing the oscillating frequency at Re = 500 and 700 for the 2D and 3D simulations the following can be stated: the frequency of the first stage was the same within the spectral resolution (Δf) for the 2D and the 3D simulations, and the frequency of the second stage became about 10% lower for the 3D case (Table 1.).

Table 1. Oscillation frequency comparison for 2D and 3D simulations at Re = 500 and 700

Re [-]	Δf [Hz]	f [Hz] - Stage I. 2D	f [Hz] - Stage I. 3D	f [Hz] - Stage II. 2D	f [Hz] - Stage II. 3D
500	15	258	268	751	686
700	17	365	374	1115	988

3.2 Results

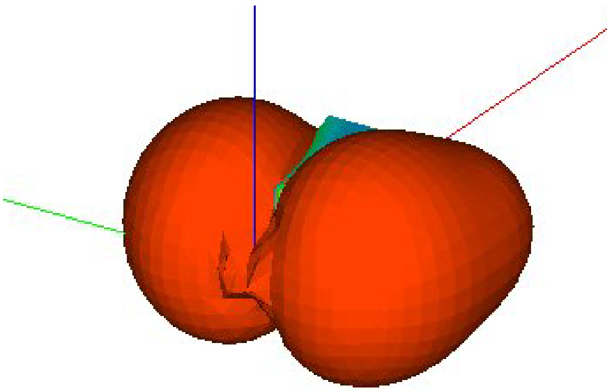

Figure 7. 2D-3D coupling for Re = 225: Acoustic pressure isosurface, p = 0.0015 Pa

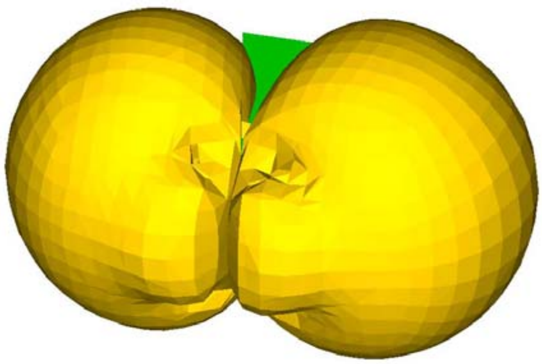

Figure 8. 3D-3D coupling for Re = 500: Acoustic pressure isosurface, p = 0.005 Pa

2D-3D coupling have been carried out for two different extrusion heights, and it was confirmed, that the acoustic pressure in an arbitrary distance is proportional with the extrusion height. The computational resource requirement of the 3D calculations is much more than of the 2D simulations. From the 2D mesh study it was seen, that the mesh resolution of the coupling region does not affect qualitatively the results. Because of this, at first a coarse mesh (with around 85000 finite elements in the whole acoustic domain) was used to obtain the qualitative results for validating the algorithm. Further simulations will be carried out with much finer acoustic mesh (with around 400000 elements) to obtain quantitative results to be able to finish the steps of the validation process. Figure 7. shows the pressure isosurface for p = 0.0015 Pa from the result of 2D-3D coupling when extruding for 9 mm. The dipole characteristics can clearly be observed, however it is evident, that the mesh is not fine enough.

Figure 8. shows the pressure iso-surface for p = 0.005 Pa from the result of the full 3D-3D coupling. Again it can be stated, that the characteristics of the sound is a dipole, but the mesh should be refined. These qualitative results show that the algorithm for the coupling between the 2D flow and the 3D acoustic simulation and also for the full 3D-3D coupling work correctly.

4. CONCLUSION AND OUTLOOK

The hybrid algorithm using commercial software ANSYS CFX and MpCCI as well as the in-house code CFS++ has been successfully tested on the edge-tone. Further coupling between 2D CFD and 3D acoustical simulations and 3D CFD and 3D acoustical simulations are planned to be carried out in order to finish the validation process. After validation, the algorithm could be used to calculate aero-acoustical noise generation of more complex geometries.

ACKNOWLEDGEMENTS

The work of the Hungarian authors has been supported by the Hungarian National Fund for Science and Research under contract Nr. OTKA T 46304. The work of the German authors has been supported by BFS (Bayerische Forschungsstiftung). The cooperation of the two research groups has been supported by the DAAD-MÖB joint funding.

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