KTH ROYAL INSTITUTE
OF TECHNOLOGY

On the Aerodynamically Generated Noise in Turbocharger Compressors

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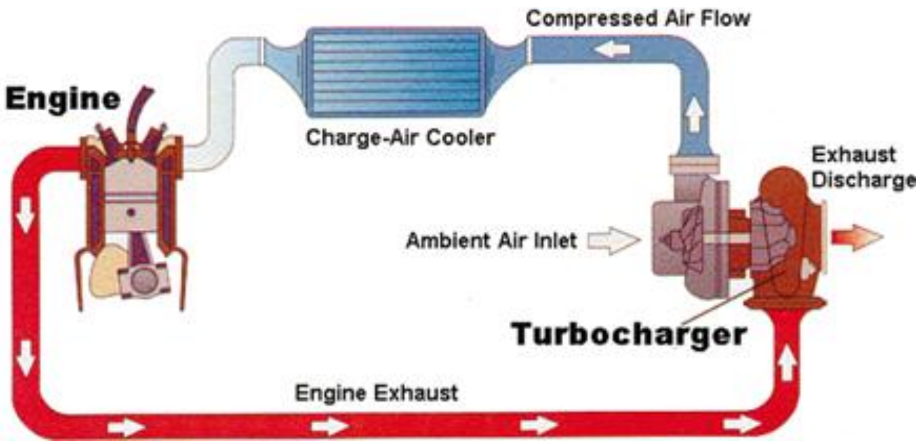
Presentation overview

- Project overview
- Research questions and approach
- Computational setup
- Results
- Summary and conclusions
- Future plans

Project overview

- **ICE downsizing in automotive industry**
  - Regulations* and fuel economy
  - Compressor noise



http://www.marine-knowledge.com/wp-content/uploads/2013/10/Turbocharger-Working.png

- **Project's objective: physics-based understanding of the aerodynamically generated noise in turbocharger compressors**
  - Investigation: CFD/CAA: RANS, URANS, LES
  - Practical relevance: Propagation in real systems: installation effects

Research questions & approach

Research questions:

- Which are the dominant acoustic sources related to turbocharger noise?
- What are the implications in sound propagation and resonance of installations of turbochargers?
- How to mitigate noise produced by automotive turbochargers?
- What are the limitations of the RANS-based formulations within the context? Trends, confidence intervals?

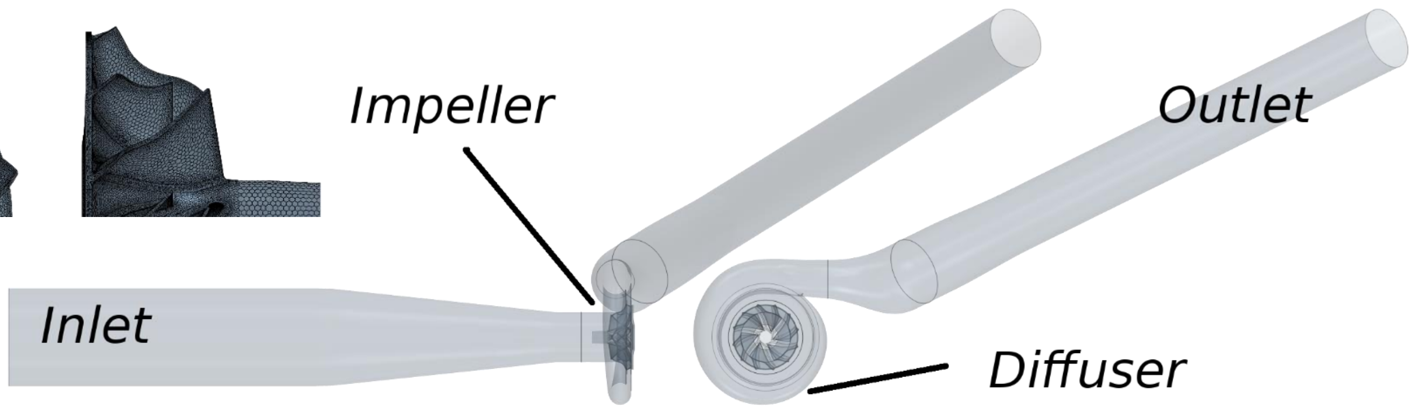
Approach:

- RANS: compressor performance and acoustic models (advantages/limitations)
- LES (at a later stage): physics-based understanding

Computational setup

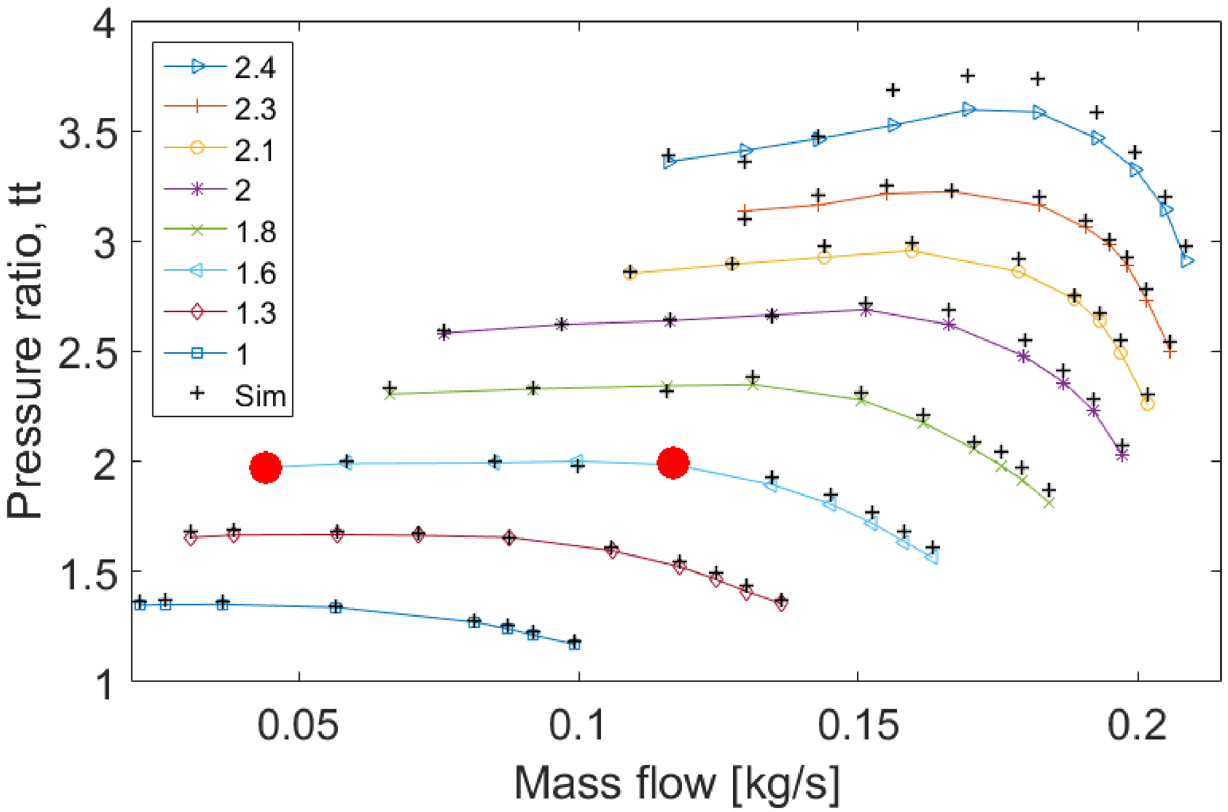
❑ Compressor system

- Governing equations: Continuity, Momentum, Energy, Equation of State
- Turbulence modelling: SST k-ω
- Solver: Coupled Flow (density based)
- Discretisation: 2nd order upwind
- Mesh: Polyhedral, ~4.5 mln cells, circumferential time averaged interface, moving reference frame

