KTH ROYAL INSTITUTE
OF TECHNOLOGY

On the Aerodynamically Generated Sound in Centrifugal Compressors

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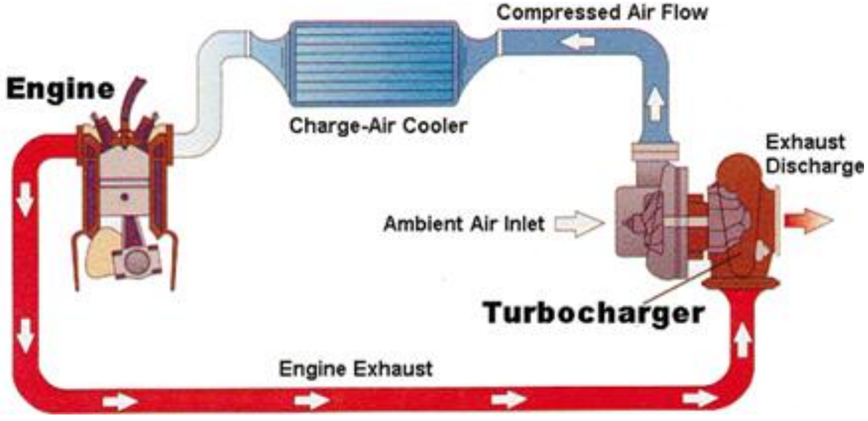
Overview

- ICE downsizing in automotive industry
  - Downsizing as a response to stringent regulations on emission of pollutants and as a solution for improved fuel economy;
  - Compressor noise: impact on both environment and driver/passenger comfort. EU regulations on automotive 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 centrifugal compressors
  - CFD/CAA method of approach: RANS, URANS, LES calculations;
  - Installation effects being considered;

Research questions & approach

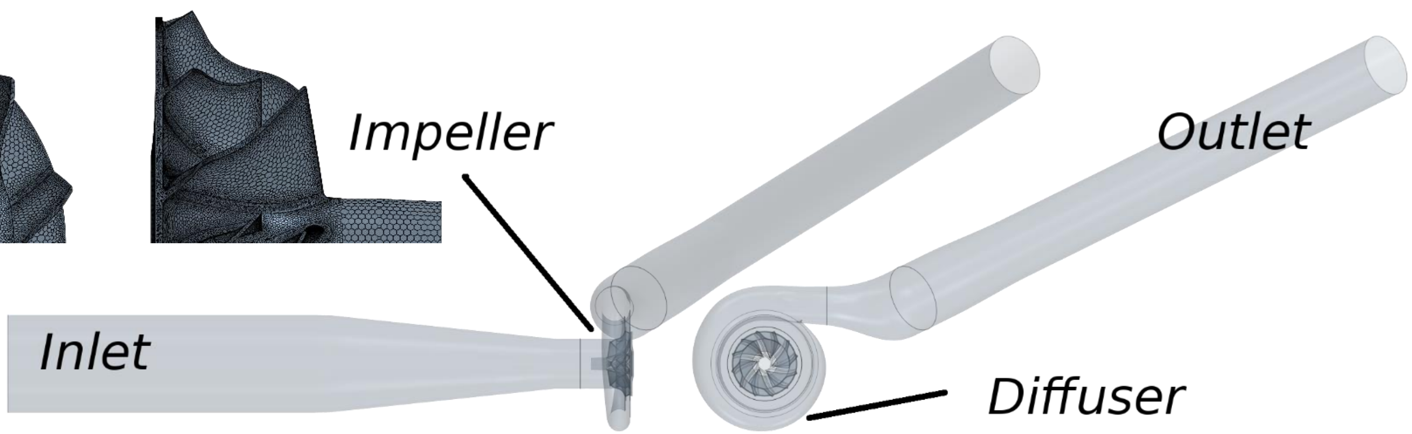
- Research questions:
  - Which are the dominant acoustic sources related to turbocharger noise?
  - What are the implications in sound propagation and resonance of installations of turbochargers?
  - How to mitigate noise produced by automotive turbochargers?

- Approach:
  - Flow field of specific compressor: steady state solutions for operating conditions for which experimental data is available;
  - Initial acoustic analysis by means of acoustic models based on RANS data: search for trends, assessment of advantages and limitations of the acoustic models considered;
  - Extent to which such data can be used during the design process?

Computational setup

- BorgWarner Turbo Systems: MP compressor
  - 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

