EXTENDED USE OF ACOUSTIC INTEGRALS FOR SOUND PROPAGATION AND SOURCE LOCALIZATION

FERI FARASSAT MEMORIAL SYMPOSIUM
– NEW CHALLENGES IN AEROACOUSTICS –

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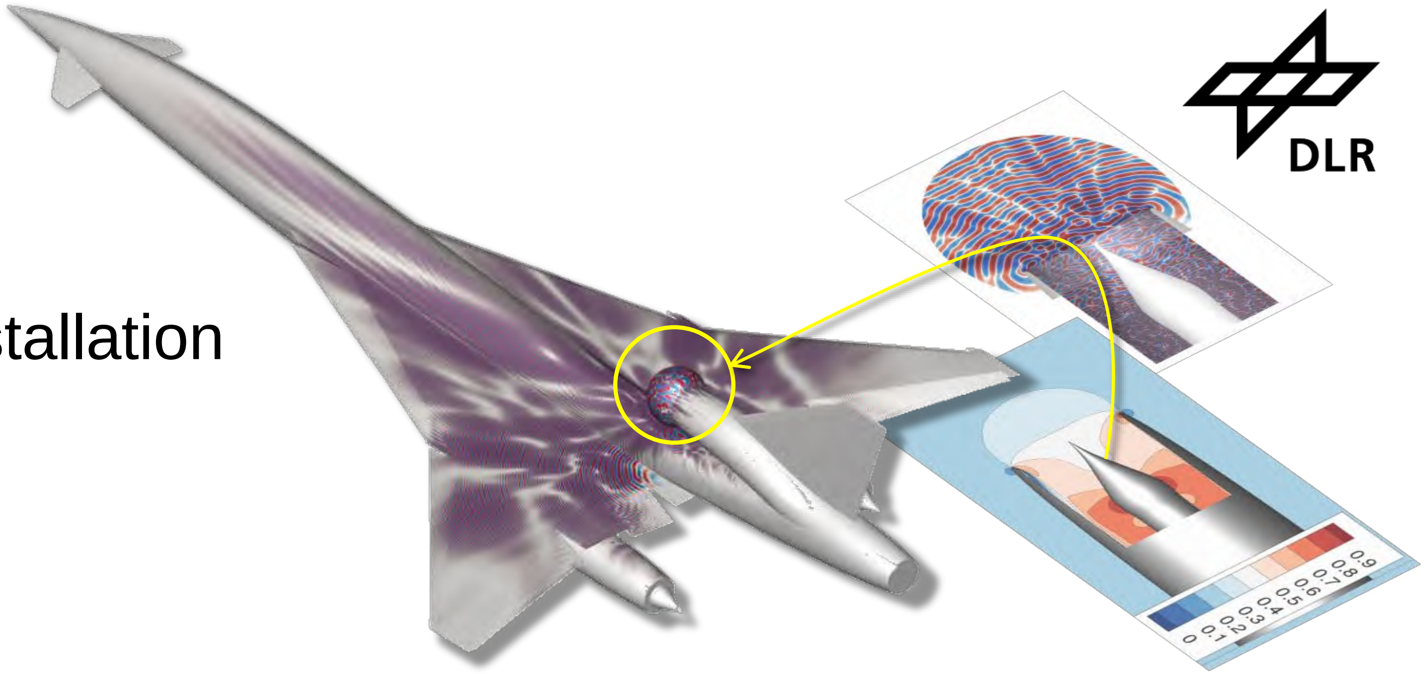
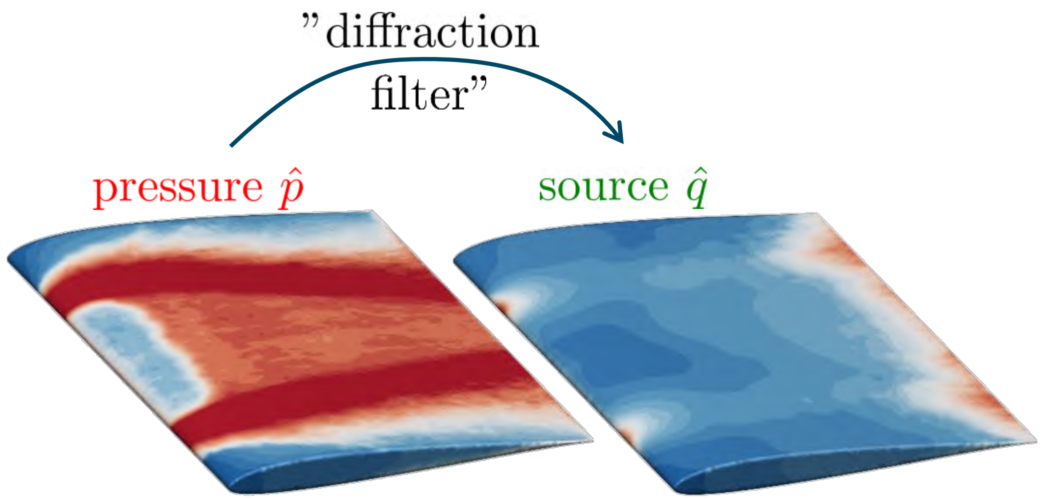
Outline

- Radiation subject to acoustic installation and locally nonuniform flow

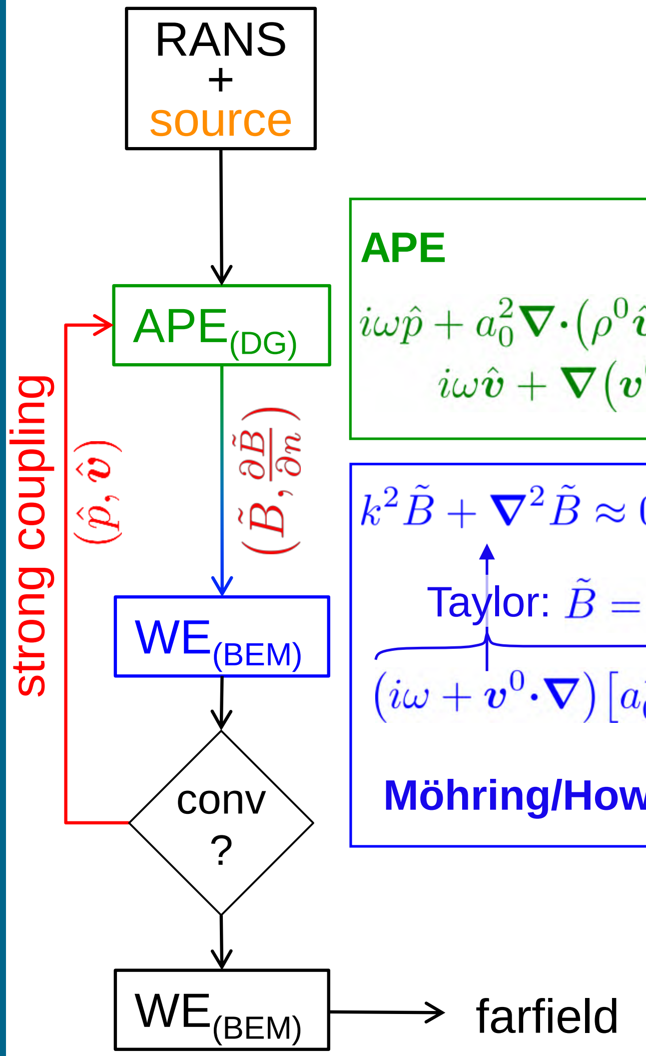


- Direct use of FW-H/Kirchhoff integrals for source localization on surfaces subject to turbulence