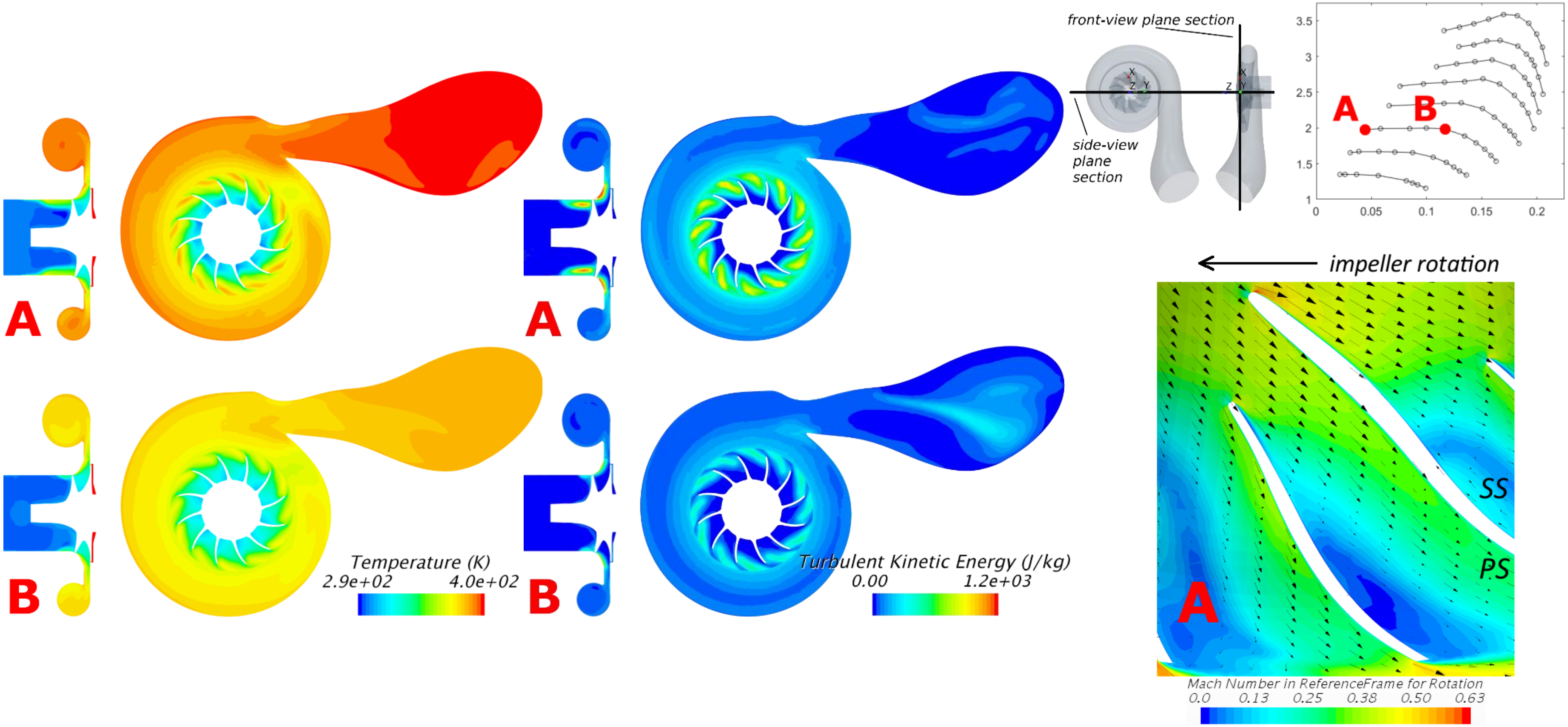


Results:
Compressor performance map

- Pressure Ratio: RANS vs. Gas-stand data



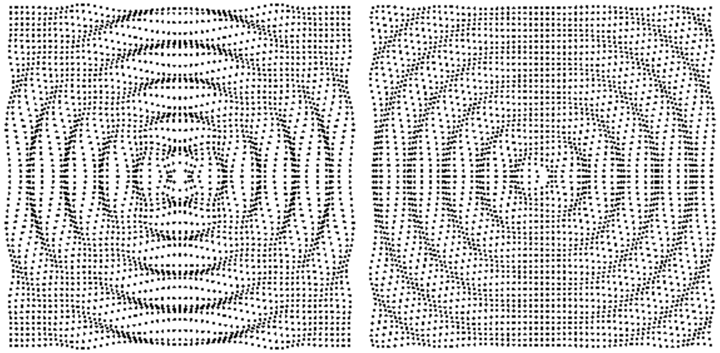
Results:
Temperature and TKE



Broadband noise source models

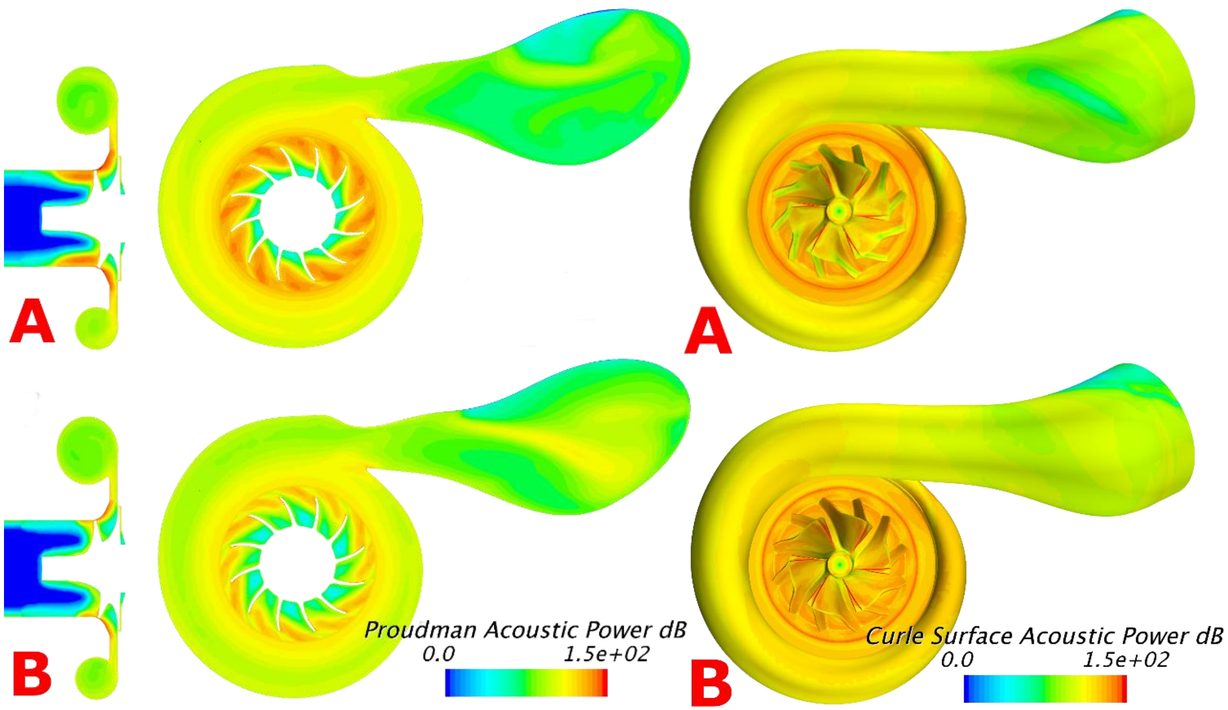
❑ Proudman model, Curle model (Lighthill's analogy)

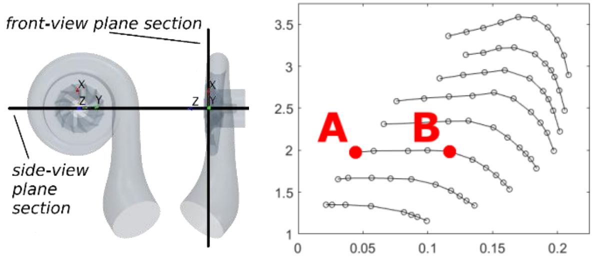
- RANS turbulence modelling, acoustic source information
- Turbulence-generated flow noise
- Proudman model: quadrupole sources
- Curle model: dipole sources