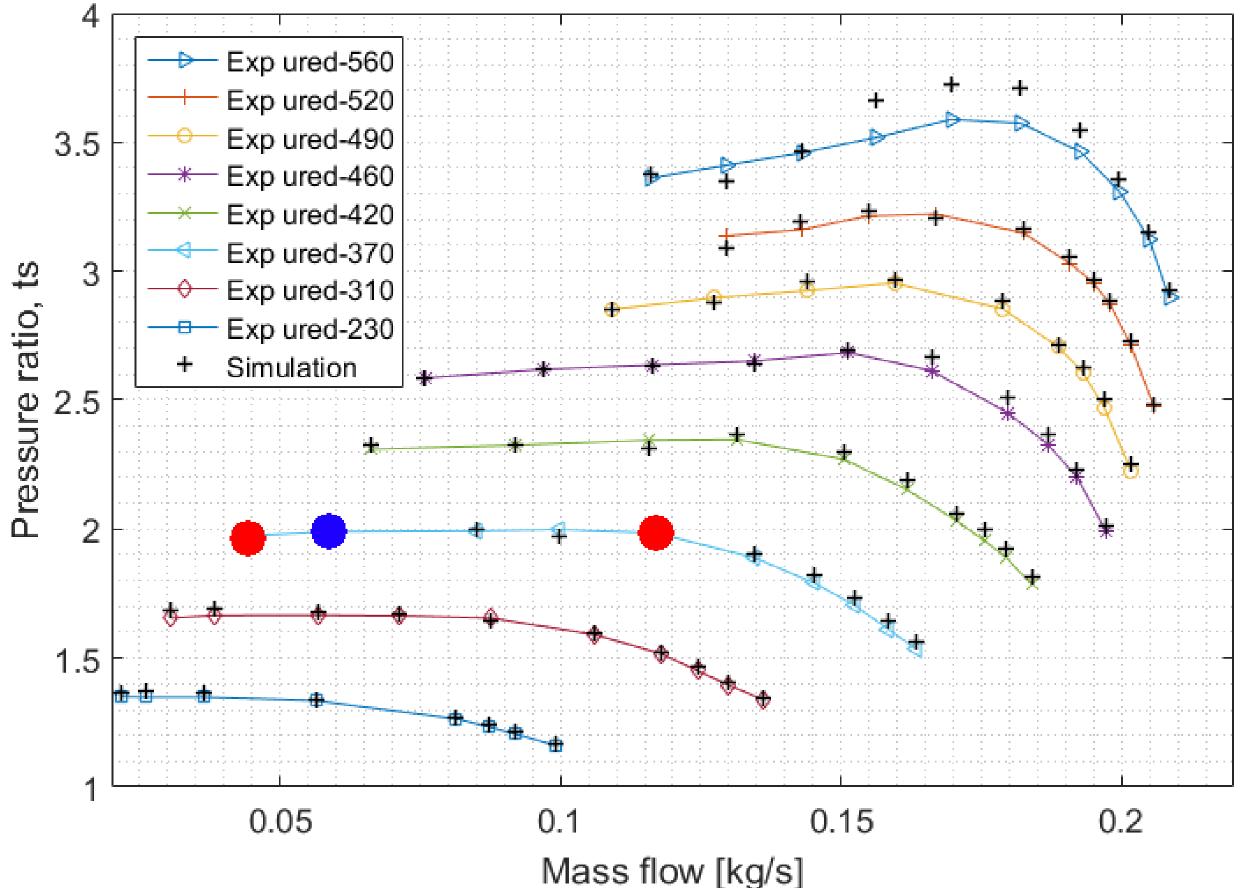
Main blades: 6
Splitter blades: 6
TRIM: 56



Compressor Map

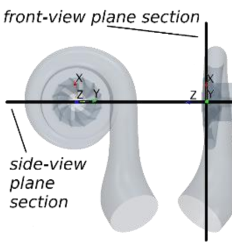
❑ BorgWarner Turbo Systems: MP compressor

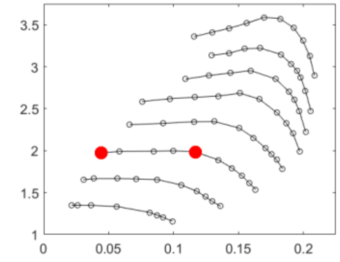
- 80 operating conditions simulated on clusters;
- Medium grid (~4.5 M cells);
- PR shows good match with experimental data for a range of operating conditions;
- Points of interest highlighted.

