Evaluation of Wall Pressure Spectrum Models for Fan Noise Prediction

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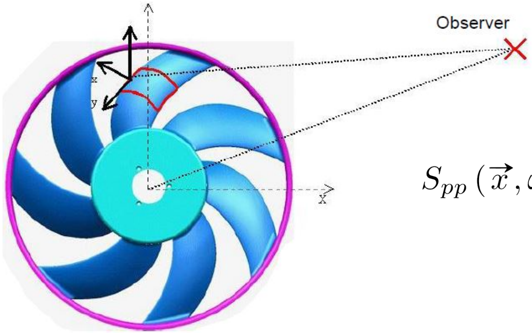
Introduction

- Noise pollution is an increasing concern
- Various applications from low speed ventilation to high speed turboengine fan systems
- CAA captures tonal and broadband noise sources at low and medium frequencies
- High frequency broadband noise mechanism more expensive
- Low-order noise method for noise prediction of turbomachinery applications

Contents

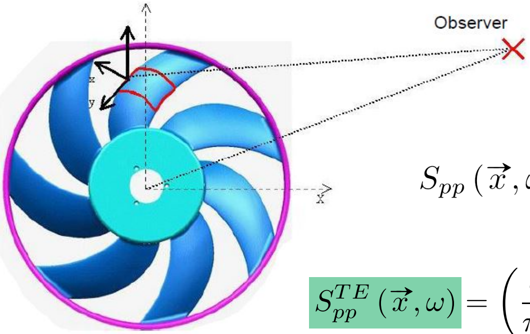
Low-order noise modelling

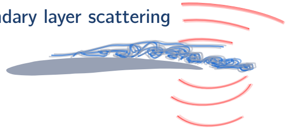


$$S_{pp}(\vec{x},\omega) = \sum_{k=0}^{N_s} \frac{B}{2\pi} \int_0^{2\pi} \left(\frac{\omega_e}{\omega}\right)^2 S_{pp}^k(\vec{x}(\phi),\omega_e)\, d\phi$$

- Blade split into strips : constant flow properties, airfoil noise emission
- Rotating noise sources computed from stationary airfoil noise (Amiet's approach)

Low-order noise modelling





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$$S_{pp}^{TE}(\vec{x},\omega) = \left(\frac{\omega b x_3}{\pi c_0 S_0^2}\right) d\, |\mathcal{L}^{TE}(\omega, U_e)|^2\, l_2(\omega)\ \Phi_{pp}(\omega, U_e, \ldots)$$

airfoil noise spectra

- Blade split into strips : constant flow properties, airfoil noise emission
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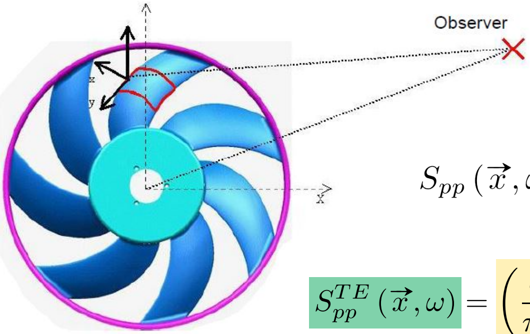
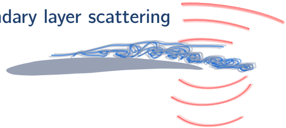


Boundary layer scattering



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airfoil span

$$S_{pp}^{TE}\left(\vec{x},\omega\right) = \left(\frac{\omega b x_3}{\pi c_0 S_0^2}\right) d \left|\mathcal{L}^{TE}\left(\omega, U_e\right)\right|^2 l_2\left(\omega\right)\ \Phi_{pp}\left(\omega, U_e, \ldots\right)$$

airfoil noise spectra — directivity — aeroacoustic transfer function

- Blade split into strips : constant flow properties, airfoil noise emission
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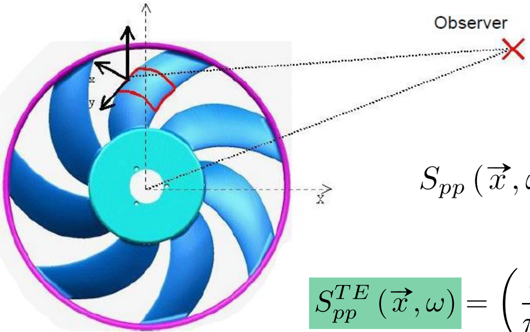
Low-order noise modelling