Radiation subject to acoustic installation and locally nonuniform flow

Problem and simulation concept



APE

$$i\omega\hat p + a_0^2\boldsymbol\nabla\cdot(\rho^0\hat{\boldsymbol v} + \boldsymbol v^0\hat p/a_0^2) = (\gamma-1)\hat\vartheta + a_0^2\hat m/\gamma$$

$$i\omega\hat{\boldsymbol v} + \boldsymbol\nabla\left(\boldsymbol v^0\cdot\hat{\boldsymbol v} + \hat p/\rho^0\right) = \hat f/\rho^0$$

high flow non-uniformity

low flow non-uniformity

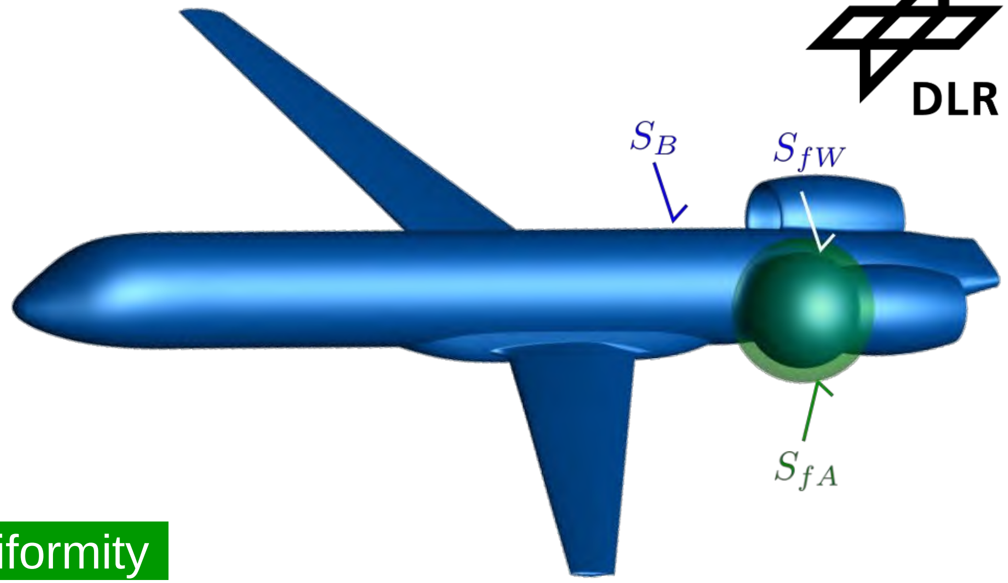
$$k^2\tilde B + \boldsymbol\nabla^2\tilde B \approx 0$$

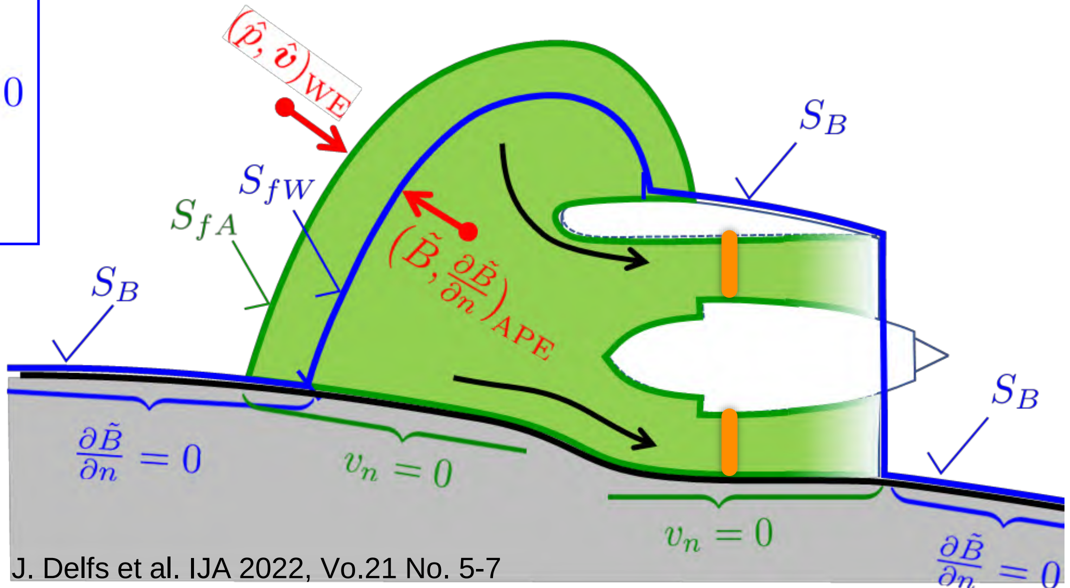
Taylor: $\tilde B = \hat B \exp\left(-i\omega\phi^0/a_0^2\right)$

$$\left(i\omega + \boldsymbol v^0\cdot\boldsymbol\nabla\right)\left[a_0^{-2}\left(i\omega\hat B + \boldsymbol v^0\cdot\boldsymbol\nabla\hat B\right)\right] - (\rho^0)^{-1}\boldsymbol\nabla\cdot(\rho^0\boldsymbol\nabla\hat B) = 0$$

