Dataset CYLinCF-01 creation pipeline: Circular cylinder in a cross flow

Mach Number 0.03 and Reynolds Number 200

Stefan Schoder, Andreas Wurzinger

TU Graz, Aeroakustik und Vibroakustik, IGTE, Inffeldgasse 18, A-8010 Graz, AT, Email: stefan.schoder@tugraz.at

Abstract

This article presents an aeroacoustic workflow (pipeline) to generate a flow and acoustic dataset for studying flow-induced sound in the context of a cylinder in cross flow. The numerical simulations are performed using OpenFOAM for the flow and openCFS for acoustics using the perturbed convective wave equation (PCWE). The workflow involves several steps, including the flow simulation, the acoustic simulation, and post-processing of the results. The simulation workflow is presented in all its details. The analysis focuses on the acoustic characteristics of the flow, including sound pressure levels, frequency spectra, and directivity patterns. The results show good agreement with the literature. The article concludes by discussing applications of the workflow for different cases that involve flow-induced sound generation.

Introduction

Flow-induced noise is an omnipresent problem in a wide range of engineering applications, from aircraft and automotive design to environmental noise control. The noise generated by the flow around an object can lead to acoustic pollution. One of the most common geometries for studying flow-induced noise is a cylinder in cross flow [10]. This simple configuration is relevant for many applications, such as heat exchangers, cooling towers, and offshore structures. The flow around the cylinder generates a wake, which interacts with the cylinder and leads to the emission of acoustic waves.

To support the development of numerical simulations techniques of flow-induced noise predictions, this benchmark dataset generation pipeline is published to the community. Since the simulation of both the flow and the acoustics is a challenging task, this dataset pipeline assures high quality from the beginning of your aeroacoustic developments. The coupling between the flow and the acoustics is described by the perturbed convective wave equation (PCWE) [23] for example, but can be modeled with any other aeroacoustic equation.

The flow is computed using the open-source software packages *OpenFOAM* and the acoustic is computed using openCFS [26]. These packages offer all methods required for an accurate flow acoustics simulation. Moreover, open-source software promotes reproducibility and collaboration, as the codes and data are freely available to the research community. This article presents a hybrid aeroacoustic workflow [18] for studying flow-induced noise in a cylinder in cross flow. The methodology is validated using data from the literature. We would like to encourage contributors having obtained nice visualizations or computations to share their knowledge with us.

Workflow in short

Flow Simulation

The flow simulation is performed using OpenFOAM, a popular open-source computational fluid dynamics software package. The Navier-Stokes equations are solved using a finite-volume method, and the cylinder is modeled as a quasi-two-dimensional object with a structured mesh around it. The inlet boundary conditions is prescribed by the free stream velocity, at the outlet the pressure is set to zero and the cylinder surface is modeled as a no-slip wall. The pressure and velocity fields are computed, stored, and the results can be post-processed to obtain information about the flow characteristics, such as the wake structure and the drag coefficient.

Source Term Computation

After the flow computation, the aeroacoustic sources are computed and interpolated onto the acoustic mesh (for details, see [32]).

Acoustic Simulation

The acoustic simulation is performed using openCFS, an open-source software package for simulating multi-physical processes including acoustics. The linearized wave equation is used to model the acoustic waves, and the sound pressure levels and spectra are computed. The boundary conditions are set to be a sound-hard cylinder wall and free-field conditions otherwise.

Case description

The first validation example demonstrates the impact of the different interpolation strategies on the near-field and far-field of acoustic sound propagation. We choose the 2D, laminar flow over a cylinder (Re = 200, Ma = $U0/c = 0.03$, see Fig. 9) to report the impact. An unsteady flow field is observed, with a periodic vortex shedding at a Strouhal number of0.205 and 0.41 [41]. This periodic fluid instability inside the wake of this cylinder generates tonal components in the sound field. The CFD was computed employing OpenFoam. The incompressible pressure was used to compute the aeroacoustic sources based on the PCWE. Afterward, this source term was conservatively interpolated to the acoustic mesh. Having obtained the sources, the acoustic propagation was computed.

