Hybrid aeroacoustics using Helmholtz decomposition

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Motivation

Flow and Acoustics

- Solve equations of fluid-dynamics
- Flow + Acoustic field (e.g. $p = \tilde{p} + p'$)

Acoustic analogy

Wave propagation model *(reformulation of flow equations)*:

$$\Box p' = \mathbf{RHS}(p, \boldsymbol{u}, \rho, \ldots) = \mathbf{RHS}(\tilde{p}, \tilde{\boldsymbol{u}}, \tilde{\rho}, p', \boldsymbol{u}', \rho', \ldots)$$

Non-radiating base flow *(e.g. incompressible Flow, (Goldstein, 2003)[a])*:

$$\tilde{\Box} p' = \mathbf{RHS}(\tilde{p}, \tilde{\boldsymbol{u}}, \tilde{\rho}, \ldots) \, .$$

[a] M. E. Goldstein. A generalized acoustic analogy. Journal of Fluid Mechanics, 488:315–333, 2003.

Content

Aim of the presentation

Show how to avoid the ambiguity of the hybrid aeroacoustic workflow *(separates flow and acoustic simulation)* by a non-radiating base flow *(vortical projection)*.

1. Compressible flow simulation ($U_\infty = 50\,\mathrm{m/s}$, $M = 0.14$, $\mathrm{Re} = 29000$)[a]
2. Helmholtz decomposition $\rightarrow$ *non-radiating base flow*
3. Acoustic propagation

[a] B. Henderson. Automobile Noise Involving Feedback- Sound Generation by Low Speed Cavity Flows. Third Computational Aerocompressibles(CAA) Workshop on Benchmark Problems, 1, 2000.

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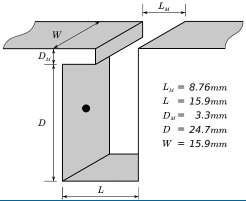
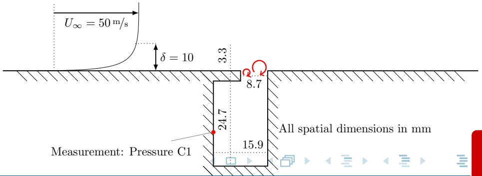
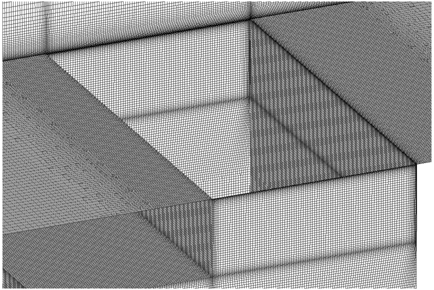


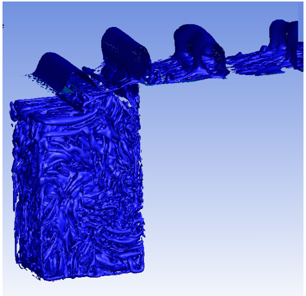


Compressible, air, DES flow simulation

CFD grid $12\,\mathrm{Mio}$ cells

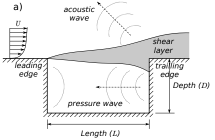


Vorticity

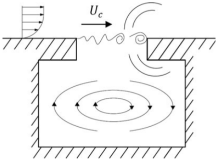


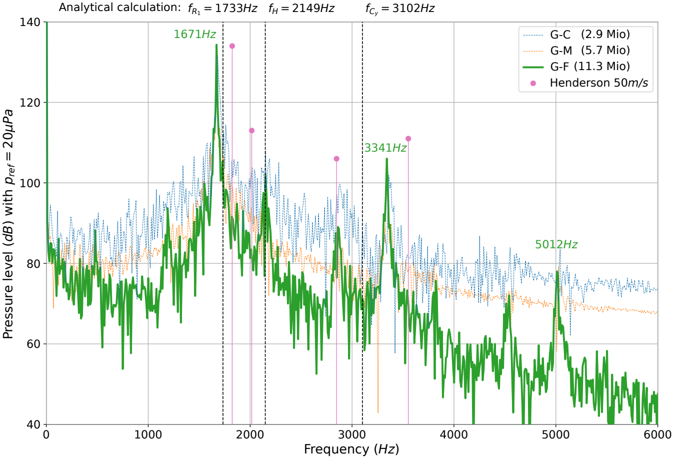
Compressible, air, DES flow simulation *(grid convergence study)*