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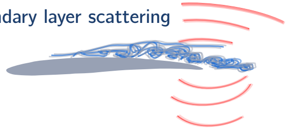

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airfoil noise spectra (S_{pp}^{TE}) — spanwise coherence length (l_2) — wall pressure spectrum (Φ_{pp})

- Blade split into strips : constant flow properties, airfoil noise emission
- Rotating noise sources computed from stationary airfoil noise (Amiet's approach)
- Statistical model for the turbulent noise sources

Wall pressure spectra approaches

- Pressure fluctuations at the wall are related to the turbulent velocity fluctuations.
- ϕ_{pp} are difficult to measure on rotating blade surface.
- Influenced by both Reynolds number and pressure gradient.
- Numerically challenging to accurately simulate
- Analytical modelling based on statistical approach (Kraichnan approach, Panton-Linebarger, TNO,...).
- Empirical approach aims at modelling the ϕ_{pp} spectral shape by calibration on parametric databases
- Fitting on airfoil and flat plate boundary layers $\longrightarrow$ Data-driven methods

Objectives

Evaluate different empirical models (from classical to recently developed advanced model) on 2 fan databases which are well documented

Wall pressure spectra modelling

Goody, Rozenberg and Lee models

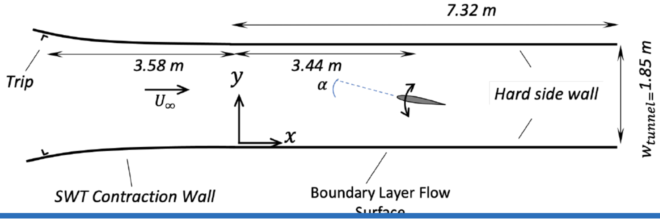
$$\beta_C = \frac{\theta}{\tau_w}\frac{dp}{dx}$$

$$Re_\theta = \frac{U_e\theta}{\nu}$$

- Scaling by outer and inner scales for low, medium and high frequency slopes respectively.
- Goody (2004): Flat plate database with ZPG, effect of Reynolds number. $Re_\theta \in [10^3, 10^4]$, $\beta_C = 0$
- Rozenberg (2012): Influence of low Reynolds and APG development of ad-hoc slope functions. $Re_\theta \simeq 10^3$, β_C up to 20.
- Lee (2018): Universal model, larger database. $Re_\theta \in [10^3, 10^4]$ β_C up to 20.

GEP models

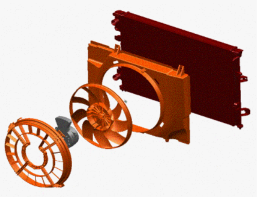
- Gene Expression Programming: evolutionary algorithm to develop mathematical expressions to reach best fit over a training database. (Shubham *et al.*, 2022, 2023)
- GEP (2022): Universal form as prescribed by Lee (2018) is coupled with random operators to be determined by the GEP.
- Large database of Virginia Tech SWT $Re_\theta > 10^4$, $\beta_C \in [-1, 1]$ (FPG, ZPG, APG).
- GEP (2023): Extension of the database to include lower Reynolds number based on CD airfoil DNS flow (Christophe, Deuse) with $Re_\theta \simeq 10^3$ and β_C up to 10.