Möhring/Howe $\hat B = \hat p/\rho^0 + \boldsymbol v^0\cdot\hat{\boldsymbol v}$

DISCO++
FMCAS





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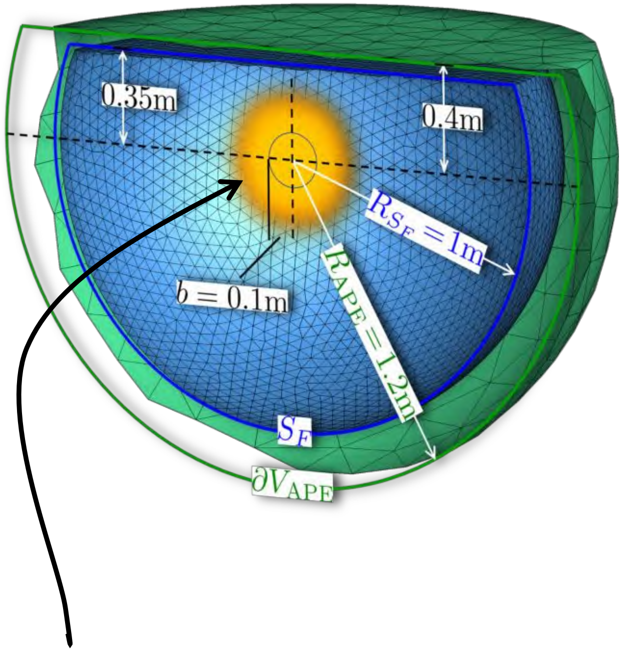
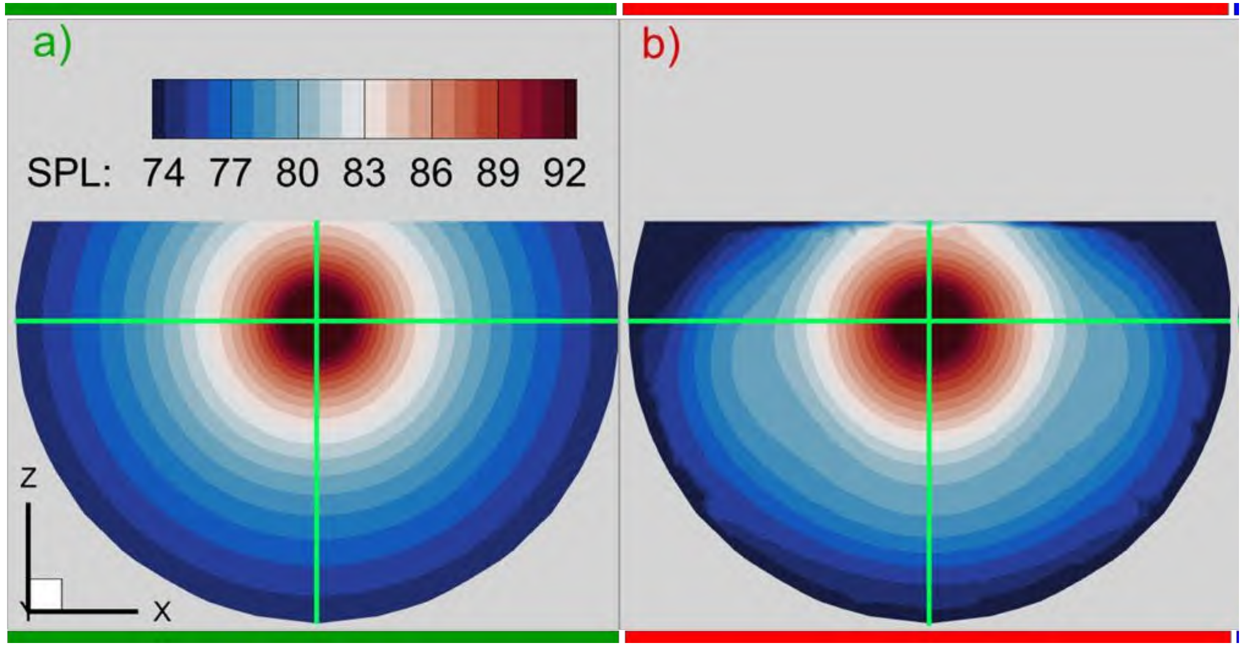
Non reflecting boundaries at very small DG domains

test case



harmonic
heat source
Gaussian type

DG-BEM strongly coupled | DG uncoupled



- large error for uncoupled DG (shallow incidence effects, near field effects)
- perfect free field condition (even in nearfield) on arbitrary domain DG-BEM coupling

→ **very small DG domains possible**

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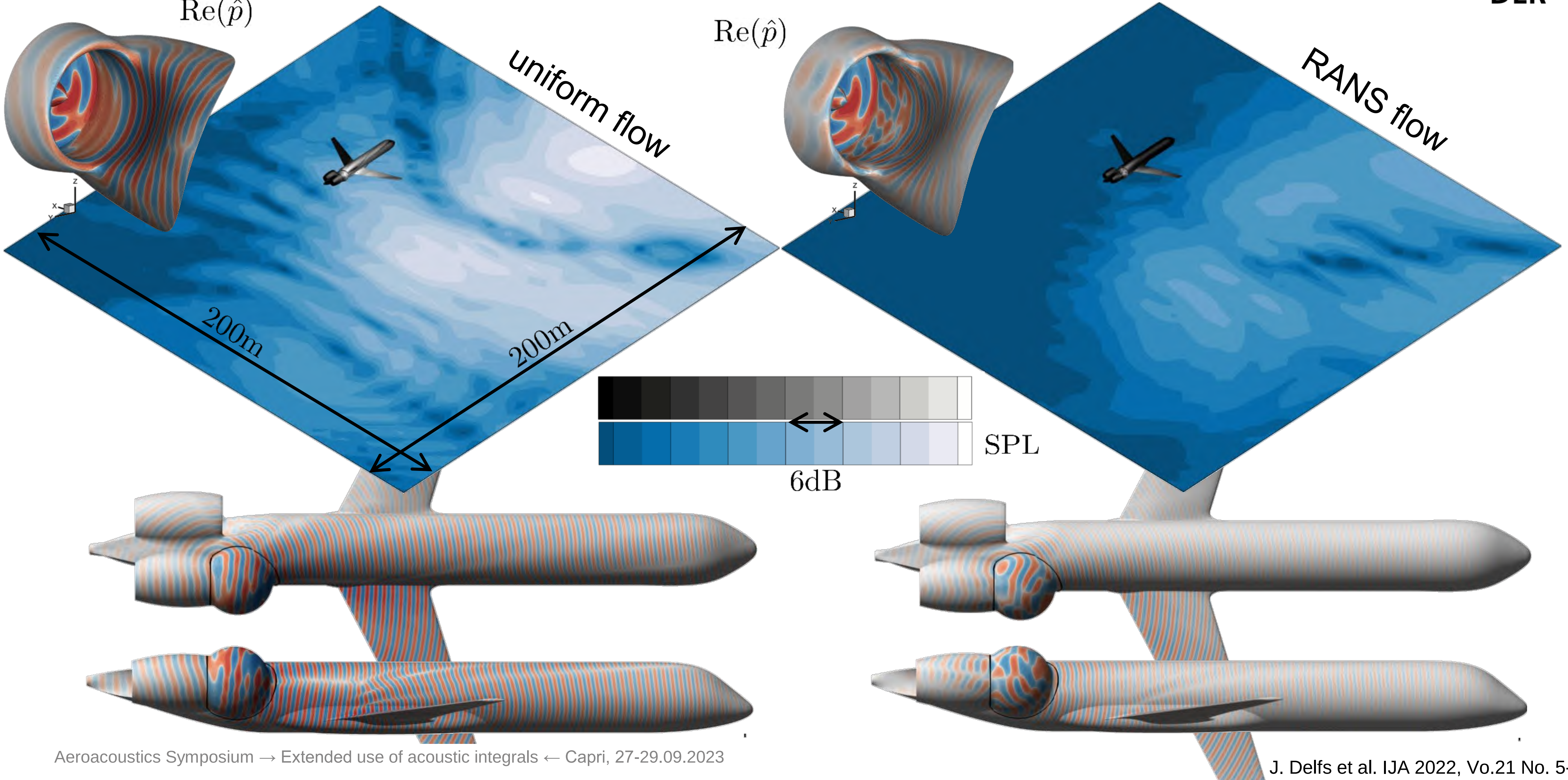
Significance of non-uniform flow