1^{st} shear layer mode f_{R_1}

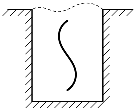


Helmholtz res. f_H





Cavity res. f_{C_y}



Content

Objectives

Hybrid aeroacoustic workflow:

- ✓ Compressible flow simulation
- 2 Helmholtz decomposition → *non-radiating base flow*
- 3 Acoustic propagation

Helmholtz decomposition

Decomposition of the velocity field into vortical part $\boldsymbol{A}_\mathrm{v} \in H(\mathrm{curl}, \Omega)$, compressible part $\phi_\mathrm{c} \in H^1(\Omega)$, and potential flow part $\boldsymbol{u}_\perp$ in the space of harmonic functions[1].

Helmholtz decomposition

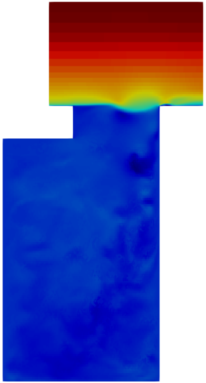
$$\begin{aligned} \boldsymbol{u} &= \quad \boldsymbol{u}_\mathrm{v} \quad + \boldsymbol{u}_\mathrm{c} \quad + \boldsymbol{u}_\perp \\ &= \nabla \times \boldsymbol{A}_\mathrm{v} + \nabla \phi_\mathrm{c} + \boldsymbol{u}_\perp \end{aligned}$$

Vortical part – *Neumann problem, Mass regularization, Nedelec-Finite Elements*

$$\begin{aligned} \nabla \times \nabla \times \boldsymbol{A}_\mathrm{v}^* &= \nabla \times \boldsymbol{u} = \omega \\ \boldsymbol{A}_\mathrm{v}^* \in \mathcal{W} &= \{\varphi \in H(\mathrm{curl}, \Omega) | \boldsymbol{n} \times \nabla \times \varphi = \boldsymbol{n} \times \boldsymbol{u} \text{ on } \Gamma\} \end{aligned}$$

[1] G. K. Batchelor. An Introduction to Fluid Dynamics. Cambridge Mathematical Library. Cambridge University Press, 2000.

Helmholtz decomposition



Vortical velocity field

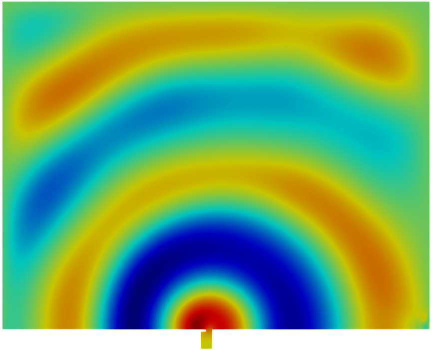
- $\boldsymbol{u}_{\mathrm{v}}^{*} = \nabla \times \boldsymbol{A}_{\mathrm{v}}^{*}$
- Shear layer
- Turbulence

Advantage *Vortical part (Schoder, 2017)*

- Simple boundary conditions
- No singularities at reentrant corners

S. Schoder, F. Toth, and M. Kaltenbacher. Hybrid computational aeroacoustics based on compressible flow data at low Mach numbers. PAMM 17.1: 687-688, 2017.