Generate a dataset using the pipeline

Description

This problem considers a 2D cylindrical obstacle (diameter d=0.02 m) within an incompressible flow. Inflow velocity $U_0 = 10$ m/s, kinematic viscosity $\nu = 0.001$ m^2

/s, Reynolds number $\mathrm{Re} \approx 200$. Air at 20°C should be

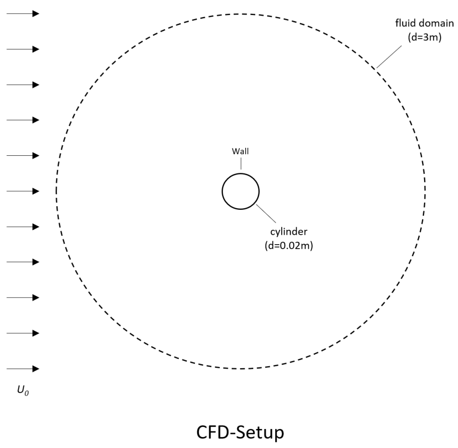

Figure 1: CFD Setup.

defined as material for the simulation (Material parameters are inside the *'air.xml'* file.). The speed of sound of air can be assumed to be $c_0 \approx 343.5 \frac{m}{s}$. The computational aeroacoustic domain is depicted below. Inside the

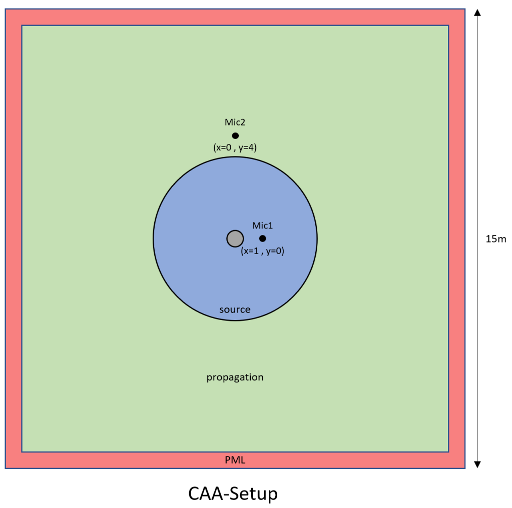

Figure 2: CAA Setup.

source region, a transient incompressible CFD Simulation is performed. Thereafter, aeroacoustic source terms can be computed from the obtained flow field. We then solve the Perturbed Convective Wave Equation (PCWE)

$$\frac{1}{c^2}\frac{\mathrm{D}^2\psi^{\mathrm{a}}}{\mathrm{D}t^2} - \nabla\cdot\nabla\psi^{\mathrm{a}} = -\frac{1}{\bar{\rho}c^2}\frac{\mathrm{D}p^{\mathrm{ic}}}{\mathrm{D}t}$$

for this low Mach number $\mathrm{Ma} \approx \frac{U_0}{c_0} = 0.03 \ll 0.3$ flow. The convective wave equation fully describes acoustic sound generated by incompressible flow structures and its wave propagation. The only unknown is the acoustic scalar potential ψ^{a} . In order to receive the acoustic pressure, we have to derive the scalar potential and scale it with the density

$$p^{\mathrm{a}} = \rho_0 \frac{\mathrm{D}\psi^{\mathrm{a}}}{\mathrm{D}t}\,.$$

For this problem, the convective part of the operator $\frac{\mathrm{D}}{\mathrm{D}t} = \frac{\partial}{\partial t} + \bar{\boldsymbol{v}}\cdot\nabla$ has a negligible effect on the acoustic field. Therefore, the convective part of the RHS source term $\boldsymbol{v}\cdot\nabla p^{\mathrm{ic}}$ is neglected for simplicity.

Here you can download the full simulation setup CylinderCrossFlow.zip. The convective part is considered in the *'file_PCWE'* files and neglected in the *'file_dpdt'* files.

Perform Transient Flow Simulation with openFOAM

Based on the Strouhal number for flows around obstacles of $\mathrm{St} \approx 0.2$ we estimate a vortex shedding frequency of

$$f = \mathrm{St}\frac{U_0}{d} \approx 100\,\mathrm{Hz}$$

Therefore, we choose a time step of $\Delta t_{\mathrm{CA}} = 5\cdot 10^{-4}\,\mathrm{s} \approx \frac{1}{20f}$.

- Set up the OpenFoam Mesh
- Define Boundary Conditions
  - Velocity inlet
  - Pressure outlet
- Specify transient controls and solution methods
  - Time stepping based on CFL < 1: $\Delta t_{\mathrm{CFD}} = 5\cdot 10^{-5}\,\mathrm{s}$
  - Standard solution methods
  - Incompressible transient flow solver: *'icoFoam'* using the PISO algorithm
- Run simulation until steady oscillation is set up
- Export pressure data as **EnSight Gold Case** (*.case) *'foamToEnsight -fields '("p.*")' -time 0.5:0.7'*
  - Standard CFD-Result file format
  - Can be exported with OpenFoam, Star-CCM++, Ansys Fluent, etc.
  - Can be visualized with ParaView

Interpolate the Flow Field and Compute Acoustic Sources

Based on the Perturbed Convective Wave Equation (PCWE) the RHS source needs to be calculated. For this example, the convective part of the RHS source is neglected and only $\frac{\partial p^{\mathrm{ic}}}{\partial t}$ needs to be calculated.