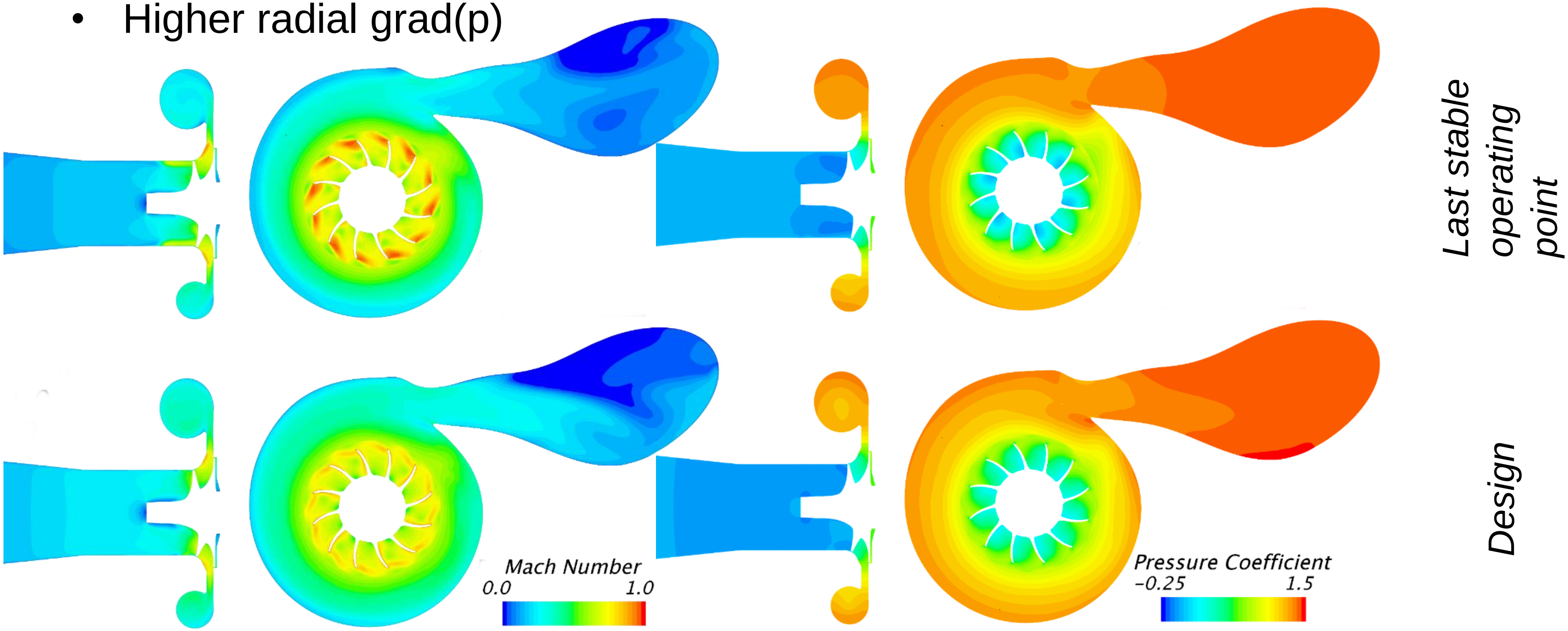


Mach number and Pressure

- Last stable operating point: flow travels upstream from diffuser through tip leakage
- Adverse pressure gradient under tongue, and flow directed there
- Higher radial grad(p)







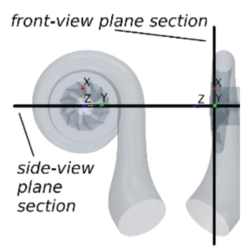
Broadband noise source models

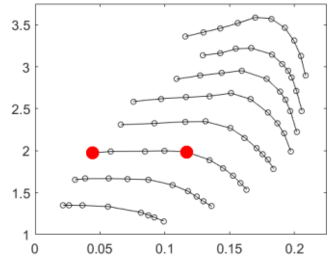
Proudman model, Curle model (Lighthill’s analogy):

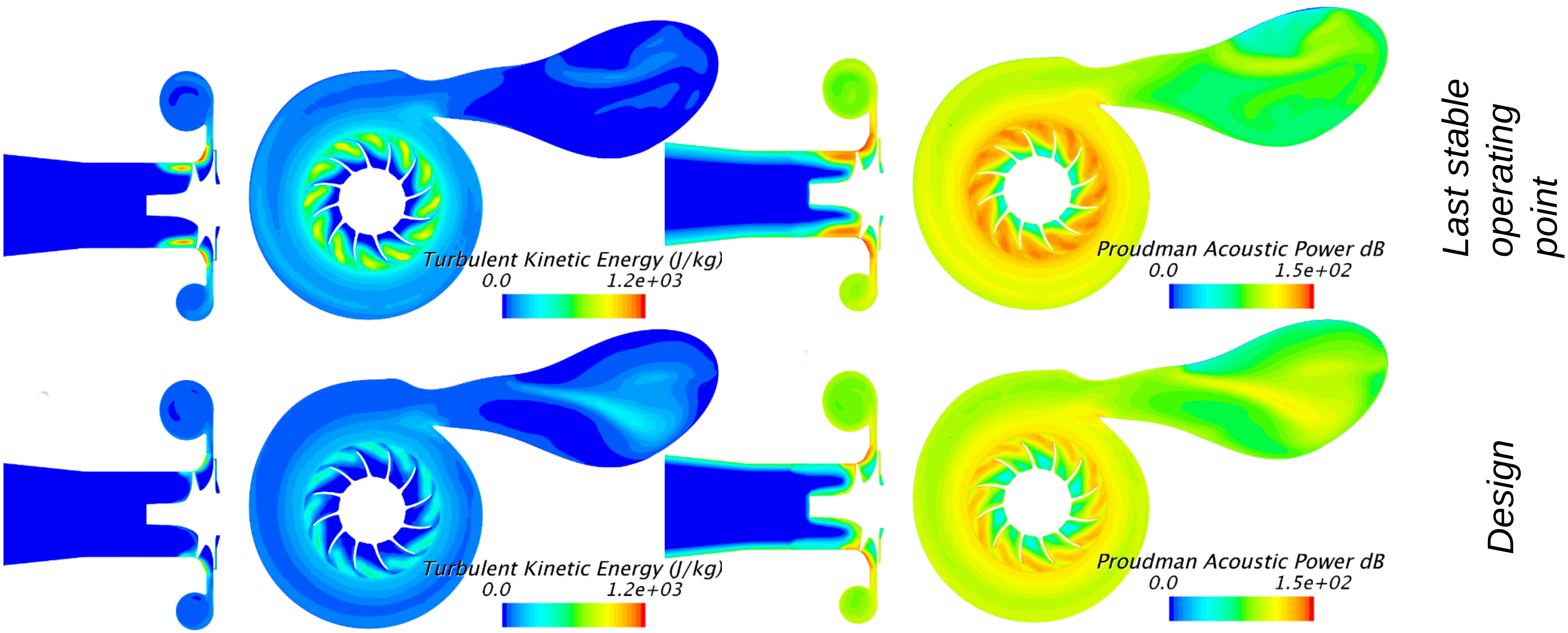
- Implicit to RANS turbulence modelling, source information through correlations;
- Turbulence-generated flow noise, contributing to total acoustic power;
- Proudman model: models volume distribution of quadrupole sources, noise from turbulent flow;
- Curle model: models surface distribution of dipole sources, noise from turbulent boundary layer flow over surfaces (fluctuating surface pressures);
- **Pros:** Identification of location of flow generated noise sources, approximation of associated sound power or dB level, comparison between component designs;
- **Cons**: unable to capture noise from large-scale flow features, such as vortex shedding.

