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# Fluid-structure-acoustic coupling for a flat plate

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ABSTRACT

The present work deals with the aeroacoustic sound radiated by a forward–backward facing step in combination with a flexible wall behind the step. A numerical flow computation with coupled aeroacoustic and vibroacoustic simulation was carried out. The structural deformations of the oscillating plate like structure in the wake of the forward–backward facing step were considered to be small and therefore not affecting the flow field. The presented approach enables a separate consideration for the aeroacoustic as well as the structural borne noise. The influence of the interactions of the acoustic medium with the flexible structure on the vibroacoustic sound radiation is investigated. One-sided and two-sided coupling approaches for the vibroacoustic analysis are introduced. The two-sided vibroacoustic computation allows for considering the damping influence of the ambient fluid on the flexible plate vibration and therefore on the sound radiation. Additional to the simulations, aeroacoustic measurements in an acoustic wind tunnel were performed for validation purposes.



## 1. Introduction

Flow induced noise is very important regarding many technical applications. As an example, the aeroacoustic as well as the vibroacoustic noise induced by the turbulent flow field around cars or planes has an unfavourable influence on the comfort for passengers and therefore, on the quality of the vehicle. In order to predict the acoustic behaviour of technical products during the design process, the usage of numerical simulation software is a valuable measure to prevent unfavourable acoustic effects. Aeroacoustic noise is induced by turbulent pressure fluctuations e.g in turbulent shear layers or recirculation areas. Vibroacoustic noise is generated by the interaction of turbulent wall bounded flows with flexible surfaces. The turbulent pressure and wall shear stress fluctuations excite the flexible structure to vibrate in their characteristic eigenmodes. According to the eigenfrequencies, sound is radiated from the flexible structures surface. Previous studies dealing with fluid-structure-acoustic interaction are shown in Schäfer et al. (2010). A large eddy simulation (LES) of a forward–backward facing step flow in the context of fluid-structure-acoustic interaction was conducted. The feasibility of a strong fluid-structure coupling producing aeroacoustic and vibroacoustic noise is demonstrated. A comparison to experimental data shows that noise radiation is overpredicted. The influence of the backcoupling of the acoustic medium on the flexible surface and therefore on the vibroacoustic sound radiation is not taken into account. Investigations on a comparable setup with application for vehicle interior noise are published in Vergne et al. (2002-03). In this study, a turbulent flow interacts with the flexible cover of a cavity. This work is focused on the noise radiation into the cavity. The influence of the structural deformations on the flow field, as well as the interaction of the acoustic field with the flexible structure are considered. However, no investigations of the influence of this interaction between structure and acoustic medium are shown. Besides the above mentioned numerical approaches, were physical fields are computed and coupled to each other in time domain, much effort has been put into the development of analytical approaches for modelling the interactions of turbulent boundary layers with elastic surfaces and the associated vibroacoustic sound generation. Fundamental information on the modelling of flow-induced vibroacoustic sound radiation can be found in Blake (1986). Current work on vibroacoustics excited by turbulent boundary layers is documented in Ichou et al. (2013).

The goal of the current work is to compute the aeroacoustic, as well as the vibroaocustic sound radiation by the combination of a turbulent flow field behind a forward–backward facing step and a flexible plate with turbulent fluid load. In computing the physical domains by numerically solving the physical basic equations (fluid dynamics, structural dynamics and linear acoustics), the presented approach overcomes the disadvantages of the analytical approaches regarding the analysis of complex geometries. By neglecting the modification of the flow due to structural displacements on condition that the displacements are small compared to turbulent flow

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**Nomenclature**

| | | |
|---|---|---|
| $\Delta$ | [m] | spanwise extension of flow geometry |
| $\delta$ | [m] | boundary layer thickness |
| $\hat{q}$ | [kg/s$^2$] | spanwise averaged acoustic source term |
| $\mu$ | [Ns/m$^2$] | dynamic viscosity |
| $\rho'$ | [kg/m$^3$] | acoustic density |
| $\rho_0$ | [kg/m$^3$] | fluid density |
| $\sigma_n$ | [N/m$^2$] | normal stresses due to acoustic pressure |
| $\tau_{ij}$ | [N/m$^2$] | viscous stress tensor |
| $\tilde{q}$ | [kg/ms$^2$] | 3D acoustic source term |
| $\xi_i$ | [m] | mechanical displacement |
| $c_0$ | [m/s] | speed of sound |
| $C_p$ | [-] | static pressure coefficient |
| $D$ | [m] | dimension of forward–backward facing step |
| $E$ | [N/m$^2$] | modulus of elasticity |
| $f_{cut-off}$ | [Hz] | cut-off frequency of the numerical grid |
| $k_{cut-off}$ | [Hz] | cut-off wavenumber of the numerical grid |
| $L$ | [m] | width of windtunnel nozzle |
| $n_i$ | [-] | vector in wall-normal direction |
| $p$ | [Pa] | static pressure |
| $p'$ | [Pa] | acoustic pressure |
| $R$ | [m] | distance between step and microphone point |
| $t$ | [s] | time |
| $T_{ij}$ | [kg/ms$^2$] | Lighthill stress tensor |
| $U_c$ | [m/s] | convective velocity |
| $u_i$ | [m/s] | fluid velocity |
| $v_i'$ | [m/s] | acoustic particle velocity |
| $x_i$ | [m] | cartesian coordinates |