- Define data input
- Define partial time derivative
- Define interpolation filter
- Define data output
- Calculate interpolated acoustic sources: *'cfsdat -p interpolation.xml -tX interpolation'* using **X** threads in parallel.

Acoustic Simulation Setup

Finally, the acoustic propagation simulation is performed using the (already integrated) RHS values of

$$-\frac{1}{\rho_0 c_0^2} \int_\Omega \frac{\partial p^{\mathrm{ic}}}{\partial t} \, d\Omega \, .$$

- Define I/O files
  - Define data and mesh input
  - Include material file (‘air.xml‘)
  - Define output file formats
- Define computational domain
  - Assign material to regions (air at 20 degrees)
  - Define non-conforming interfaces between the different regions/parts (Nitsche-type Mortaring)
  - Define microphone points for evaluation
- Define simulation
  - Specify simulation type (transient)
  - Define the acoustic PDE (Potential formulation)
    * Specify regions to use in calculation
    * Specify used NC interfaces
    * Specify damping for perfectly-matched-layer (PML) regions
    * Specify background flow for convective wave operator
    * Define RHS node values (multiply with $-\frac{1}{\rho_0 c_0^2}$)
    * Define output results
- Run the acoustic propagation simulation: *’cfs -p propagation.xml -tX propagation’* using **X** threads in parallel.

Post-Processing Simulation Results

View the acoustic field result with ParaView nightly or 5.12 and greater versions that support the native cfs format directly. More on the postprocessing can be found in the openCFS documentation on opencfs.org.

Selected Applications using openCFS

Further contributions using workflows implemented with openCFS [26] and *openCFS-Data* [27] are presented in this section. For instance, the software packages were used to implement the SNGR method and applied to cavity noise [39, 40]. Furthermore, hybrid aeroacoustic workflow using high-resolved flow data was also used to compute the cavity noise, recently[33, 18, 34]. The spatial derivatives of source terms were computed by a radial basis function scheme [17, 30]. Recently developed equations can be leveraged by the implemented methods [20, 13]. Also, the combination with a Helmholtz decomposition [29, 28, 19, 24] is possible. Furthermore, the software and methodologies developed can be valuable for automotive OEMs [1, 3, 22, 40, 12]. The hybrid aeroacoustic workflow was found to be applicable for low-pressure axial fan noise computations [16, 35, 32, 36, 37, 15], the noise propagation simulations of the turbocharger compressor [5, 6, 4], the acoustics of fluid-structure-acoustic-interaction processes [31, 38, 42, 23, 2, 8, 11, 25, 9, 14, 7]. Potential nonphysical behavior generated by the source computation can be identified using the methods in [21] to assess statistical convergence.

Summary and Benchmark Proposal

In this article, a hybrid aeroacoustic workflow for studying flow-induced noise of a cylinder in cross flow using OpenFOAM for the flow and openCFS for the acoustics has been presented. The methodology has been validated using data from the literature. The proposed data generation pipeline based on the PCWE can be used to test your aeroacoustic workflows and new equations in aeroacoustics. This is a community call, if you generate data with this workflow and want to discuss the results or detect discrepancies in our methods used (we were not aware of), please report them to us.

References

[1] R. Engelmann, C. Gabriel, S. Schoder, and M. Kaltenbacher. A generic testbody for low-frequency aeroacoustic buffeting. Technical report, SAE Technical Paper, 2020.

[2] S. Falk, S. Kniesburges, S. Schoder, B. Jakubaß, P. Maurerlehner, M. Echternach, M. Kaltenbacher, and M. Döllinger. 3d-fv-fe aeroacoustic larynx model for investigation of functional based voice disorders. *Frontiers in physiology*, 12:616985, 2021.

[3] C. Freidhager, P. Maurerlehner, K. Roppert, A. Wurzinger, A. Hauser, M. Heinisch, S. Schoder, and M. Kaltenbacher. Simulationen von strömungsakustik in rotierenden bauteilen zur entwicklung von antriebskonzepten der autos der zukunft. *e & i Elektrotechnik und Informationstechnik*, 138(3):212–218, 2021.