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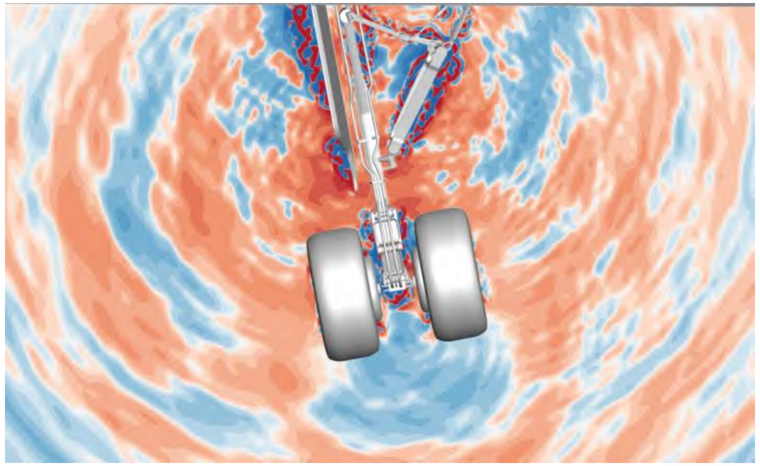
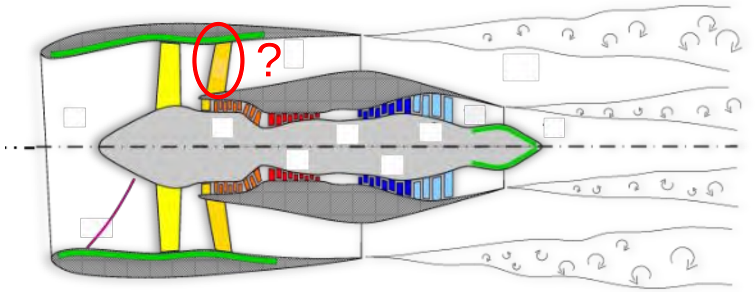
Direct use of FW-H/Kirchhoff integrals for source localization on surfaces subject to turbulence

Motivation for more research into identification/localization of sources

Given the fluctuating pressure on an aerodynamic surface:

- Where exactly happens the sound **generation** inside a complex structure ?
- How unique are source maps from beamforming ?
- How much of the sound is **generated** at a highly installed component ?
- What is a „source of sound“ at all (T_{ij} being „the source of the source“) ?
  → Can one define a true source quantity on surfaces subject to turbulence ?
- Can one extract a „source indicator“ without propagation to the farfield ?
- Can one overcome assumptions in beamforming and do localization based on first principles ?





Concept for alternative source localization – governing equations

Solid surface FW-H equation (pressure form), surface at $f(\boldsymbol{x},t)=0$:

$$\frac{1}{a_\infty^2}\frac{\partial^2 Hp'}{\partial t^2}-\Delta(Hp')=Q_p^{FWH}-\boldsymbol{\nabla}\cdot\left(\left[-\boldsymbol{\tau}+p'\boldsymbol{I}\right]\boldsymbol{\nabla}f\delta(f)\right)+\frac{\partial}{\partial t}\left(\rho_\infty \boldsymbol{v}_B\cdot\boldsymbol{\nabla}f\delta(f)\right)$$

$$Q_p^{FWH}=\boldsymbol{\nabla}\cdot\boldsymbol{\nabla}\cdot\left[H(f)(\rho\boldsymbol{v}\boldsymbol{v}-\boldsymbol{\tau})\right]+\frac{\partial^2}{\partial t^2}\left[H(f)\left(\frac{p'}{a_\infty^2}-\rho'\right)\right]$$

$$\vdots$$

Equivalent rearrangement to Kirchhoff form:

$$\frac{1}{a_\infty^2}\frac{\partial^2 Hp'}{\partial t^2}-\Delta(Hp')=H(f)Q_p^{LH}-\boldsymbol{\nabla}\cdot\left(p'\boldsymbol{\nabla}f\delta(f)\right)-\boldsymbol{\nabla}p'\cdot\boldsymbol{\nabla}f\delta(f)-\frac{1}{a_\infty^2}\frac{\partial}{\partial t}\left(p'\boldsymbol{v}_B\cdot f\delta(f)\right)-\frac{1}{a_\infty^2}\frac{\partial p'}{\partial t}\boldsymbol{v}_B\cdot\boldsymbol{\nabla}f\delta(f)$$

$$Q_p^{LH}=\boldsymbol{\nabla}\cdot\boldsymbol{\nabla}\cdot\left[(\rho\boldsymbol{v}\boldsymbol{v}-\boldsymbol{\tau})\right]+\frac{\partial^2}{\partial t^2}\left[\left(\frac{p'}{a_\infty^2}-\rho'\right)\right]$$

Concept for alternative source localization – governing equations

Assume uniform motion, wind tunnel situation, low Mach No. (→ Curle), freq. domain:

$$\hat{p}(\boldsymbol{x}) = \hat{p}_f(\boldsymbol{x}) + \frac{1}{4\pi} \int\limits_{\partial V_B} \exp(-ikr)(ikr+1)\frac{\boldsymbol{e}_r \cdot \boldsymbol{n}}{r^2}\hat{p}(\boldsymbol{\xi}) - \underbrace{\frac{1}{r}\frac{\partial \hat{p}}{\partial n}}_{\approx 0} dS(\xi)$$

$$\hat{p}_f = \frac{1}{4\pi} \int\limits_{V_\infty^+} \frac{\hat{Q}_p^{LH}}{r} \exp(-ikr)\, dV(\xi)$$

free field signature of volume sources

$\boldsymbol{x}$ observer position

$\boldsymbol{\xi}$ source position

$r = |\boldsymbol{x} - \boldsymbol{\xi}|$

$\boldsymbol{e}_r = \boldsymbol{r}/r$

Concept for alternative source localization – source hypothesis

Sound is generated on those surface points where (locally) the mirror principle is violated

or: no sound **generation** by pure reflection of the incident pressure field $\hat{p}_f$
or: the source of sound on surfaces is **pure diffraction** of the incident pressure field $\hat{p}_f$

