Impact of Geometric Variations on the Flow and Generated Sound

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Introduction

A large amount of the noise in our daily life is caused by turbulent flows (e.g. airplanes, cars, air conditioning systems, etc.). In order to reduce noise levels of new products, modern product development cycles include the prediction of flow induced noise by means of numerical computations. Since the product optimization with respect to noise is subject to restrictions posed by functional requirements, it is difficult to find geometries, which reduce the product's noise emission. Therefore, we conducted numerical computations to analyze the effect of simple geometry variations on the noise generated by a turbulent flow around a cylinder stump. Such structures occur in a lot of applications (e.g. housings of fans, side-mirrors of cars), but still are simple enough to fully understand the underlying physics of noise generation. The obtained results were validated by experiments and allowed us to deduce design rules, that can be taken into account at an early stage in product development.

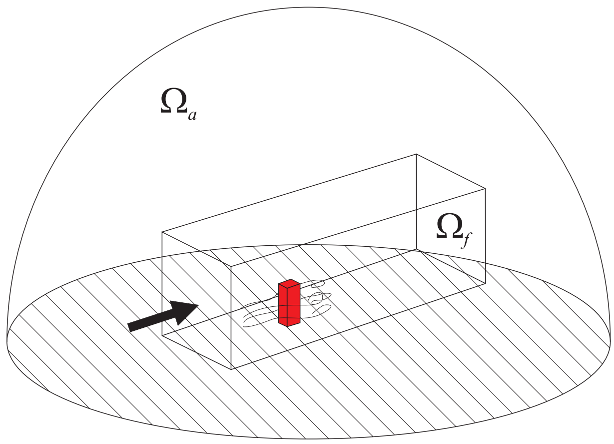


Figure 1: Schematic overview of the simulation setup divided into fluid domain Ω_f and acoustic domain Ω_a

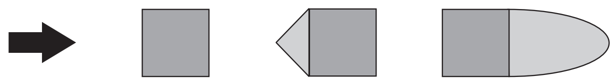


Figure 2: Standard profile and the two geometric variations

Basic Setup and Geometry Variations

Our basic setup is a cylinder with square profile mounted on a flat plate. The cylinder's profile measures 20 mm × 20 mm, the height is 120 mm, which leads to an aspect ratio of six. Therefore, the height of the cylinder cannot be assumed to be large compared to edge length. This results in a truly three-dimensional flow field, since the flow over the roof edge of the cylinder may not be neglected. The cylinder is placed in a cross flow with velocity $u_0 = 10\frac{\text{m}}{\text{s}}$, which result in a Reynolds number of $Re \approx 13300$. The simulation domain Ω_f of the fluid dynamics computation (see figure 1) can be kept quite small in order to reduce the computational effort. The acoustic domain Ω_a, which encompasses the flow region, is considerably larger, because we are interested in the free field sound propagation.

As geometric variations we use a wedge (width 10 mm) and a half-ellipse (width 30 mm) that can be mounted to the cylinder in upstream or downstream direction (see figure 2). In the following we investigate the effect of the different geometries on the flow field and consequently on the sound generated by the turbulent flow.

Numerical Approach

The incompressible unsteady flow field is computed in the domain depicted in figure 3, with an inflow boundary on the left hand side and a convective exit boundary on the right hand side. The cylinder and the bottom plate were modeled as no-slip boundaries, and on the remaining boundaries a symmetry condition is applied.

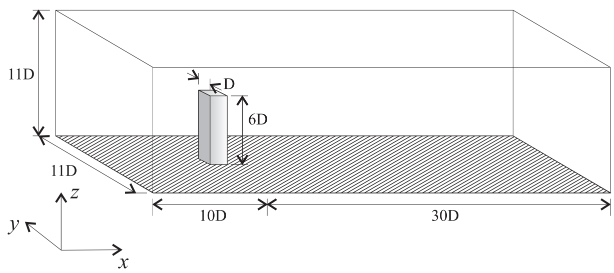


Figure 3: Computational domain of the fluid flow simulation; D = 20 mm

As flow solvers two different CFD codes were employed, which provide the data needed to compute the acoustic sources. One solver is `FASTEST-3D`, developed at the Chair of Fluid Mechanics based on LES (Large Eddy Simulation) using the Smagorinsky model. The other fluid solver was the commercial CFD code `ANSYS-CFX`, which implements a turbulence modeling approach based on SAS (Scale Adaptive Simulation). The SAS approach allows to use coarser grids than those used in LES computations.