TKE and Proudman

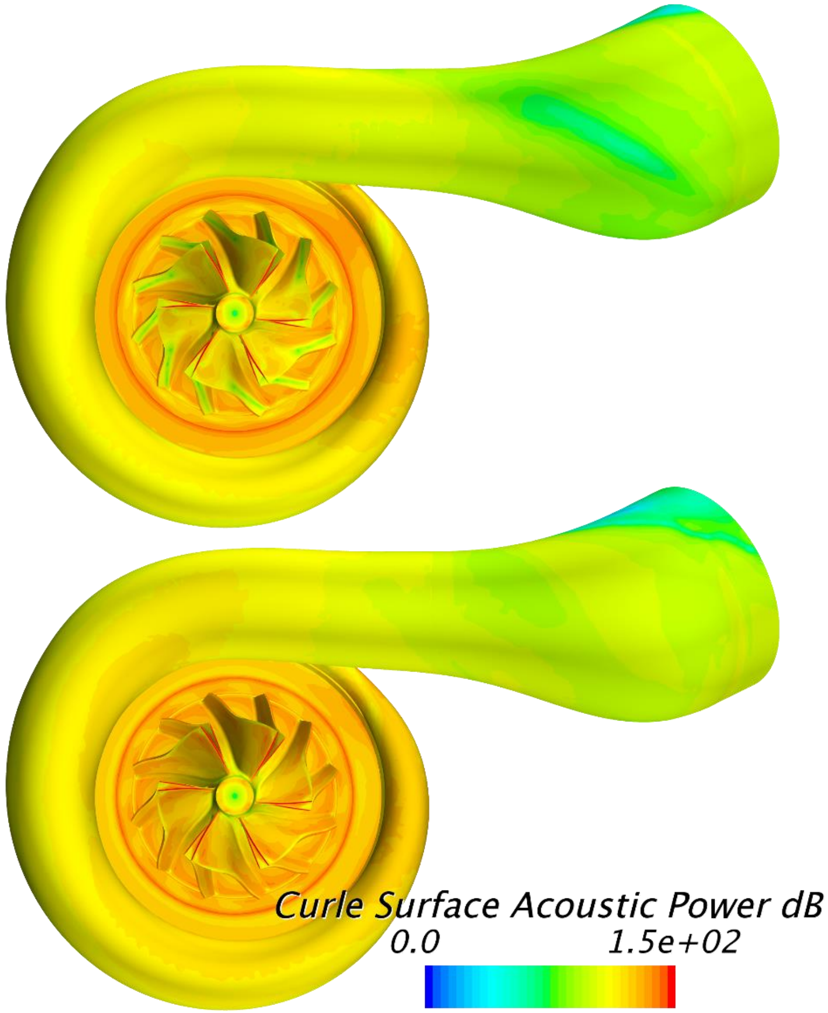
- Last stable operating point: high production of TKE and Proudman acoustic power in same areas
- Last stable operating point has a broader area of high noise generation.