Choose observer point infinitely close to surface → singularity $r \to 0$

$$\boldsymbol{x} \in \partial V_B : \quad \hat{p}(\boldsymbol{x}) = \hat{p}_f(\boldsymbol{x}) + \frac{2\pi}{4\pi}\hat{p}(\boldsymbol{x}) + \frac{1}{4\pi} \fint_{\partial V_B} \exp(-ikr)(ikr+1)\frac{\boldsymbol{e}_r \cdot \boldsymbol{n}}{r^2}\hat{p}\; dS(\xi)$$

$$\boldsymbol{x} \in \partial V_B : \quad \hat{p}_S := \hat{p}(\boldsymbol{x}) - 2\hat{p}_f(\boldsymbol{x}) = \frac{1}{2\pi} \fint_{\partial V_B} \exp(-ikr)(ikr+1)\frac{\boldsymbol{e}_r \cdot \boldsymbol{n}}{r^2}\hat{p}\; dS(\xi)$$

„acoustic surface pressure“

diffraction filter $F_d[\hat{p}]$ on surface pressure

Acoustic surface pressure $\hat{p}_S$ and the surface source $\hat{q}$

Ensuring $\frac{\partial \hat{p}_S}{\partial n} \stackrel{!}{=} 0$ requires introduction to a surface source quantity $\hat{q}$

$$\hat{p}_S(\boldsymbol{x}) = 2\hat{q} + \frac{1}{2\pi} \fint_{\partial V_B} \exp(-ikr)(ikr+1)\frac{\boldsymbol{e}_r \cdot \boldsymbol{n}}{r^2} \hat{p}_S(\boldsymbol{\xi})\ dS(\xi)$$

$\Rightarrow \hat{p}_S$ is physically realizable pressure field

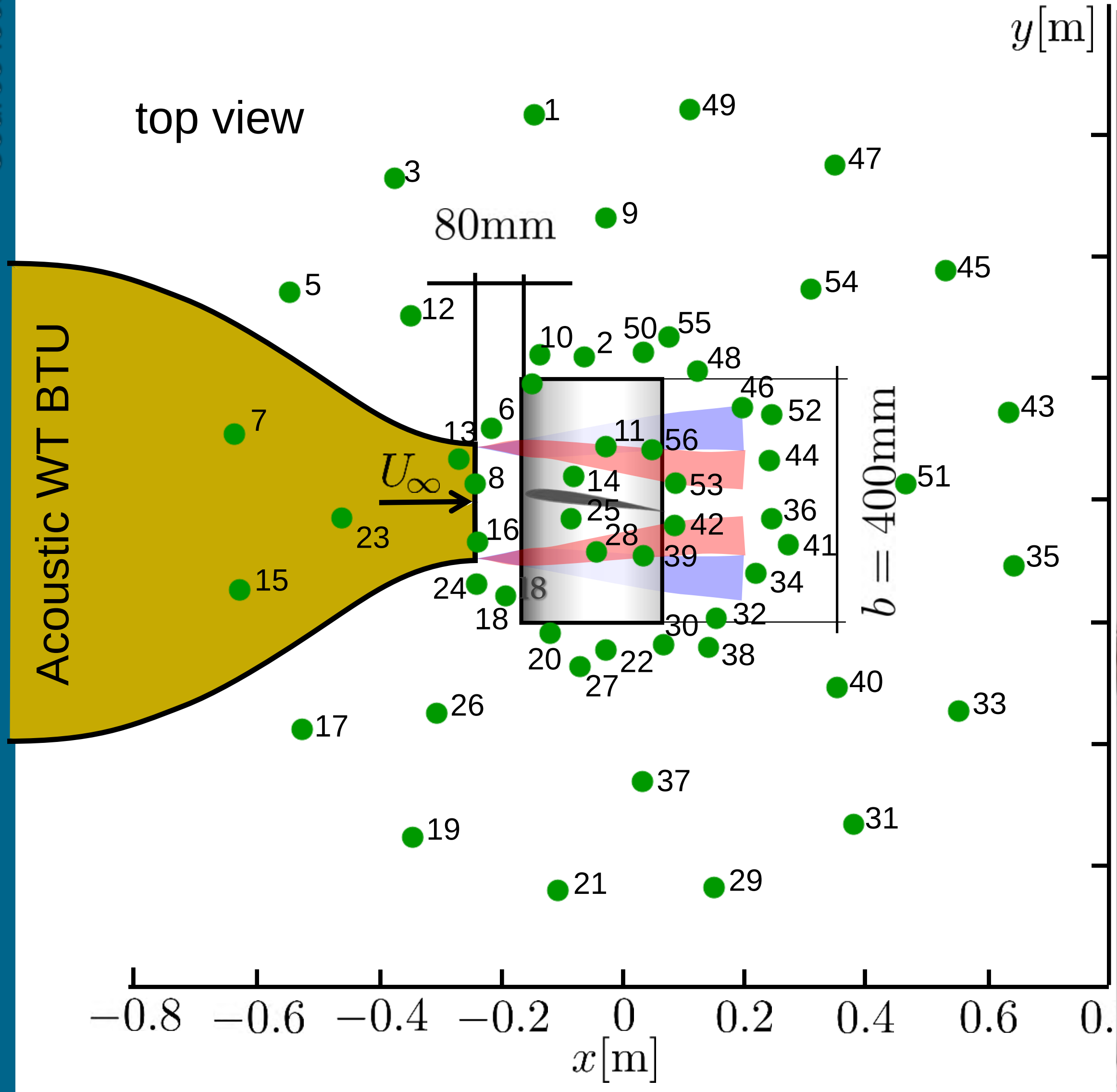
$$\hat{q}(\boldsymbol{x}) = \frac{1}{2\pi} \fint_{\partial V_B} \exp(-ikr)(ikr+1)\frac{\boldsymbol{e}_r \cdot \boldsymbol{n}}{r^2} \hat{p}_f(\boldsymbol{\xi})\ dS(\xi) = F_d[\hat{p}_f] = \tfrac{1}{2}\left(F_d[\hat{p}] - F_d^2[\hat{p}]\right)$$

the acoustic surface pressure is the diffraction filtered surface pressure: $\hat{p}_S = F_d[\hat{p}]$