[4] C. Freidhager, S. Schoder, and M. Kaltenbacher. The influences of spatial and temporal discretization in flow simulation on lighthill’s aeroacoustic source terms applied to a turbocharger. In *AIAA AVIATION 2020 FORUM*, page 2546, 2020.

[5] C. Freidhager, S. Schoder, P. Maurerlehner, A. Renz, S. Becker, and M. Kaltenbacher. Applicability of two hybrid sound prediction methods for assessing in-duct sound absorbers of turbocharger compressors. *Acta Acustica*, 6:37, 2022.

[6] M. Kaltenbacher, C. Freidhager, and S. Schoder. Modelling and numerical simulation of the noise generated by automotive turbocharger compressor. Technical report, SAE Technical Paper, 2020.

[7] F. Kraxberger, A. Wurzinger, and S. Schoder. Machine-learning applied to classify flow-induced sound parameters from simulated human voice. *arXiv preprint arXiv:2207.09265*, 2022.

[8] M. Lasota, P. Šidlof, M. Kaltenbacher, and S. Schoder. Impact of the sub-grid scale turbulence model in aeroacoustic simulation of human voice. *Applied Sciences*, 11(4):1970, 2021.

[9] M. Lasota, P. Šidlof, P. Maurerlehner, M. Kaltenbacher, and S. Schoder. Anisotropic minimum dissipation subgrid-scale model in hybrid aeroacoustic simulations of human phonation. *arXiv preprint arXiv:2301.00606*, 2023.

[10] F. Margnat, W. J. G. da Silva Pinto, and C. Noûs. Cylinder aeroacoustics: experimental study of the influence of cross-section shape on spanwise coherence length. *Acta Acustica*, 7:4, 2023.

[11] P. Maurerlehner, S. Schoder, C. Freidhager, A. Wurzinger, A. Hauser, F. Kraxberger, S. Falk, S. Kniesburges, M. Echternach, M. Döllinger, et al. Efficient numerical simulation of the human voice. *e & i Elektrotechnik und Informationstechnik*, 138(3):219–228, 2021.

[12] P. Maurerlehner, S. Schoder, J. Tieber, C. Freidhager, H. Steiner, G. Brenn, K.-H. Schäfer, A. Ennemoser, and M. Kaltenbacher. Aeroacoustic formulations for confined flows based on incompressible flow data. *Acta Acustica*, 6:45, 2022.

[13] S. Schoder. cpcwe–perturbed convective wave equation based on compressible flows. *arXiv preprint arXiv:2209.11410*, 2022.

[14] S. Schoder. Pcwe for fsai–derivation of scalar wave equations for fluid-structure-acoustics interaction of low mach number flows. *arXiv preprint arXiv:2211.07490*, 2022.

[15] S. Schoder and F. Czwielong. Dataset fan-01: Revisiting the eaa benchmark for a low-pressure axial fan. *arXiv preprint arXiv:2211.12014*, 2022.

[16] S. Schoder, C. Junger, and M. Kaltenbacher. Computational aeroacoustics of the eaa benchmark case of an axial fan. *Acta Acustica*, 4(5):22, 2020.

[17] S. Schoder, C. Junger, K. Roppert, and M. Kaltenbacher. Radial basis function interpolation for computational aeroacoustics. In *AIAA AVIATION 2020 FORUM*, page 2511, 2020.

[18] S. Schoder and M. Kaltenbacher. Hybrid aeroacoustic computations: State of art and new achievements. *Journal of Theoretical and Computational Acoustics*, 27(04):1950020, 2019.

[19] S. Schoder, M. Kaltenbacher, and K. Roppert. Helmholtz's decomposition applied to aeroacoustics. In *25th AIAA/CEAS Aeroacoustics Conference*, 2019-2561.

[20] S. Schoder, M. Kaltenbacher, É. Spieser, H. Vincent, C. Bogey, and C. Bailly. Aeroacoustic wave equation based on pierce's operator applied to the sound generated by a mixing layer. In *28th AIAA/CEAS Aeroacoustics 2022 Conference*, page 2896, 2022.

[21] S. Schoder, F. Kraxberger, S. Falk, A. Wurzinger, K. Roppert, S. Kniesburges, M. Döllinger, and M. Kaltenbacher. Error detection and filtering of incompressible flow simulations for aeroacoustic predictions of human voice. *The Journal of the Acoustical Society of America*, 152(3):1425–1436, 2022.

[22] S. Schoder, I. Lazarov, and M. Kaltenbacher. Numerical investigation of a deep cavity with an overhanging lip considering aeroacoustic feedback mechanism. *arXiv preprint arXiv:2006.03279*, 2020.