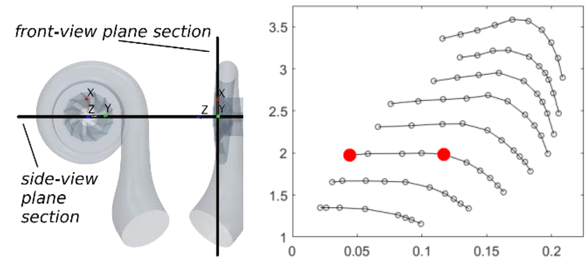


Curle acoustic model



Last stable operating point

Design



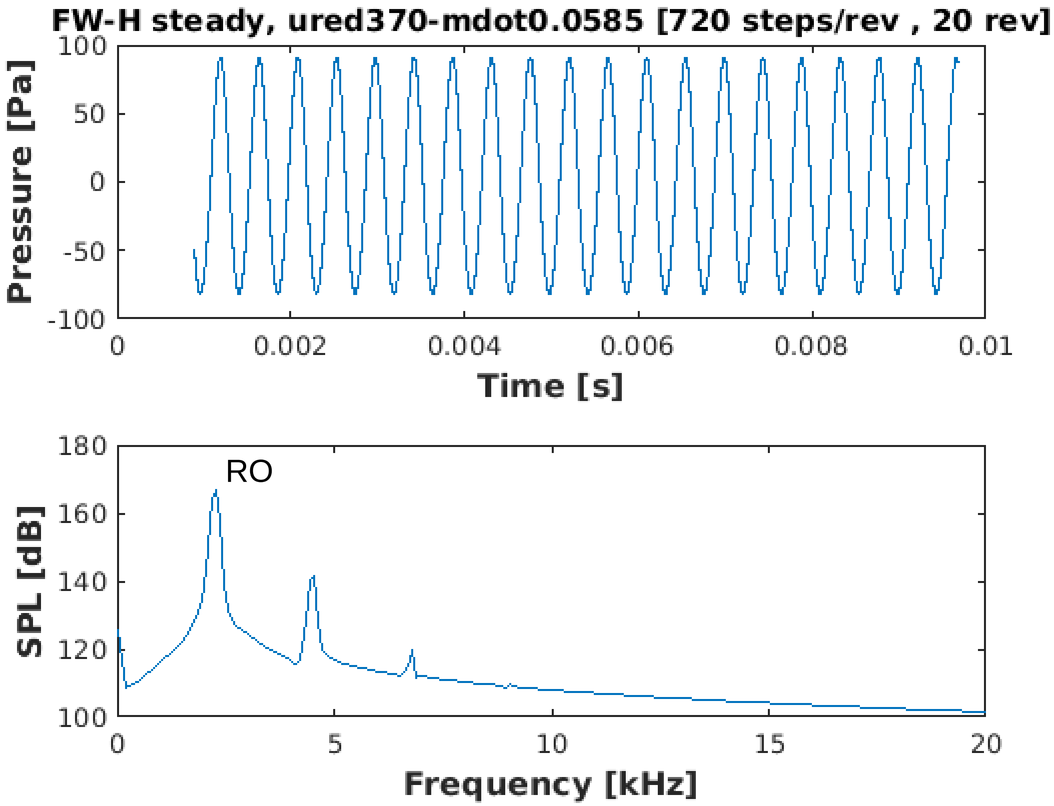
- Both points: peaks at leading edges and higher noise production under volute tongue
- Last stable operating point: smaller contribution from blade tip area; higher acoustic power under the tongue region

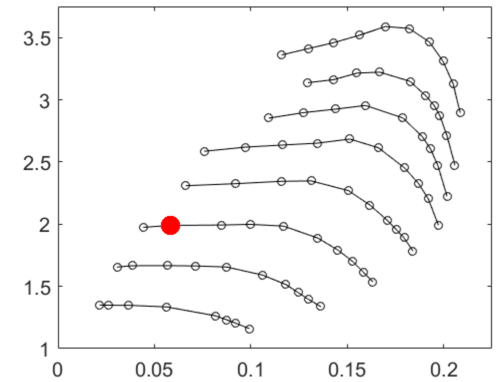
FW-H steady model

Steady state model calculates far-field sound signal radiated from near-field flow data from CFD simulation. Prediction of small amplitude acoustic pressure fluctuations at a receiver

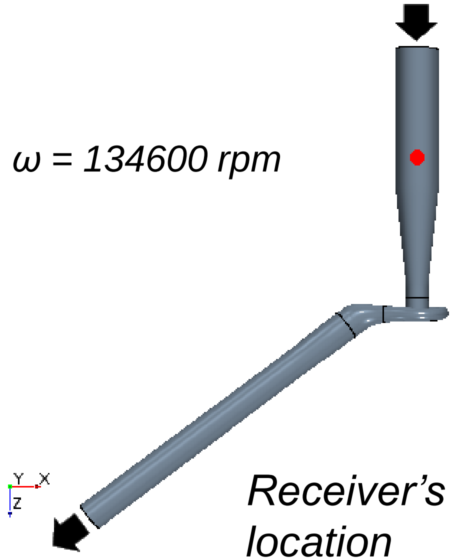
- Applies to 3D rotating cases;
- Thickness noise and Loading noise are major contributors when there is no installation effect;
- Propagation of sound in free space is considered. No sound reflections, refraction, or material property change are considered;
- Prediction of an unsteady time signal defining an artificial unsteady timestep;

FW-H steady model: 720 steps/rev, 20 rev





ω = 134600 rpm



Receiver's location

Future plans:

BorgWarner Turbo Systems – MP compressor:

- Analyse data gathered from broadband acoustic models and FW-H steady model along paths of interest, look for trends;
- Test grids' acoustic sensitivity, other receivers (FW-H steady model);
- Refine grids in view of unsteady simulations; run unsteady simulations (URANS, LES) on selected operating points;
- Data from unsteady simulations will be used to assess the validity of the acoustic predictions based on steady-state models;
- Installation effects: upstream/downstream elements in an intake system;
- LES: correlation of acoustic sources with far-field noise, addressing industry towards noise suppression technologies.

Competence Center for Gas Exchange

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"Charging for the future"

Energimyndigheten SCANIA VOLVO BorgWarner

Appendix: Curle model

The Curle boundary layer model is the Curle integral based on Lighthill's theory, which determined the equations of sound propagation in a medium at rest from the equation of continuity and momentum.

The Curle surface integral computes the sound generated by dipoles representing the fluctuating surface pressures with which the solid boundaries act on the fluid. **The model evaluates far field noise emitted by turbulent boundary layer flow over a solid body at low Mach number.**

Appendix: Curle model

The Curle surface integral is:

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

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:

$$\frac{p}{\rho^{\gamma}} = ct \tag{955}$$

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

$$\mathrm{p}' = a_0^2 \rho' \tag{956}$$

Appendix: Curle model

Then Eqn. (954) becomes:

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

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

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

where:

A_c is the correlation area

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

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

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

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

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.