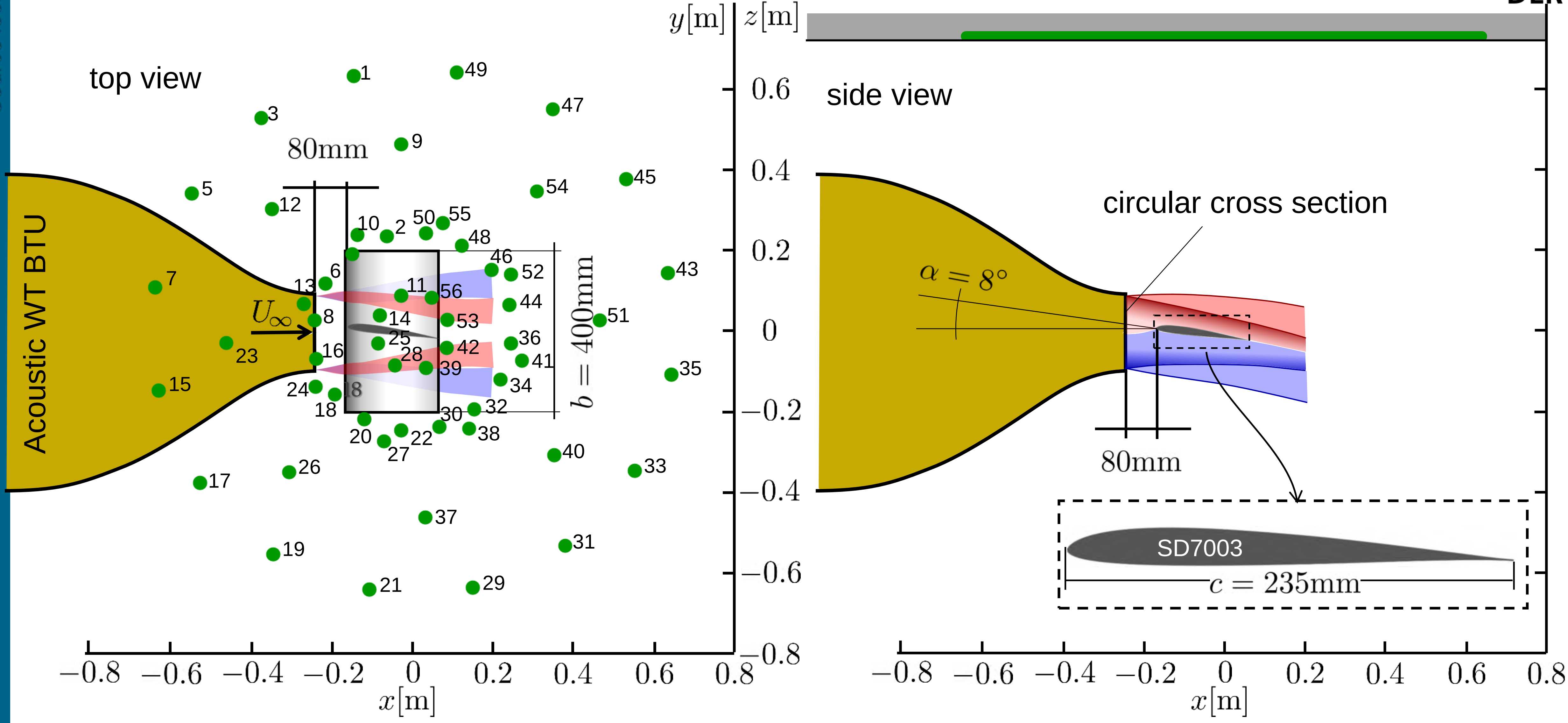
the surface source quantity is the diffraction filtered incident pressure $\hat{q} = F_d[\hat{p}_f]$

$$F_d[\hat{(.)}] = \frac{1}{2\pi} \fint_{\partial V_B} \exp(-ikr)(ikr+1)\frac{\boldsymbol{e}_r \cdot \boldsymbol{n}}{r^2} \hat{(.)}\ dS(\xi)$$