[23] S. Schoder, P. Maurerlehner, A. Wurzinger, A. Hauser, S. Falk, S. Kniesburges, M. Döllinger, and M. Kaltenbacher. Aeroacoustic sound source characterization of the human voice production-perturbed convective wave equation. *Applied Sciences*, 11(6):2614, 2021.

[24] S. Schoder, E. Museljic, F. Kraxberger, and A. Wurzinger. Post-processing subsonic flows using physics-informed neural networks. In *2023 AIAA AVIATION Forum*, 2022.

[25] S. Schoder and K. Roppert. Learning expertise actively to model domain knowledge (lead) with application to human phonation. *arXiv*, 2022.

[26] S. Schoder and K. Roppert. opencfs: Open source finite element software for coupled field simulation–part acoustics. *arXiv preprint arXiv:2207.04443*, 2022.

[27] S. Schoder and K. Roppert. opencfs-data: Data pre-post-processing tool for opencfs–aeroacoustics source filters. *arXiv preprint arXiv:2302.03637*, 2023.

[28] S. Schoder, K. Roppert, and M. Kaltenbacher. Helmholtz's decomposition for compressible flows and its application to computational aeroacoustics. *SN Partial Differ. Equ. Appl.*, pages 1–20, 2020.

[29] S. Schoder, K. Roppert, and M. Kaltenbacher. Post-processing of direct aeroacoustic simulations using helmholtz decomposition. *AIAA Journal*, pages 1–9, 2020.

[30] S. Schoder, K. Roppert, M. Weitz, C. Junger, and M. Kaltenbacher. Aeroacoustic source term computation based on radial basis functions. *International Journal for Numerical Methods in Engineering*, 121(9):2051–2067, 2020.

[31] S. Schoder, M. Weitz, P. Maurerlehner, A. Hauser, S. Falk, S. Kniesburges, M. Döllinger, and M. Kaltenbacher. Hybrid aeroacoustic approach for the efficient numerical simulation of human phonation. *The Journal of the Acoustical Society of America*, 147(2):1179–1194, 2020.

[32] S. Schoder, A. Wurzinger, C. Junger, M. Weitz, C. Freidhager, K. Roppert, and M. Kaltenbacher. Application limits of conservative source interpolation methods using a low mach number hybrid aeroacoustic workflow. *Journal of Theoretical and Computational Acoustics*, 29(01):2050032, 2021.

[33] S. J. Schoder. *Aeroacoustic analogies based on compressible flow data*. PhD thesis, Wien, 2018.

[34] S. J. Schoder, C. Junger, M. Weitz, and M. Kaltenbacher. Conservative interpolation of aeroacoustic sources in a hybrid workflow applied to fan. *arXiv preprint arXiv:2009.02341*, 2020.

[35] M. Tautz, K. Besserer, S. Becker, and M. Kaltenbacher. Source formulations and boundary treatments for lighthill's analogy applied to incompressible flows. *AIAA Journal*, 56(7):2769–2781, 2018.

[36] L. Tieghi, S. Becker, A. Corsini, G. Delibra, S. Schoder, and F. Czwielong. Machine-learning clustering methods applied to detection of noise sources in low-speed axial fan. In *2022 Turbomachinery Technical Conference & Exposition: ASME Turbo Expo 2022*, 2022.

[37] L. Tieghi, S. Becker, A. Corsini, G. Delibra, S. Schoder, and F. Czwielong. Machine-learning clustering methods applied to detection of noise sources in low-speed axial fan. *Journal of Engineering for Gas Turbines and Power*, 145(3):031020, 2023.

[38] J. Valášek, M. Kaltenbacher, and P. Sváček. On the application of acoustic analogies in the numerical simulation of human phonation process. *Flow, Turbulence and Combustion*, 102(1):129–143, 2019.

[39] M. Weitz. *An approach to compute cavity noise using stochastic noise generation and radiation*. PhD thesis, Wien, 2019.

[40] M. Weitz, S. Schoder, and M. Kaltenbacher. Numerical investigation of the resonance behavior of flow-excited helmholtz resonators. *PAMM*, 19(1):e201900033, 2019.

[41] M. M. Zdravkovich. *Flow around circular cylinders: Volume 2: Applications*, volume 2. Oxford university press, 1997.

[42] S. Zörner, P. Šidlof, A. Hüppe, and M. Kaltenbacher. Flow and acoustic effects in the larynx for varying geometries. *Acta Acustica united with Acustica*, 102(2):257–267, 2016.