structures or viscous sublayer thickness, the high computational costs of a strong fluid-structure coupling can be saved and the sufficient resolution of the turbulent flow field can be focused on. The coupling between flow field and acoustic field is realized by calculating aeroacoustic source terms from the velocity field at simulation time. In a post-processing step, the acoustic field is computed on the basis of the acoustic source terms. The vibroacoustic sound radiation is based on the surface velocity of the flexible structure. To show the influence of the interaction between structure and acoustic medium, one-sided and two-sided coupled vibroacoustic simulations are carried out and compared to each other. In case of a one-sided coupling, the computation of the transient mechanic deformation of the flexible plate and the vibroacoustic field are performed subsequently. In the two-sided coupled case, a coupled system of acoustic and mechanic equations is solved to allow for the interactions between the two systems. The two-sided vibroacoustic coupling is capable of considering the damping effects due to the ambient acoustic medium which is shown by comparison of velocity and sound pressure level spectra. Hence, in the current approach, the fluid-structure coupling is shifted into the vibroacoustic analysis. Therefore, the computational amount of a strong two-sided fluid structure coupling during the LES can be saved. Besides the numerical investigations, microphone measurements of the sound radiated by the forward–backward facing step were carried out in a low-noise wind tunnel. A comparison between numerical and experimental results will be given and discussed.

## 2. Numerical setup

### 2.1. Fluid mechanical setup

The three-dimensional flow field generated by the forward–backward facing step was computed by means of LES. The flow computation was carried out using the software FASTEST-3D (Durst and Schäfer, 1996). This code solves the transient, incompressible Navier-Stokes equations on structured grids:

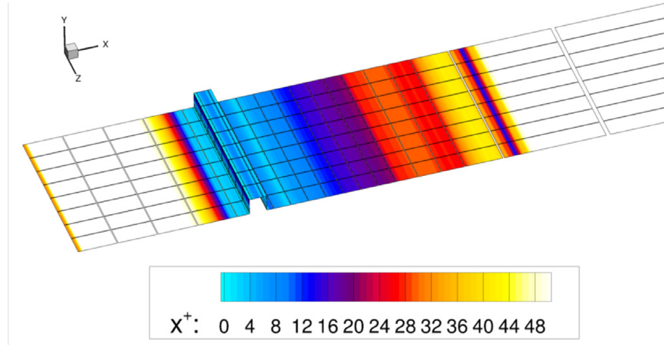


**Fig. 1.** Time averaged $x^+$ - distribution.

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{1}$$

$$\rho_0\left(\frac{\partial u_j}{\partial t} + \frac{\partial (u_i u_j)}{\partial x_i}\right) = -\frac{\partial p}{\partial x_j} - \frac{\partial \tau_{ij}}{\partial x_i} \tag{2}$$

with

$$\tau_{ij} = \mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) \tag{3}$$

The equations were discretised using the finite volume method (FVM). The influence of the unresolved flow scales was modelled with a Smagorinsky subgrid scale model. The Smagorinsky constant was set to 0.1. Time discretisation was performed with a 4th-order Runge–Kutta Scheme. For the calculation of the convective fluxes, a central difference scheme was used. The velocity-pressure coupling was conducted with the predictor–corrector algorithm.

The forward–backward facing step was a quadratic obstacle attached to a flat plate with edge length of $D = 0.02$ m. The spanwise extend of the geometry was chosen to be 10$D$. In spanwise direction, periodic boundary conditions were applied. The height of the computational domain was 20$D$. At the outflow boundary a convective boundary condition was used. At the inflow boundary, a laminar boundary layer profile was set. This boundary layer profile origins from LDA-measurements during previous performed experimental investigations (Schäfer et al., 2010) of the current geometry. The velocity at the boundary layer edge was 20 m/s. This yields a Reynolds number of 26.000, based on inflow velocity and step height $D$. The grid size was chosen to obtain a wall normal resolution of $y^+ < 1$ (Fig. 2). The streamwise and spanwise resolution in the wake region of the step was $x^+ < 40$ (Fig. 1) and $z^+ < 20$ (Fig. 3), respectively. The overall number of hexahedron control volumes was 91.6 Millions. To get a CFL-number below 1, the time step size was chosen to be $4 \times 10^{-7}$ s.

For the usage of periodic boundary conditions, the spanwise domain size has to be large enough to cover the biggest turbulent structures (Frölich et al., 2005) and the spanwise correlations have to drop to zero. Thereby, a self influencing of the turbulent structures in spanwise direction can be prevented. The correlations of the velocity fluctuations were computed along several lines upstream and downstream of the obstacle (Fig. 4). In Figs. 5 and 6, the streamwise velocity correlations $R_{uu}$ are exemplary illustrated. For the lines upstream of the obstacle (Fig. 6), a rapid decay of the streamwise velocity correlations becomes obvious. The streamwise correlations $R_{uu}$ at the spanwise lines downstream of the obstacle show increased values compared to the positions upstream.