

Computational Aeroacoustics of a Backward Facing Step

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Introduction

Since the beginning of Computational AeroAcoustics (CAA), several numerical methodologies have been proposed, each trying to overcome the challenges that the specific problems under investigation pose for an effective and accurate computation of the radiated sound. The main difficulties that have to be considered for the simulation of flow sound problems include energy and length scale disparity, preservation of the multipole character of the acoustic sources and dispersion and dissipation occurring in numerical schemes. Due to the large disparities of length and energy scales between flow and acoustic quantities, the hybrid methodologies still remain the most commonly used approaches for aeroacoustic computations. In order to provide a basis for a real benchmark problem, we have performed highly resolved DNS (Direct Numerical Simulation) computations of a backward facing step with well defined boundary conditions for the flow. We will provide detailed analysis of the flow field as well as occurring acoustic field based on a Finite Element (FE) scheme solving Lighthill's acoustic analogy.

Setup

We consider the internal backward-facing step of a Newtonian fluid assuming constant density and viscosity [1]. The flow is in the transitional regime and thus most reliably predicted based on a DNS (Direct Numerical Simulation). The geometry of the flow configuration is sketched in Fig. 1. Essentially, it consists of a plane

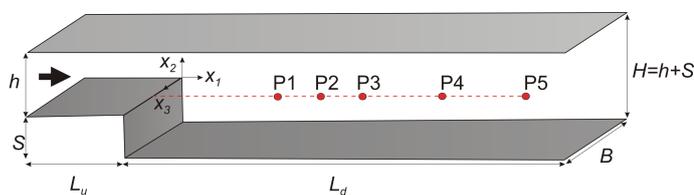


Figure 1: Sketch of the flow configuration and the definition of length scales (P_i defines observation points).

channel with a sudden stepwise expansion of the cross-section. A block-profile with 8.5 m/s velocity for the inflow boundary condition has been used, resulting in a Reynolds number of 6000. The height of the channel in front of the step is denoted by h and the depth of the channel by $B = \pi h$. Downstream the step, the channel height is given by $H = h + S$, where S defines the step height, which is set to $S = 0.9423h$. Consequently, an expansion ratio $r = H/h = 1 + S/h = 1.9423$ results. Up-

stream and downstream of the step, the computational domain has an extension of $L_u = 5h$ and $L_d = 32h$, respectively. Since the origin of the coordinate system is located at the edge of the step (see Fig. 1), the inlet section is at $x_1 = -L_u$, and the outlet section at $x_1 = L_d$. For the acoustic computation, we have rescaled the geometry to fit to air as medium.

A suitable computational grid had to be chosen which sufficiently resolves the critical regions of the domain, namely the boundary layers and the evolving free shear layers. An important point is that too large grid spacing in the main flow direction may cause numerical oscillations. To eliminate such grid-induced oscillations, two grids with different spacings in the main flow direction are used. The grids contain about 4.5 million control volumes (coarse grid) and 8.7 million control volumes (fine grid). Both grids are orthogonal and offer a refinement of the grid cells next to the walls and at the step.

Computational Fluid Dynamics

For the present investigation, the general-purpose computational fluid dynamics (CFD) package FASTEST-3D developed at LSTM Erlangen is applied [4]. With this program both laminar and turbulent steady and unsteady flows including heat and mass transfer can be simulated numerically. The three-dimensional incompressible Navier-Stokes equations expressing the conservation of mass, momentum and energy are solved based on a fully conservative finite-volume discretization on non-orthogonal curvilinear grids with a collocated arrangement of the variables. In order to resolve complex geometries, block-structured grids are used.

Computational Aeroacoustics

The aeroacoustic approach is based on the solution of the inhomogeneous wave equation as obtained by applying Lighthill's acoustic analogy [2]. In this type of approach, acoustic sources are computed from the flow velocity field. The inhomogeneous wave equation is solved employing the Finite-Element (FE) method to obtain the generated acoustic field. For the accurate evaluation of the acoustic source term we apply a FE-library on the fluid computational side (using the fine fluid grid resolution). The nodal acoustic loads from this computation are then transferred to the acoustic solver. The interpolation of the acoustic sources from the fluid to the acoustic grid is performed in a conservative way. The developed

scheme allows a direct coupling in time and frequency domain. It provides the acoustic sound field not only in the far field but also in the region of the flow. Furthermore, we can investigate the acoustic source terms in the flow region and the scheme is well suited for complex geometries and fluid structure interaction. To account for free radiation conditions at the inlet and outlet, we apply a PML (Perfect Matched Layer) technique. The newly unsplit PML formulations is based on an inverse Fourier transformation. To avoid convolution terms in the time domain formulation, we used additional auxiliary variables [3].