Helmholtz decomposition



Compressible velocity field

$$\boldsymbol{u} = \nabla \times \boldsymbol{A}_{\mathrm{v}} \quad + \nabla \phi_{\mathrm{c}} + \boldsymbol{u}_{\perp} \quad | \nabla \cdot$$
$$\Delta \phi_{\mathrm{c}}^{*} = \nabla \cdot \boldsymbol{u}$$

- $\boldsymbol{u}_{\mathrm{c}}^{*} = \nabla \phi_{\mathrm{c}}^{*}$
- Singularities at reentrant corners

Advantage *Compressible part*

Fast computation during the flow simulation (*pressure correction equation*)

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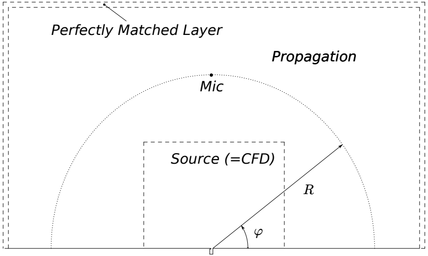
Acoustic model

Vortex sound *(Howe, 1975)*

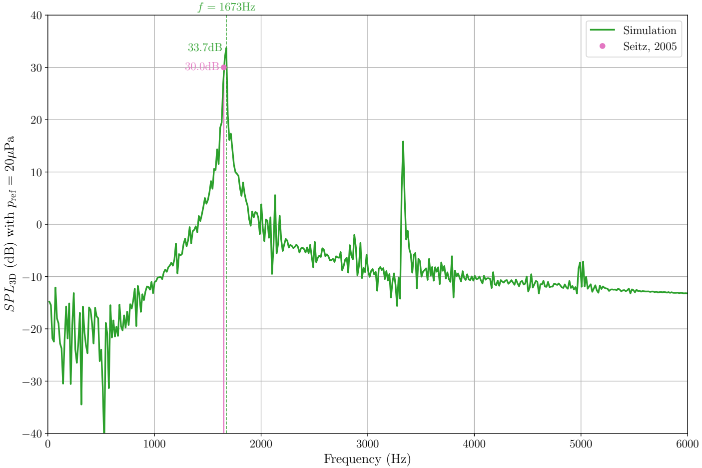
$$\frac{1}{c^2}\frac{\mathrm{d}_\mathrm{v}^2}{\mathrm{d}t^2}H - \nabla\cdot\nabla H = \nabla\cdot(\omega\times\mathbf{u}^\mathrm{v}) \quad \text{with} \quad \frac{\mathrm{d}_\mathrm{v}}{\mathrm{d}t} := \frac{\partial}{\partial t} + \mathbf{u}^\mathrm{v}\cdot\nabla$$

- Linearized around the vortical flow

M. S. Howe. Contributions to the theory of aerodynamic sound, with application to excess jet noise and the theory of the flute. Journal of Fluid Mechanics, 71(04):625673, 1975.



Acoustic



T. Seitz. Experimentelle Untersuchungen der Schallabstrahlung bei der Überströmung einer Kavität. Master thesis, FAU Erlangen, Germany, 2005.

Conclusion

Objectives

Hybrid aeroacoustic workflow *(separates flow and acoustic simulation)*:

- ✓ Compressible flow simulation → *aeroacoustic feedback*
- ✓ Helmholtz decomposition → *non-radiating base flow*
- ✓ Acoustic propagation

Outlook

Hybrid aeroacoustic workflow *(separates flow and acoustic simulation)*:

1. Study of the neglected interaction terms
2. Helmholtz decomposition, increase performance of AMG
3. First investigations at M=0.8

Thanks to Ivan Lazarov[1] and the Vienna Scientific Cluster (VSC).

[1] I. Lazarov. Strömungsakustische Simulation einer tiefen Kavität, Diplomarbeit. TU Wien, 2018.

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Content

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1. Compressible flow simulation → *aeroacoustic feedback*
2. Helmholtz decomposition → *non-radiating base flow*
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