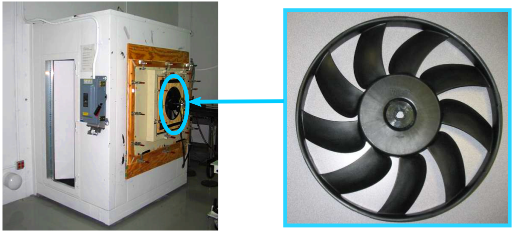


CD airfoil

H380EC01 Fan database

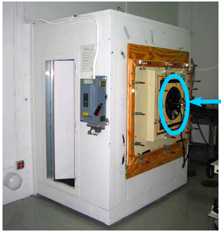
Fan configuration and databases

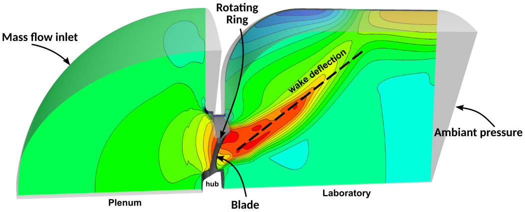




- Experimental campaigns
  - Valeo: acoustics and performances
  - MSU: Wake measurements (HW, PIV)

Fan configuration and databases





- Experimental campaigns
  - Valeo: acoustics and performances
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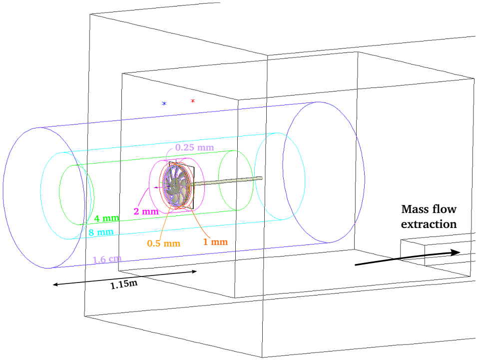
- ANSYS CFX 12 simulations
  - Incompressible and isothermal fluid
  - RANS $k-\omega$ SST
  - Structured mesh with $y^+ = 5$

Fan configuration and databases



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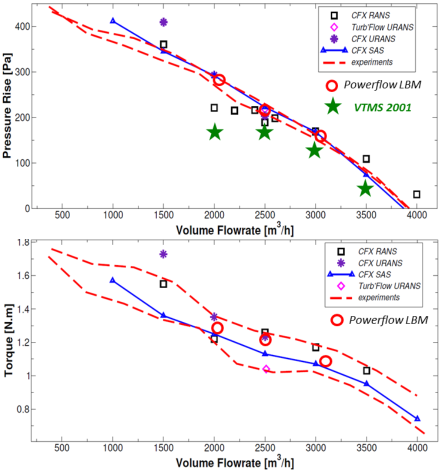
  - Valeo: acoustics and performances
  - MSU: Wake measurements (HW, PIV)
- ANSYS CFX 12 simulations
  - Incompressible and isothermal fluid
  - RANS $k - \omega$ SST
  - Structured mesh with $y^+ = 5$
- PowerFLOW 5.0a simulations
  - Wall modelled LBM
  - $y^+ \in [25, 50]$
  - Wall pressure spectra
  - Direct acoustics and FWH