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:

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

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:

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

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:

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

Appendix: Proudman model

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:

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

with:

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

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:

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

where P_{ref} is the reference acoustic power.

Appendix: FW-H steady model

FW-H Surface Terms

When the integration surface coincides with the body, the monopole term Eqn. (1002), the dipole term Eqn. (1003), and the quadrupole term Eqn. (1004) are called:

- The **Thickness Surface Term**, $p'_T(\vec{x}, t)$, resulting from the displacement of fluid as the body passes. The term is defined in Eqn. (1011) for general flows and in Eqn. (1016) for flows with rigid body motion or moving reference frames.
- The **Loading Surface Term**, $p'_L(\vec{x}, t)$, resulting from the unsteady motion of the force distribution on the body surface. The term is defined in Eqn. (1011) for general flows and in Eqn. (1017) for flows with rigid body motion or moving reference frames.
- The **Total Surface Term**, $p'_S(\vec{x}, t)$, resulting from the sum of the **Thickness Surface Term** and the **Loading Surface Term**. The term is defined in Eqn. (1010).

$$p'_S(\vec{x}, t) = p'_T(\vec{x}, t) + p'_L(\vec{x}, t) \quad \textbf{(1010)}$$

Appendix: FW-H steady model

Farrassat's Formulation 1A

This formulation is for general subsonic source regions, for general far-field noise prediction. See [164] and [165].

$$p'_T(\vec{x},t) = \frac{1}{4\pi}\left(\int_{(f=0)}\left[\frac{\rho_0(\dot{U}_n + U_{\dot{n}})}{r(1-M_r)^2}\right]_{ret} \mathrm{d}S + \int_{(f=0)}\left[\frac{\rho_0 U_n\left[r\dot{M}_r + a_0\left(M_r - M^2\right)\right]}{r^2(1-M_r)^3}\right]_{ret} \mathrm{d}S\right) \tag{1011}$$

$$p'_L(\vec{x},t) = \frac{1}{4\pi}\left(\frac{1}{a_0}\cdot\int_{(f=0)}\left[\frac{\dot{L}_r}{r(1-M_r)^2}\right]_{ret} \mathrm{d}S + \int_{(f=0)}\left[\frac{(L_r - L_M)}{r^2(1-M_r)^2}\right]_{ret} \mathrm{d}S + \frac{1}{a_0}\cdot\int_{(f=0)}\left[\frac{L_r\left[r\dot{M}_r + a_0\left(M_r - M^2\right)\right]}{r^2(1-M_r)^3}\right]_{ret} \mathrm{d}S\right) \tag{1012}$$

and:

$$M_i = U_i / a_0 \tag{1013}$$

Appendix: FW-H steady model

$$r = x_{\text{observer}} - y_{\text{face}} \quad \textbf{(1014)}$$

where:

- $f = 0$ denotes a mathematical surface to embed the exterior flow problem $f > 0$ in an unbounded space.
- $f = 0$ represents the emission surface and is made coincident with a body, impermeable surface, or permeable surface.

If the data surface coincides with a solid surface, then the normal velocity of the fluid is the same as the normal velocity of the surface:

$$u_n = v_n \quad \textbf{(1015)}$$

In this case, Eqn. (1011) and Eqn. (1012) correspond to the Impermeable FW-H Surface type and some of the terms are eliminated.

Dunn-Farrassat-Padula Formulation 1A

This formulation is based on modification of Farassat's Formulation 1A, which it was used in both ANOPP (Aircraft Noise Prediction Program) and DFP-ATP (Dunn-Farassat-Padula Advanced Turboprop Prediction) for subsonic rotating blades to compute the acoustic pressure, based on Hubbard [181].

For the Permeable FW-H Surface type, the FW-H Surface integrals are computed on the internal interface boundary, from an in-place interface.

$$\mathrm{p}'_T(\vec{x}, t) = \frac{1}{4\pi}\left(\int_{(f=0)}\left[\frac{\rho_0 v_n\left[\left(r\dot{M}_r\right) + a_0\left(M_r - M^2\right)\right]}{r^2\left(1 - M_r\right)^3}\right] \mathrm{d}S\right) \quad \textbf{(1016)}$$

Appendix: FW-H steady model

$$p'_L(\vec{x},t) = \frac{1}{4\pi}\left(\frac{1}{a_0}\cdot\int_{(f=0)}\left[\frac{\dot{L}_i r_i}{r(1-M_r)^2}\right]\mathrm{d}S + \int_{(f=0)}\left[\frac{(L_r - L_i M_i)}{r^2(1-M_r)^2}\right]\mathrm{d}S\right.$$

$$\left. + \frac{1}{a_0}\cdot\int_{(f=0)}\left[\frac{L_r\left[(r\dot{M}_r) + a_0\left(M_r - M^2\right)\right]}{r^2(1-M_r)^3}\right]\mathrm{d}S\right) \tag{1017}$$

and:

$$\dot{M}_r = \dot{M}_i r_i \tag{1018}$$

where:

- L_i is the blade load vector.
- $\dot{L}_i$ is the time derivative of the blade load vector with respect to source time.
- v_i is the local velocity of the blade surface with respect to the quiescent fluid.
- v_n is the surface normal velocity.
- r_i is the distance from a source point to the observer.
- M_r is the Mach number of the source toward the observer.