Test case airfoil edge noise

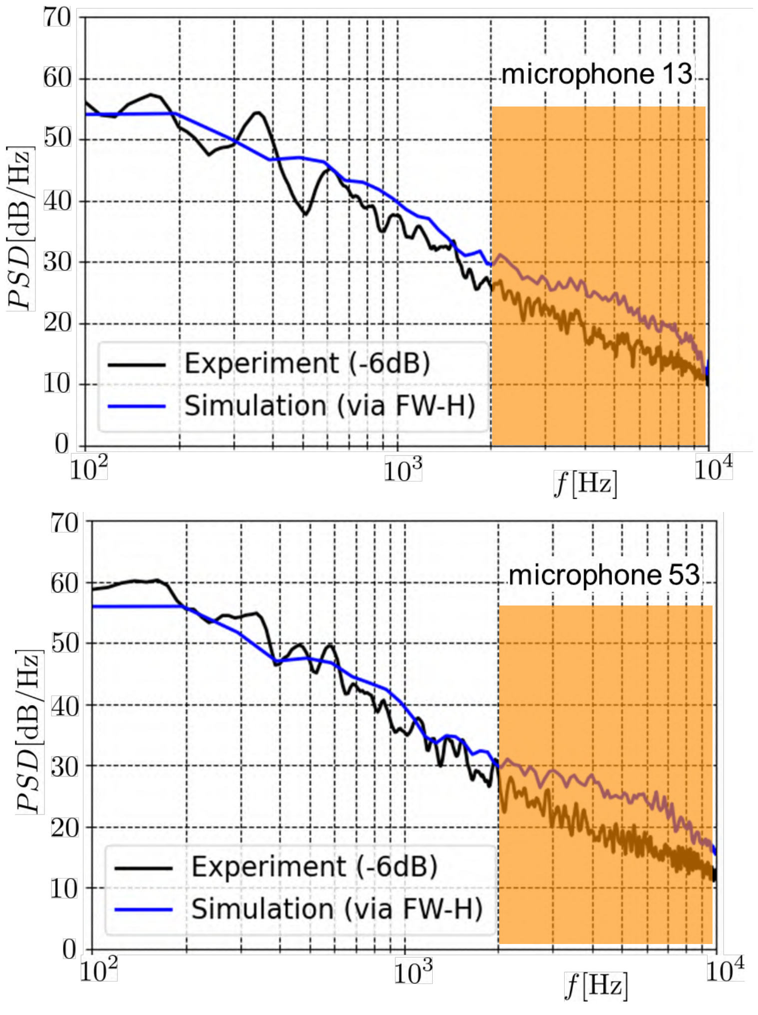


Test case airfoil edge noise

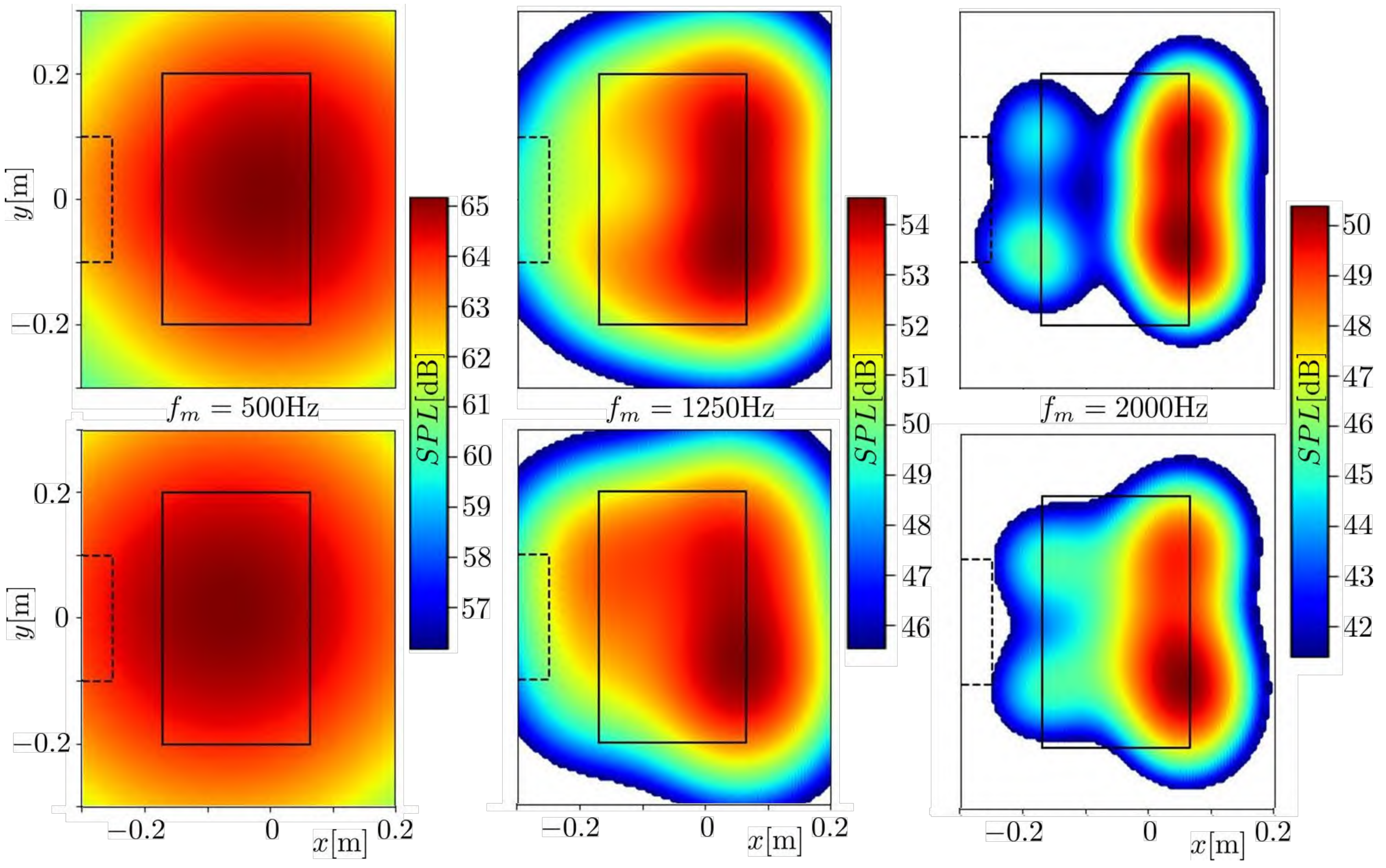


Test case airfoil edge noise – simulation data base

SRS/FW-H results, 23M polyeder cells, Siemens Star-CCM+, courtesy of ebmpapst

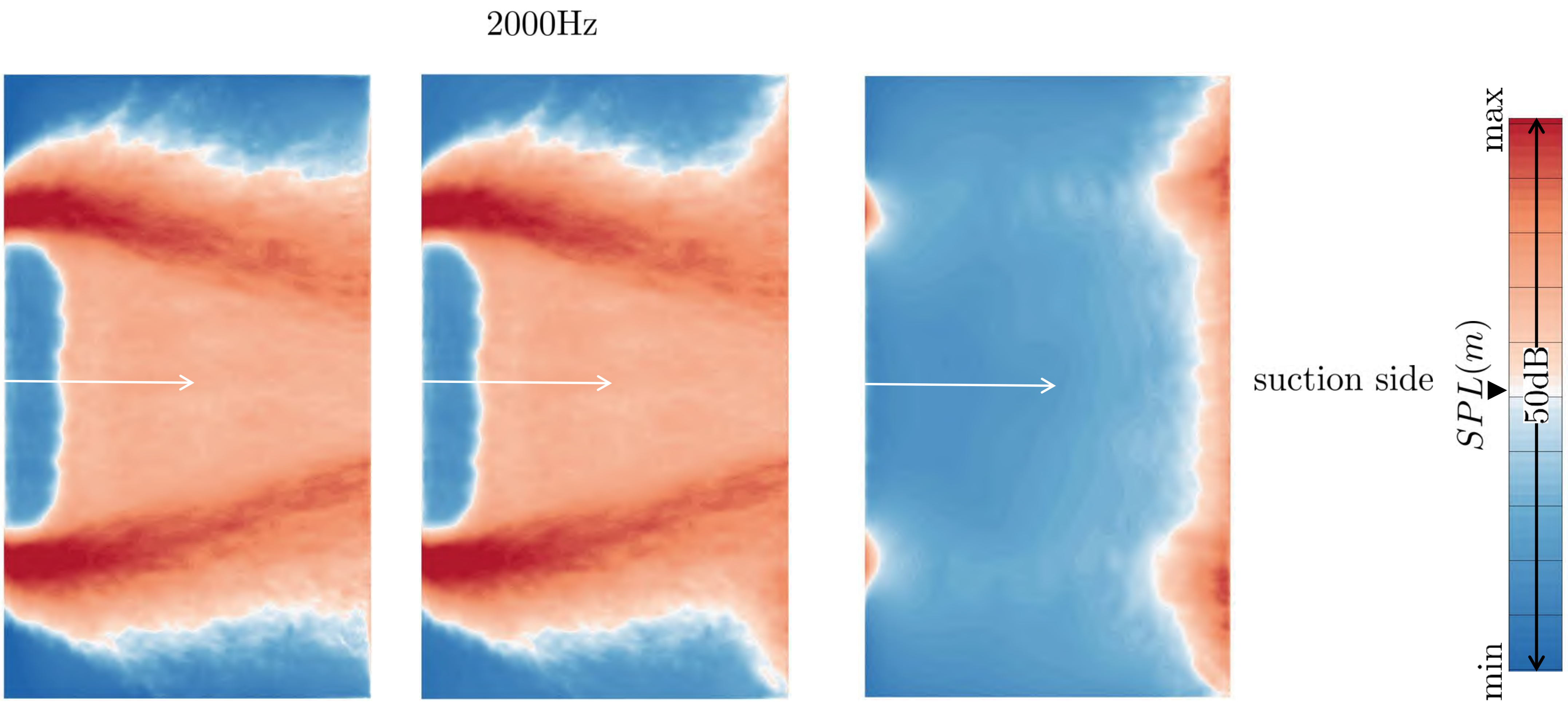


experiment



simulation