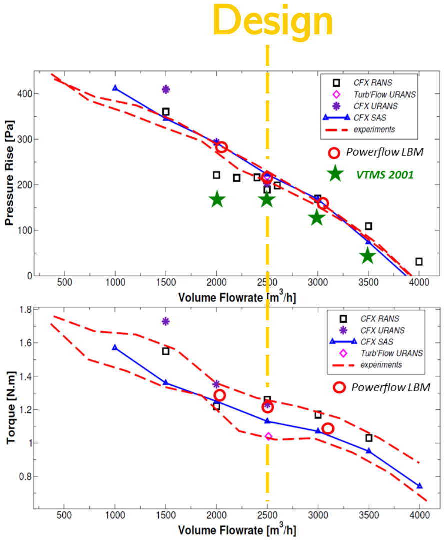
RANS and LBM databases

- RANS and LBM validated against experimental performances

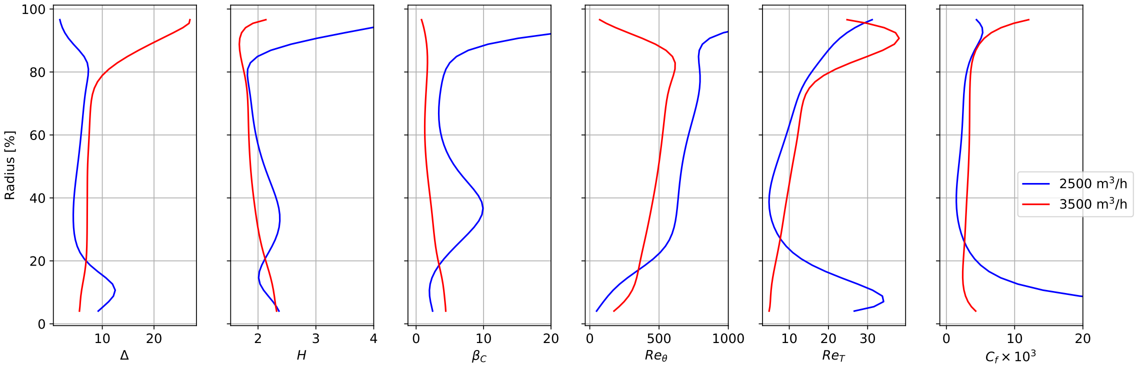


RANS and LBM databases

- RANS and LBM validated against experimental performances
- RANS simulations provide BL parameters on the blade suction side
- Experiments and LBM provide far-field noise
- LBM provide ϕ_{pp} on blade suction side (limited accuracy given y^+ resolution)



Boundary layer parameters



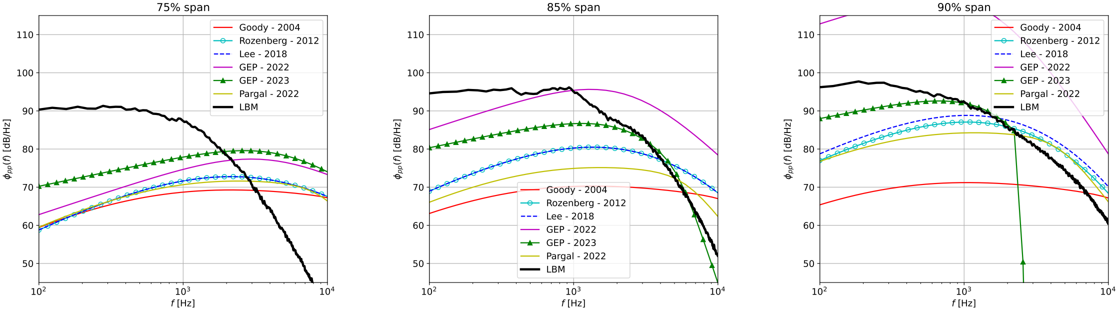
- Low range of $Re_\theta < 1000$
- Blade mainly loaded at the tip
- High levels of APG on the last 20% of the blade