Results

Figure 2 depicts velocity profiles at different positions x_1/S . Over a long distance behind the step, the main flow moves between the upper channel wall and the primary recirculation region. The flow is confined by the wall and the separation bubble in such a way that the profile changes only very little down to $x_1/S = 12.5$. Aeroacoustic source terms occur neither upstream nor di-

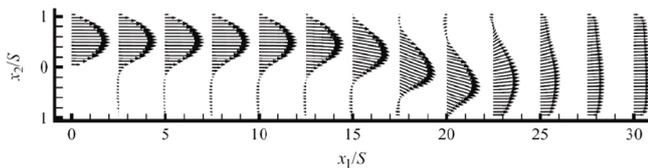


Figure 2: Sketch of the flow configuration and the definition of length scales

rectly downstream of the step. Sources reach a significant magnitude only at a distance of $x_1/S \approx 8$ downstream of the backward facing step (see Fig. 3). In the range

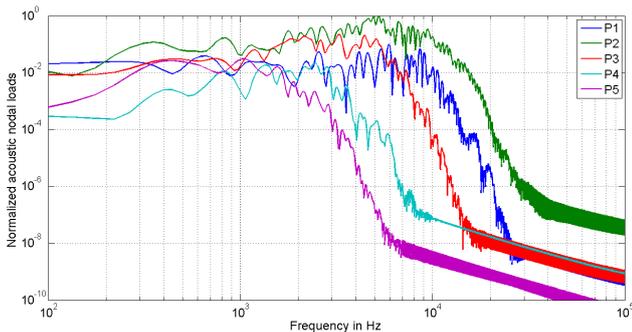


Figure 3: Frequency spectra of the acoustic nodal loads at different positions (see Fig. 1)

of $x_1/S = [8, 15]$ we observe the acoustically most active region. Not only the local sound pressure reaches its maximum there, but we also find sound waves originating there, that travel to the far field. Further downstream ($x_1/S > 15$) we also see flow induced sound pressure fluctuations, but these do not radiate waves to the far field. In Fig. 4 we display for a characteristic time step the computed acoustic sound field on the mid-plane. Since the acoustic computations have been performed in 2D (on the mid-plane), we scale the results with B . Both

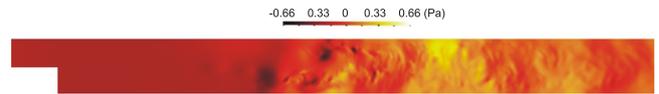


Figure 4: Acoustic sound field at a characteristic time step

flow and acoustic field computations use a time step of $\Delta t = 2.9 \mu\text{s}$. Thus the maximum frequency that can still be resolved sufficiently is approx. 20 kHz. Figure 5 shows two spectra of sound pressure level, recorded at inflow and outflow positions at a half of the channel's height. We observe an overall broadband spectrum decaying with -20 dB per decade up to a frequency of approx. 6 kHz. Above that frequency the decay rate amounts to -60 dB per decade.

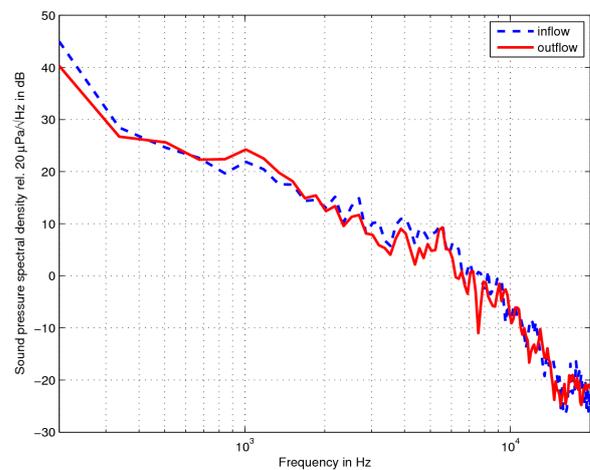


Figure 5: Sound spectra at in- and outflow position

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