For the acoustic wave propagation a finite element discretization of Lighthill's inhomogeneous wave equation [1]

$$\frac{1}{c^2}\frac{\partial^2 p'}{\partial t^2} - \frac{\partial^2 p'}{\partial x_i^2} = \frac{\partial^2 L_{ij}}{\partial x_i \partial x_j} \qquad (1)$$

is solved for the acoustic pressure p' (c: speed of sound in air). The Lighthill tensor $[L]$, obtained by an incompressible flow computation, is approximated by $L_{ij} \approx \rho_0 u_i u_j$, where u_i and u_j are the i-th and j-th component of the velocity vector, respectively. This method was implemented in the in-house FEM code `CFS++` developed at the Chair of Sensor Technology. For a detailed discussion of the method we refer to [2].

Results

It is well understood, that a turbulent flow around a cylinder generates a significant aeolian tone. The frequency of this tone corresponds to the frequency of vortex shedding in the turbulent boundary layer. Figure 4 shows that the typical directivity pattern corresponds to a dipole source. This dipole characteristics is not affected by the additional bodies. Summarizing our results in table 1, the geometric variations have an impact on two values:

1. the frequency of the aeolian tone,
2. the amplitude of the radiated sound.

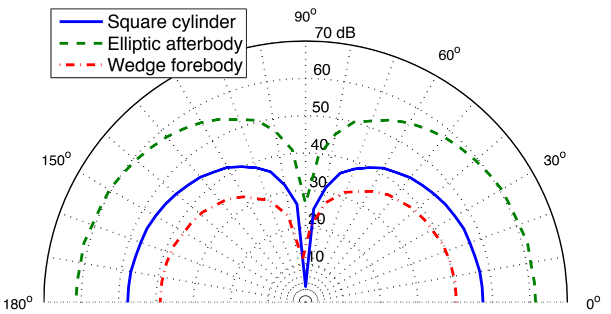
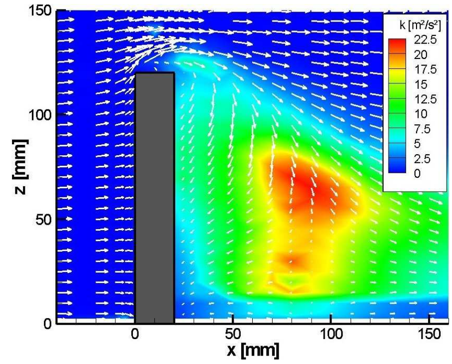


Figure 4: Directivity patterns of SPL in crossflow (yz-plane) for different geometries

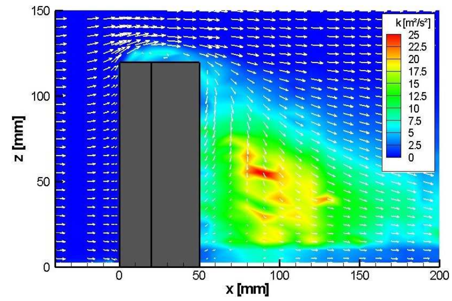
Table 1: Comparison of SPL and frequency f of the aeolian tone, and measured coefficient of drag c_D for different geometries

Profile	Wedge	Square	Elliptic
SPL sim.	40 dB	47 dB	61 dB
SPL meas.	34 dB	44 dB	60 dB
f sim.	63 Hz	55 Hz	39 Hz
f meas.	58 Hz	53 Hz	36 Hz
c_D	0.4	1.9	0.9

We find that a forebody leads to a reduction of noise, while an afterbody causes an unexpected increase of generated noise. In any case, the additional body reduces the pressure-based drag at the cylinder and, thereby, also the turbulent kinetic energy in the wake of the cylinder should decrease. Although this is true (see figure 5), the sound pressure level is increased by adding an afterbody to the cylinder. The reason for this phenomenon is, that the boundary layer reattaches at the roof of the enlarged cylinder. On the other hand in case of an unmodified cylinder, the roof vortex interacts destructively with the Karman vortex street, thus disturbing the generation of the aeolian tone.



(a) Unmodified square cylinder



(b) Square cylinder with elliptic afterbody

Figure 5: Turbulent kinetic energy in xz-plane ($y = 0$)

Conclusions

Simulations of the flow-induced noise around several different cylinder geometries were conducted and validated by experiments. Results have shown that a reduction in turbulent kinetic energy does not necessarily lead to a reduction of noise. However, the interaction of roof vortices with the Karman vortex street is essential to a decrease in loudness. As a conclusion one can derive the following design rules for cylinder-like structures:

- A cylinder's roof should be kept small in order to avoid reattachment of the boundary layer at the roof.
- Eliminating leading edges should be preferred to eliminating trailing edges.

References

[1] Lighthill, M. J.: On sound generated aerodynamically: I. General theory. Proc. Royal Society 211 (1952), 564–587

[2] Escobar, M.: Finite Element Simulation of Flow-Induced Noise using Lighthill's Acoustic Analogy. Dissertation, Universität Erlangen-Nürnberg, 2007