$$\Delta = \delta/\delta^* \qquad H = \delta^*/\theta$$

$$C_f = \frac{\tau_w}{\frac{1}{2}\rho_\infty U_e^2}$$

$$R_T = (\delta/U_e)/(\mu/\tau_w)$$

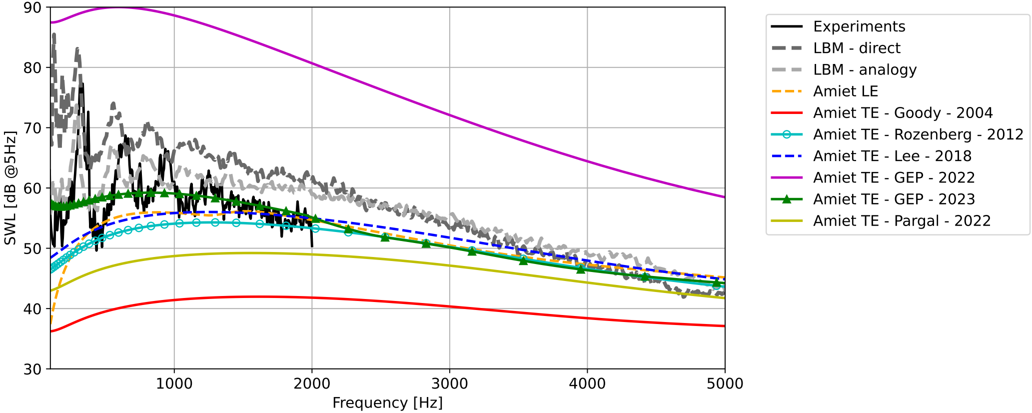
WPS comparison at design



Intermediate conclusions

- Goody's model fail to account for span loading
- Lee's and GEP-2023 models provide best levels
- GEP models have limited robustness

Acoustic predictions - design



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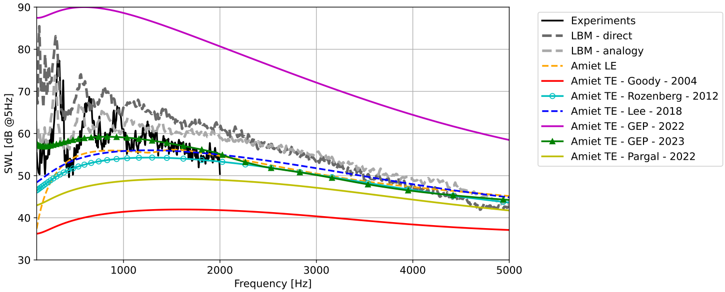
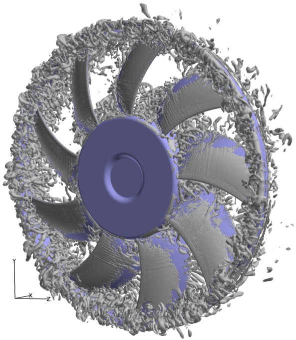




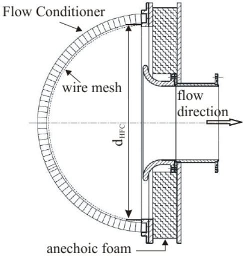
Intermediate conclusions

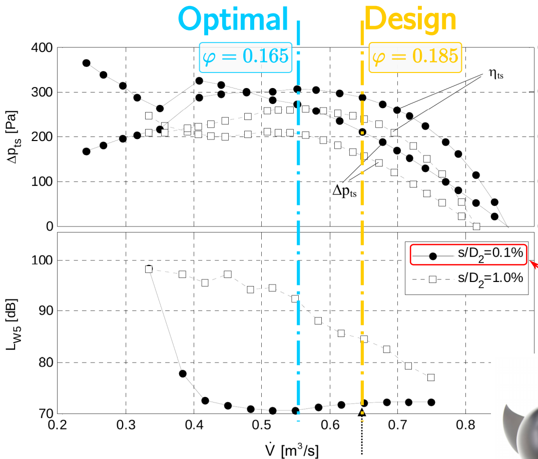
- Best performance for GEP-2023 and Lee's models
- Low frequency noise levels dominated by sub-harmonics humps

USI7 Fan database

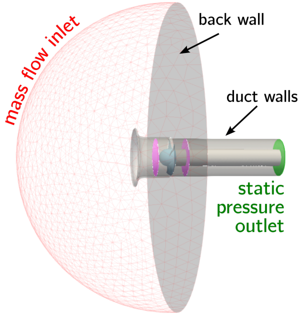
USI7 configuration

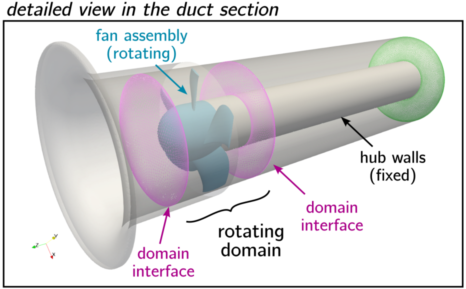
- Low speed fan compressor in duct-configuration (Carolus,2015)
- Huge influence of the tip gap size on aerodynamic and acoustic performances (Zhu, 2016)