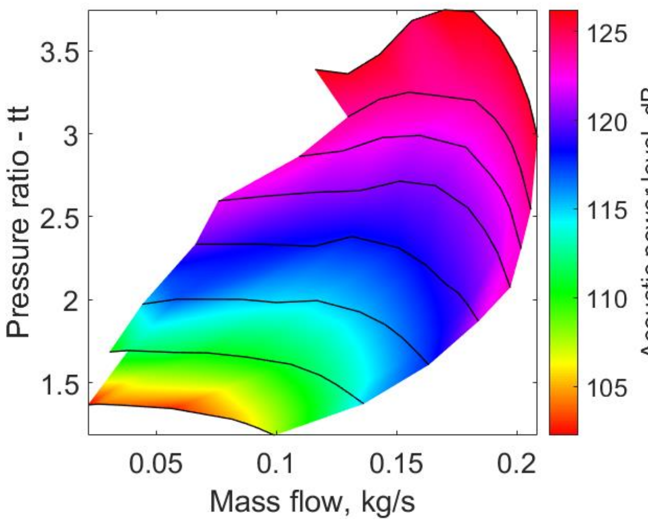


https://www.acs.psu.edu/drussell/

Results:
Proudman and Curle models







Summary and conclusions

❑ Steady-state based investigation of compressor noise

- Specific compressor performance parameters validated to experimental data
- Acoustic models in STAR-CCM+ utilised to localise areas of noise generation and estimate acoustic power level dB

❑ Conclusions

- Suitable computational setup (compressor map)
- Noise generation areas: backflow/separation areas, volute tongue, leading edges
- Noise map: generated acoustic power proportional rpm, higher on surge/choke lines

Applicability of broadband noise source models to predict acoustic behaviour?

Future plans

- **Development towards correlation of sources and noise**

  - Refine grids for unsteady simulations (URANS → LES) on selected operating points
  - Assess the validity of the RANS acoustic predictions
  - Installation effects: upstream/downstream
  - Compressible LES: quantification of acoustic sources and correlation of acoustic sources with far-field noise → Noise reduction technologies

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Thank you for your attention!