Appendix: FW-H steady model

where:

- L_i is the blade load vector.
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- v_n is the surface normal velocity.
- r_i is the distance from a source point to the observer.
- M_r. is the Mach number of the source toward the observer.

Accounting for Time-Lag

The major task in evaluating the FW-H integrals is how to account for the time-lag between emission and reception times.

The advanced time algorithm looks forward in time to see when the observer perceives the currently generated sound waves:

- The procedure starts with a sequence of emission times (conveniently taken as the flow times).
- The source strengths are calculated (thickness surface noise and loading surface noise) at all source elements (faces of the integration surfaces) for a given emission time.
- The contribution of the sources is interpolated in the far-field time domain to build the sound signal.

The total sound pressure the observer perceives consists of the contribution from all source elements. The sound pressure at the receiver is obtained by accumulating the arriving signals in time slots. The overall observer acoustic signal is found from the summation of the acoustic signal from each source element of the FW-H surface during the same source time.

Appendix: FW-H steady model

FW-H Volume Terms

The quadrupole noise is a volume distribution of sources, which accounts for nonlinearities in the flow.

These nonlinearities are of two types, as Lighthill described [186]. First, the local speed of sound is not constant, but varies due to particle acceleration. Second, the finite particle velocity near the body (for example blade) influences the velocity of sound propagation. When strong shear layers exist in the flow or when the Mach number increases, the quadrupole term is not negligible.

Farassat and Brentner [164] have shown that the noise contribution from the quadrupole, $\mathrm{p}'_Q(\bar{x},t)$, may be expressed as a "collapsing-sphere" formulation. Using this formulation, the space derivatives from Eqn. (1004) are transformed into time derivatives:

$$\mathrm{p}'_Q(\bar{x},t) = \frac{1}{4\pi}\left(\left(\frac{1}{c}\right)\left(\frac{\partial^2}{\partial t^2}\right)\int_{-\infty}^{t}\left[\int_{(f>0)}\frac{T_{rr}}{r}\,\mathrm{d}\,\Omega\right]\mathrm{d}\,\tau + \left(\frac{\partial}{\partial t}\right)\int_{-\infty}^{t}\left[\int_{(f>0)}\frac{3T_{rr}-T_{ii}}{r^2}\,\mathrm{d}\,\Omega\right]\mathrm{d}\,\tau\right) + \left(c\int_{-\infty}^{t}\left[\int_{(f>0)}\frac{3T_{rr}-T_{ii}}{r^3}\,\mathrm{d}\,\Omega\right]\mathrm{d}\,\tau\right) \quad \textbf{(1019)}$$

where:

- T_{rr} is the double contraction of T_{ij}.
- r_i and r_i are the components of the unit vector in the direction of radiation.
- T_{ij} is the Lighthill stress tensor.

Eqn. (1019) is transformed from a collapsing-sphere formulation to an advanced time formulation using equations Eqn. (1020), Eqn. (1021), Eqn. (1022) and Eqn. (1023). In these equations, the time derivatives at the observer are moved into the integrals to prevent numerical time differentiation of the integrals. The "source-time-dominant" algorithm from [167] is used to allow the estimation of the $\mathrm{p}'_Q(\bar{x},t)$ volume term of the FW-H equation as follows:

Appendix: FW-H steady model

$$p'_Q(\bar{x},t) = \frac{1}{4\pi}\left(\int_{(f>0)}\left[\frac{K_1}{c^2 r} + \frac{K_2}{c r^2} + \frac{K_3}{r^3}\right]_{ret} \mathrm{d}V\right) \quad \textbf{(1020)}$$

$$K_1 = K_{11} + K_{12} + K_{13} = \left[\frac{\ddot{T}_{rr}}{(1-M_r)^3}\right] + \left[\frac{\ddot{M}_r T_{rr} + 3\dot{M}_r \dot{T}}{(1-M_r)^4}\right] + \left[\frac{3\dot{M}_r^2 T_{rr}}{(1-M_r)^5}\right] \quad \textbf{(1021)}$$

$$K_1 = K_{21} + K_{22} + K_{23} + K_{24} = \left[\frac{-\dot{T}_{ii}}{(1-M_r)^2}\right] + \left[\frac{4\dot{T}_{M_r} + 2T_{\dot{M}_r} + \dot{M}_r T_{ii}}{(1-M_r)^3}\right] + \left[\frac{3\left[\left(1-M^2\right)\dot{T}_{rr} - 2\dot{M}_r T_{Mr} - M_i \dot{M}_i T_{rr}\right]}{(1-M_r)^4}\right] + \left[\frac{6\dot{M}_r\left(1-M^2\right)T_{rr}}{(1-M_r)^5}\right] \quad \textbf{(1022)}$$

$$K_3 = K_{31} + K_{32} + K_{33} = \left[\frac{2T_{MM} - \left(1-M^2\right)T_{ii}}{(1-M_r)^3}\right] - \left[\frac{6\left(1-M^2\right)T_{Mr}}{(1-M_r)^4}\right] + \left[\frac{3\left(1-M^2\right)^2 T_{rr}}{(1-M_r)^5}\right] \quad \textbf{(1023)}$$

and:

$$T_{rr} = T_{ij} r_i r_j \quad \textbf{(1024)}$$

Appendix: FW-H steady model

$$T_{MM} = T_{ij}M_iM_j \tag{1025}$$

$$T_{Mr} = T_{ij}M_ir_j \tag{1026}$$

$$T_{\dot{M}r} = T_{ij}\dot{M}_ir_j \tag{1027}$$

$$\dot{T}_{Mr} = \dot{T}_{ij}M_ir_j \tag{1028}$$

$$\dot{T}_{rr} = \dot{T}_{ij}r_ir_j \tag{1029}$$

$$\ddot{T}_{rr} = \ddot{T}_{ij}r_ir_j \tag{1030}$$

$$M_i = \frac{v_i}{c} \tag{1031}$$

$$M_r = M_ir_i \tag{1032}$$

$$\dot{M}_r = \dot{M}r_i \tag{1033}$$

Appendix: FW-H steady model

$$M_i = \frac{v_i}{c} \tag{1031}$$

$$M_r = M_i r_i \tag{1032}$$

$$\dot{M}_r = \dot{M} r_i \tag{1033}$$

$$\ddot{M}_r = \ddot{M}_i r_i \tag{1034}$$

$$\ddot{M}_{rr} = \ddot{M} r_i r_i \tag{1035}$$

$$r_i = \frac{x_i - y_i}{r} \tag{1036}$$

where:

- r_i denotes the unit vector in the direction of radiation.
- A dot above a variable denotes the time derivative with respect to source time of that variable.

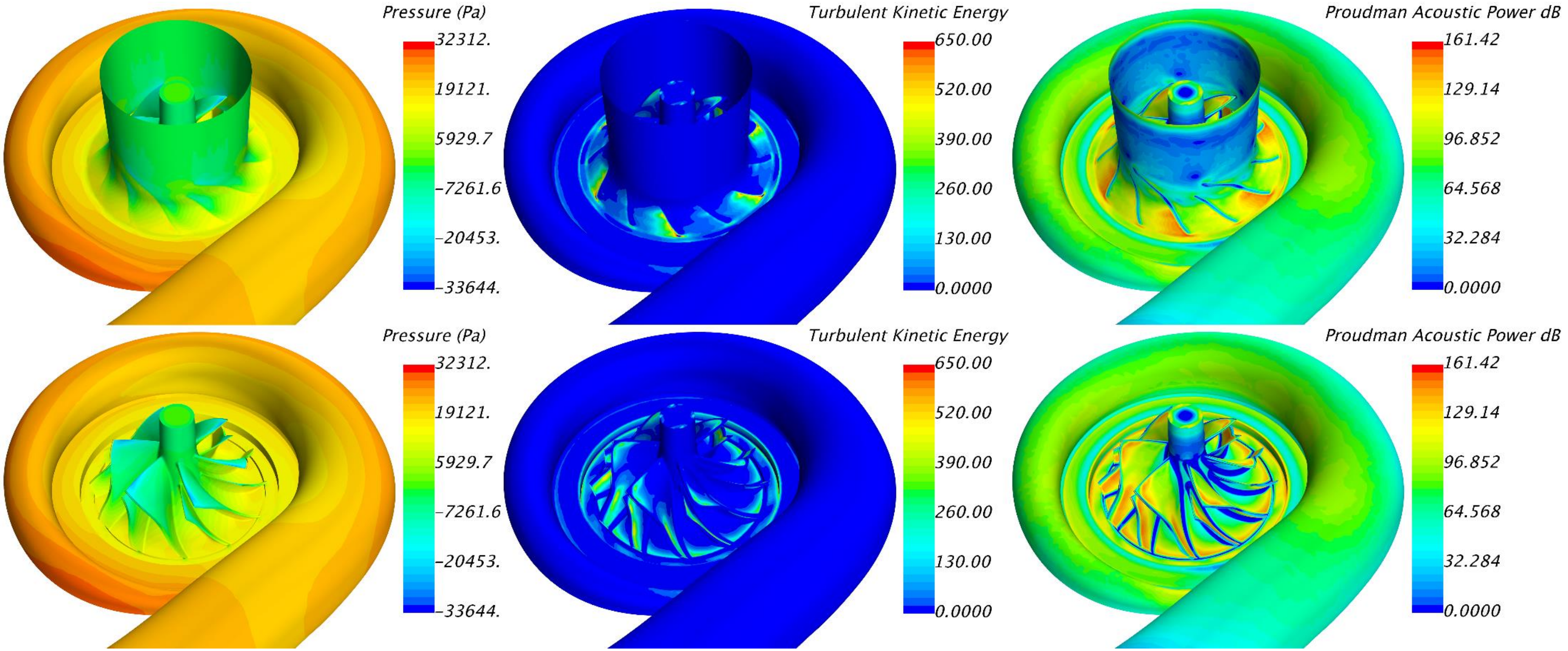
Broadband noise source models

Implicit to RANS turbulence modelling (isotropic turbulence assumption):

- Turbulence-generated flow noise;
- Volume distribution of quadrupole sources, Surface distribution of dipole sources. Contributions to total acoustic power;
- Curle model: noise from turbulent boundary layer flow over surfaces (fluctuating surface pressures);
- Proudman model: noise from turbulent flow;
- Aim: to localize areas where it is necessary to optimize the mesh, to capture flow-generated aeroacoustic sources and frequencies of interest (mesh frequancy cut-off);

$$f_{MC} = \frac{\sqrt{\frac{2}{3}k}}{2\left(V_{cell}\right)^{1/3}}$$

Appendix: Initial correlations



Appendix: efficiency map