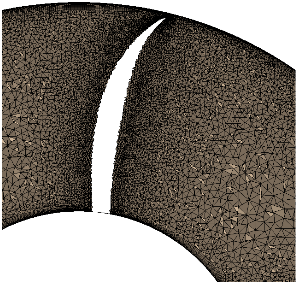
RANS simulations

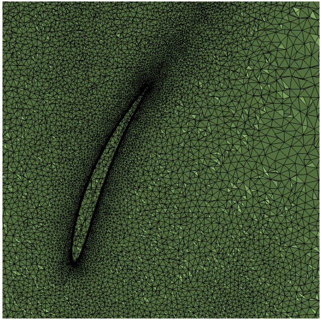




- RANS, ANSYS-CFX 2021.R2, incompressible
- Multiple reference frame
- Influence of the turbulence modelling: Fully turbulent ($k - \omega$ SST) and Transitional ($k - \omega$ SST γRe_θ)
- Unstructured mesh (prisms/tetra): v1 $y^+ \simeq 7$ and v2 $y^+ \simeq 1$

RANS simulations





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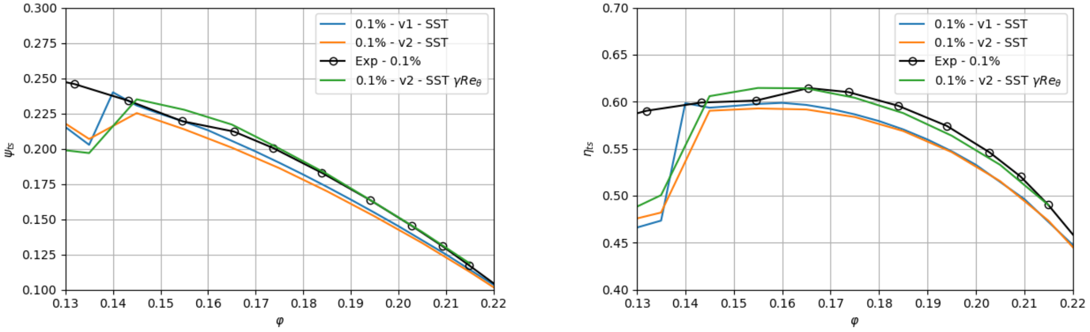
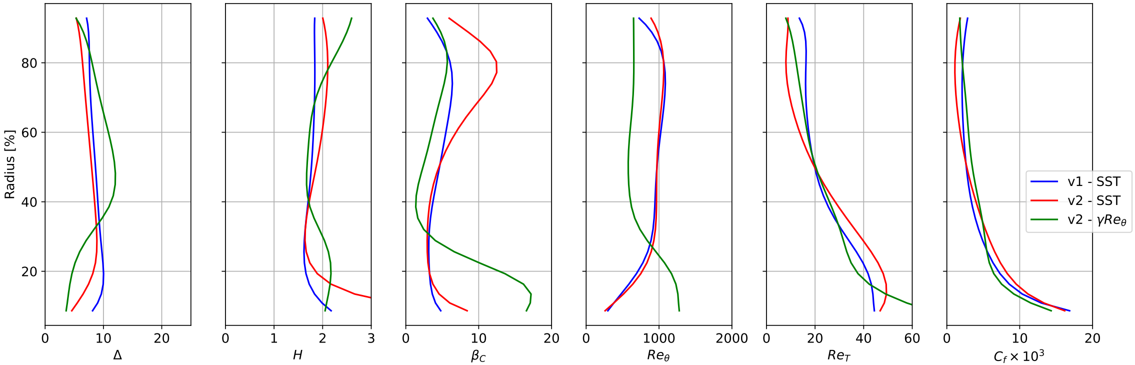
Overall performances



- Excellent agreement with experiments
- Limited mesh effects
- Transitional effects due to low-Reynolds number flow yield 2pt efficiency over a large range of flowrate