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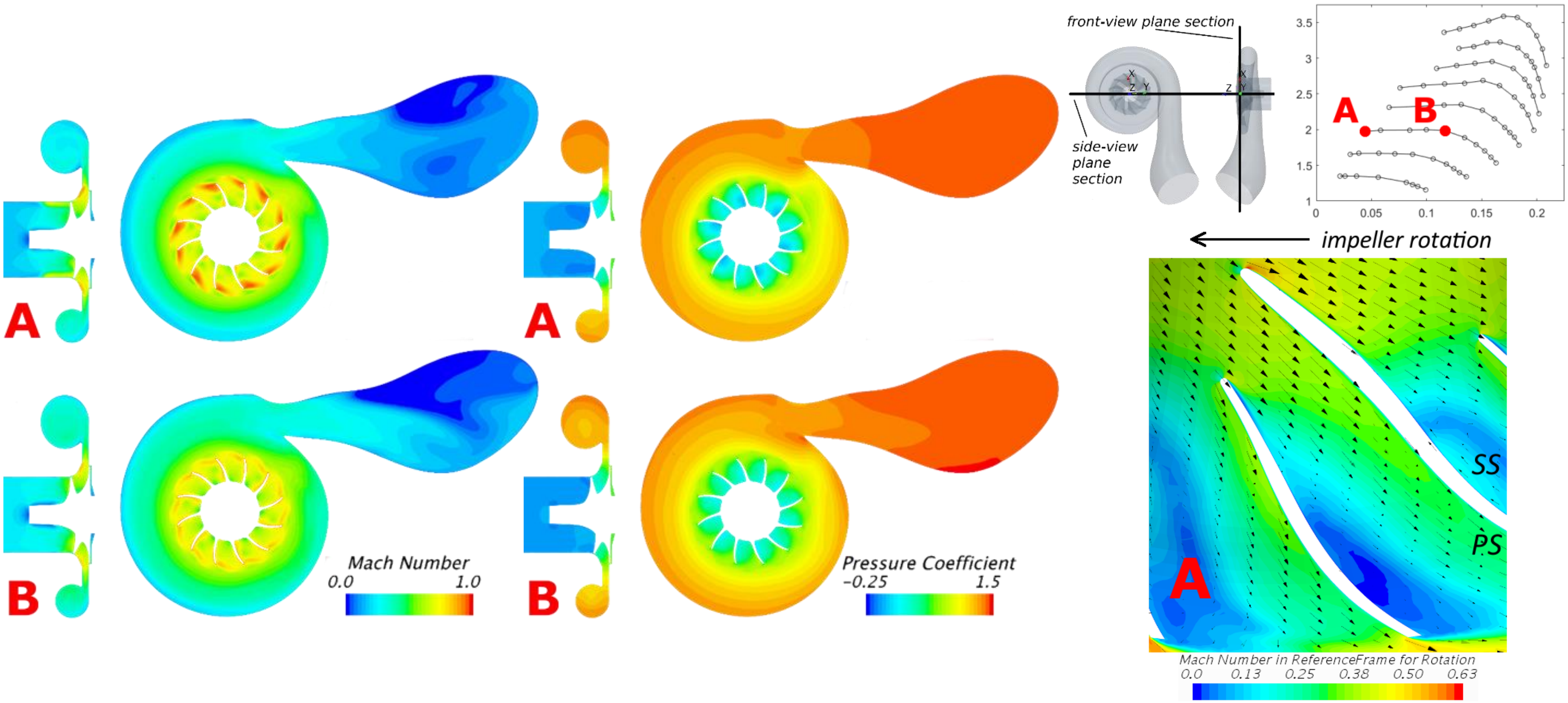
Competence Center for Gas Exchange

CCGEx

"Charging for the future"

Appendix

Results:
Mach number and Cp



Appendix: Curle model

The Curle surface integral is:

$$\rho'(\bar{x}, t) = \frac{1}{(4\pi a_0^3)} \int_S \left[\frac{(\bar{x} - \bar{y})}{r^2} \frac{\partial p}{\partial t}\left(\bar{y}, t - \frac{r}{a_0}\right) \right] \bar{n} \, \mathrm{d}S(\bar{y}) \quad (954)$$

where:

- $t - r / a_0$ is the emission time
- p the surface pressure
- ρ' the acoustic pressure
- a_0 the far-field sound speed.

On the assumption of small perturbations and an adiabatic problem, then:

$$\frac{p}{\rho^{\gamma}} = ct \quad (955)$$

which can be used to relate variations in acoustic pressure with density perturbations:

$$\mathrm{p}' = a_0^2 \rho' \quad (956)$$

From STAR-CCM+ User Manual

Appendix: Curle model

Then Eqn. (954) becomes:

$$p'(\bar{x}, t) = \frac{1}{(4\pi a_0)} \int_S \left[\frac{(\bar{x} - \bar{y})}{r^2} \frac{\partial p}{\partial t}\left(\bar{y}, t - \frac{r}{a_0}\right) \right] \bar{n} \, \mathrm{d}S(\bar{y}) \qquad \textbf{(957)}$$

The acoustical directional intensity per unit surface of the solid body on the far field prediction is approximated with:

$$\overline{p'^2} \approx \frac{1}{16\pi^2 a_0^2} \int_S \frac{(\cos\theta)^2}{r^2} \overline{\left[\frac{\partial p}{\partial t}\left(\bar{y}, t - \frac{r}{a_0}\right)\right]^2} A_c(\bar{y}) \, \mathrm{d}S(\bar{y}) \qquad \textbf{(958)}$$

where:

A_c is the correlation area

$r = (\bar{x} - \bar{y})$

θ is the angle between r and the $\bar{n}$ wall-normal direction.

The measure of the local contribution to acoustic power per unit surface area can be computed from:

$$SAP = \frac{1}{\rho_0 a_0} \left[\int_0^{(2\pi)} \int_0^{\pi} \overline{p'^2} r^2 \sin\theta \, d\theta \, d\gamma \right] = \int_S I(\bar{y}) \, \mathrm{d}S(\bar{y}) \qquad = \int_S \frac{A_c(\bar{y})}{\left(12\rho_0 \pi a_0^3\right)} \overline{\left(\frac{\partial p}{\partial t}\right)^2} dS(\bar{y}) \qquad \textbf{(959)}$$

From STAR-CCM+ User Manual

Appendix: Curle model

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where $I(\vec{y})$ is the directional acoustic intensity per unit surface.

The model can be enabled for steady and unsteady cases with Reynolds-Averaged Navier-Stokes (RANS) models which can provide turbulence time scale, turbulence length scale and wall shear stress necessary to compute $\overline{(\partial p / (\partial t))^2}$, the mean-square time derivative of the source surface pressure [180].

The acoustic power per unit surface can be reported in dimensional units ($\mathrm{W/m^2}$) and in dB:

$$SAP(\mathrm{dB}) = 10 \;\; \log\frac{SAP}{P_{ref}} \tag{960}$$

where P_{ref} is the reference acoustic power.

From STAR-CCM+ User Manual

Appendix: Proudman model

The analytical result of Proudman estimated the local acoustic power generated by unit volume of isotropic turbulence having no mean flow.

See [194]. Proudman considered the generation of noise by isotropic turbulence and using statistical models of various two-point moments, using the Lighthill analogy. In Proudman's high-Reynolds model for isotropic turbulence in near incompressible flow, Lilley added the effects of retarded time in th evaluation of the two-point covariance of Lighthill's tensor (an effect previously neglected by Proudman), and obtained the following expression for acoustic power, AP per unit volume:

$$AP = \alpha\rho_0 \frac{u^3}{l}\frac{u^5}{a_0^5} \quad \textbf{(990)}$$

where α is a constant related to the shape of the longitudinal velocity correlation, u is the root mean square of one of the velocity components, l is the longitudinal integral length scale of the velocity, ρ_0 is the far-field density and a_0 is the far-field sound speed.

In Proudman's original derivation [194], α is approximately 13. Lilley [187] found it to be about 10.96. In a DNS simulation done by Sarkar and Hussain [198] α = 2.6, and in the LES study done by Witkowska and Juve [199] α = 2.5. In Proudman's paper, the terms of u and ε can be written as:

$$u = \sqrt{\left(\frac{2}{3}k\right)} \quad , \qquad \varepsilon = \frac{1.5u^3}{l} \quad \textbf{(991)}$$

In terms of STAR-CCM+ of the turbulence velocity scale and of the turbulence length scale, the local acoustic power due to the unit volume of isotropic turbulence (in $\mathrm{W/m^3}$) becomes:

$$AP = \alpha_c\,\rho_0 \frac{U^3}{L}\frac{U^5}{a_0^5} \quad \textbf{(992)}$$

From STAR-CCM+ User Manual

Appendix: Proudman model

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$$AP = \alpha_c \rho_0 \frac{U^3}{L} \frac{U^5}{a_0^5} \quad \textbf{(992)}$$

with:

$$U = \frac{L}{T} \ , \qquad \alpha_c = 0.629 \quad \textbf{(993)}$$

where ρ_0 is the far-field density, U is the turbulence velocity, L is the turbulence length scale, T is the turbulence time scale and a_0 is the far-field sound speed.

The rescaled constant is based on Direct Numerical Simulation for isotropic turbulence done by Sarkar and Hussaini [198].

The total acoustic power per unit volume can be reported in dimensional units ($\mathrm{W/m^3}$) and in dB:

$$AP(\mathrm{dB}) = 10 \ \log\left(\frac{AP}{P_{ref}}\right) \quad \textbf{(994)}$$

where P_{ref} is the reference acoustic power.

From STAR-CCM+ User Manual