Boundary layer parameters



- $Re_\theta \simeq 1000$
- Quite uniform loading along the span
- High levels of APG over all the blade
- Influence of mesh resolution and turbulence modelling

$$\Delta = \delta/\delta^* \qquad H = \delta^*/\theta$$

$$C_f = \frac{\tau_w}{\frac{1}{2}\rho_\infty U_e^2}$$

$$R_T = (\delta/U_e)/(\mu/\tau_w)$$

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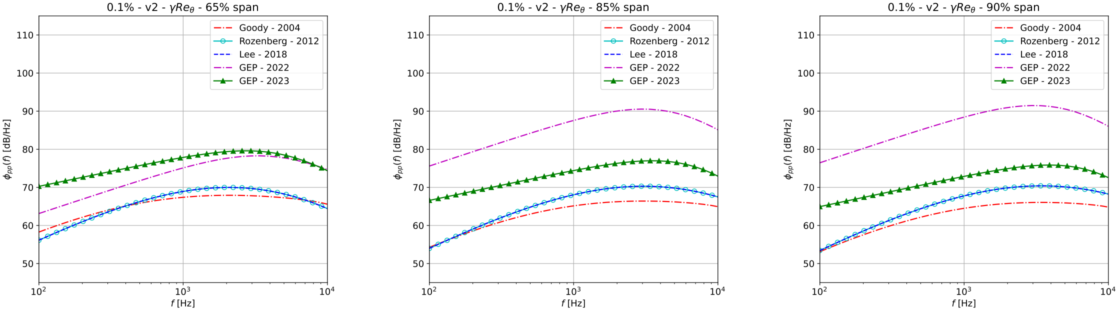
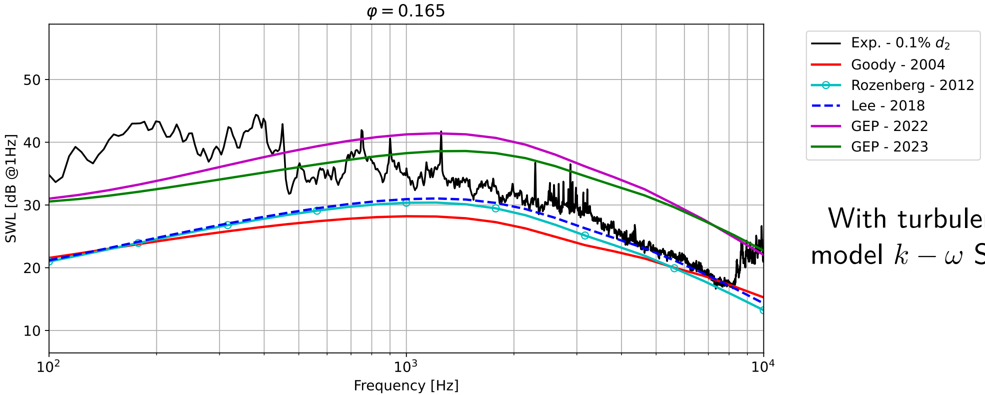


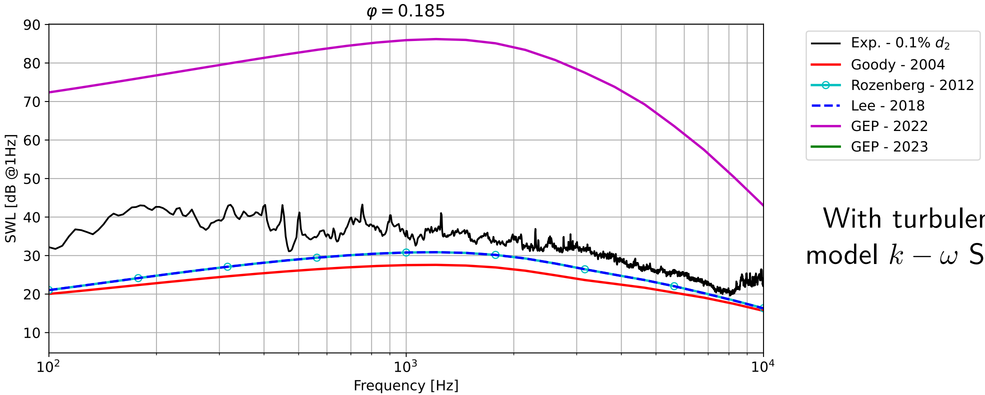
- Large discrepancies
- GEP-2022 levels exaggerated

Acoustic predictions



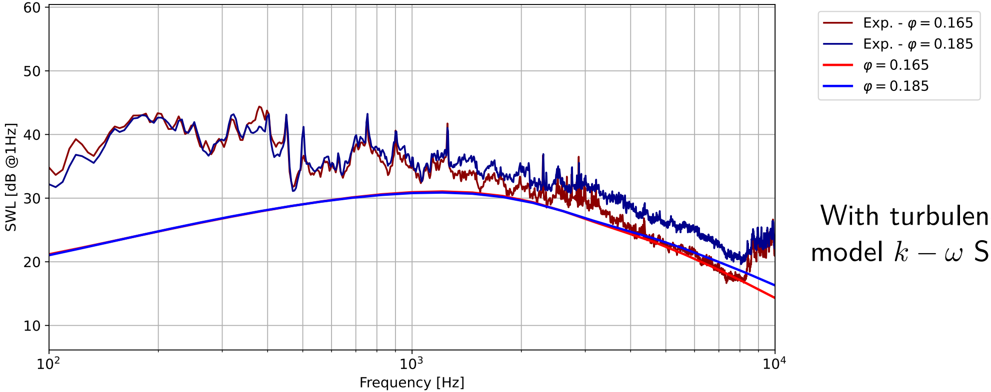
With turbulent model $k - \omega$ SST

Acoustic predictions



With turbulent model $k - \omega$ SST

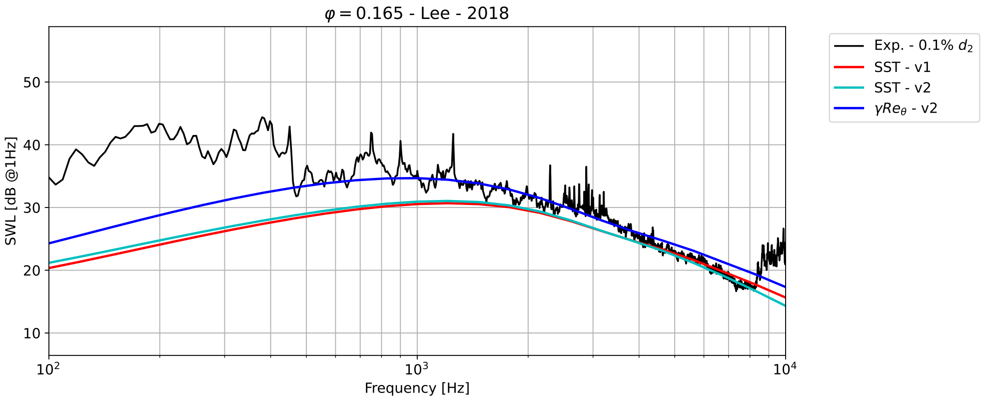
- GEP models largely over predict the noise level, GEP2023 diverges at design
- Best performance for Lee's model



With turbulence model $k - \omega$ SST

- Lee's model captures the right evolution with flowrate
- Best agreement with experiments for the most accurate flow solution.

Acoustic predictions - Lee's model sensibility



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- Best agreement with experiments for the most accurate flow solution.

Conclusions

Conclusions and perspectives

- Five classical and advanced empirical wall pressure spectra tested
- Low speed fan configurations
- Best performance for GEP-2023 and Lee's models on the H380 database
- GEP-2023 fails on the USI7 database (further from training range)
- Robustness of GEP models need to be improved
- Need for experimental and numerical wall pressure spectra databases for low-speed fan

Acknowledgement

Thank you ! Questions ?

Digital Research Alliance of Canada

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