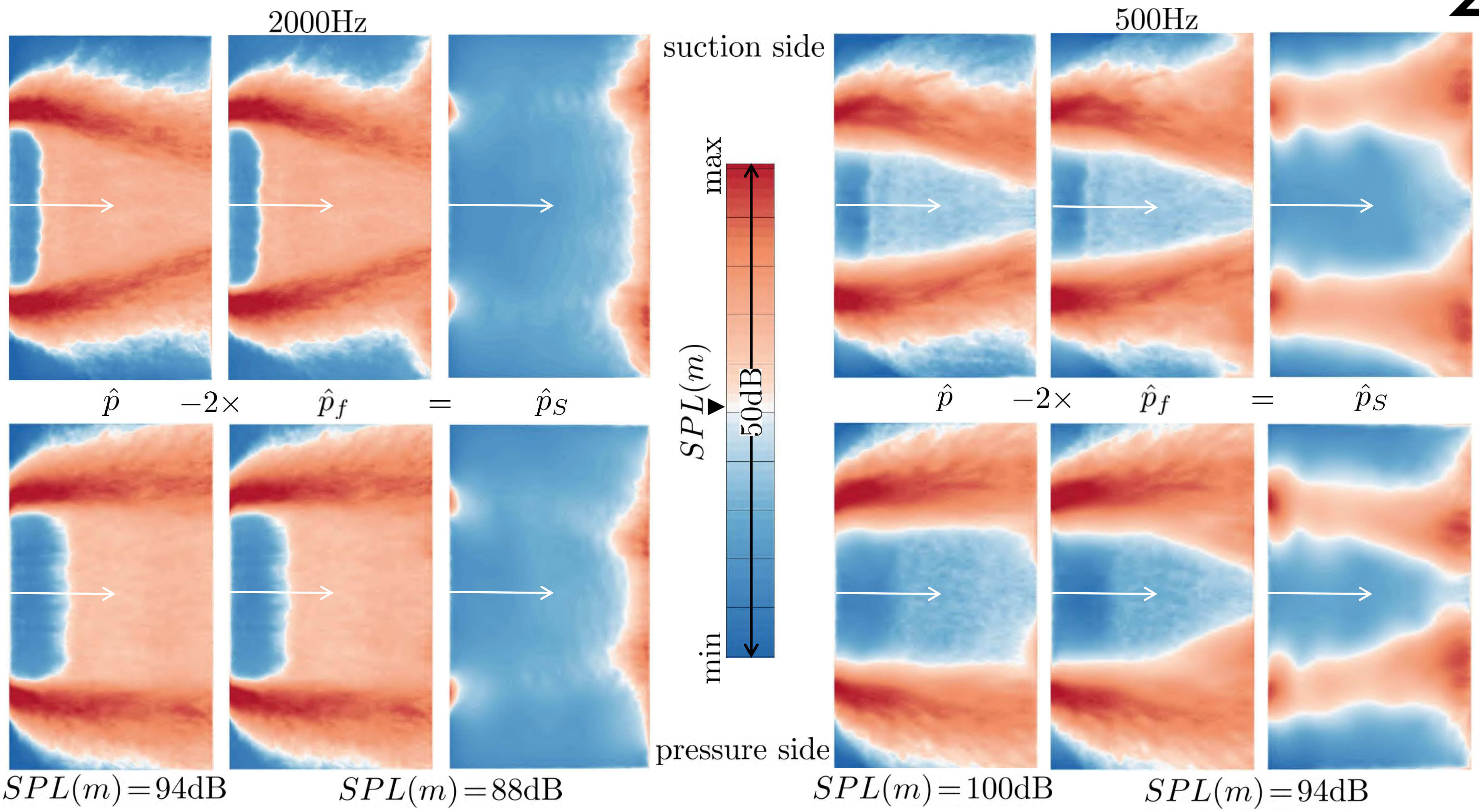
Results: acoustic surface pressure $\hat{p}_S$



$$\hat{p} \quad -2\times \quad \hat{p}_f \quad = \quad \hat{p}_S$$

$SPL(m) = 94\text{dB}$ $\qquad$ $SPL(m) = 88\text{dB}$

Results: acoustic surface pressure $\hat{p}_S$



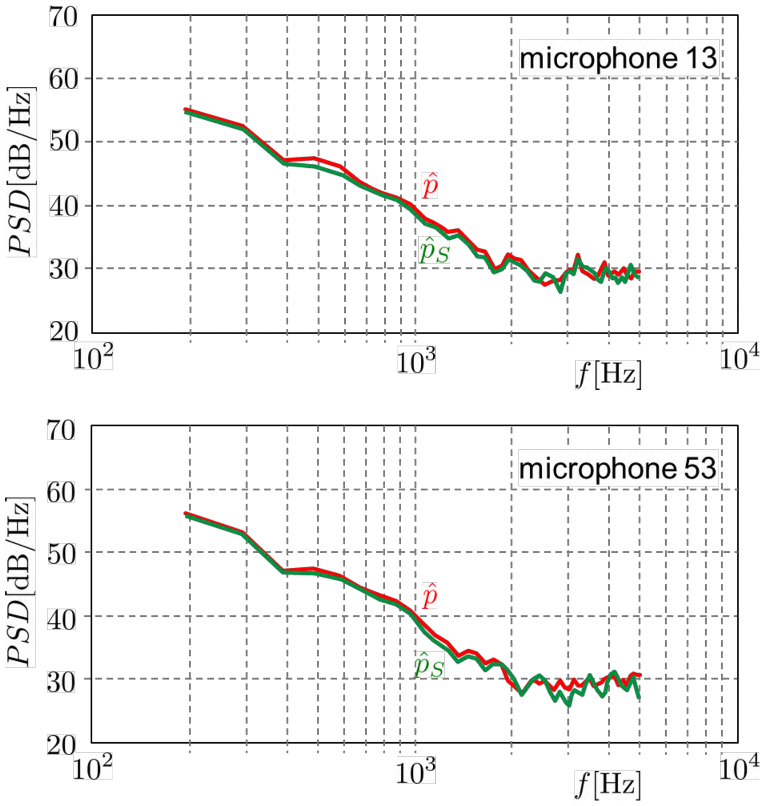
Concept validation – acoustic surface pressure

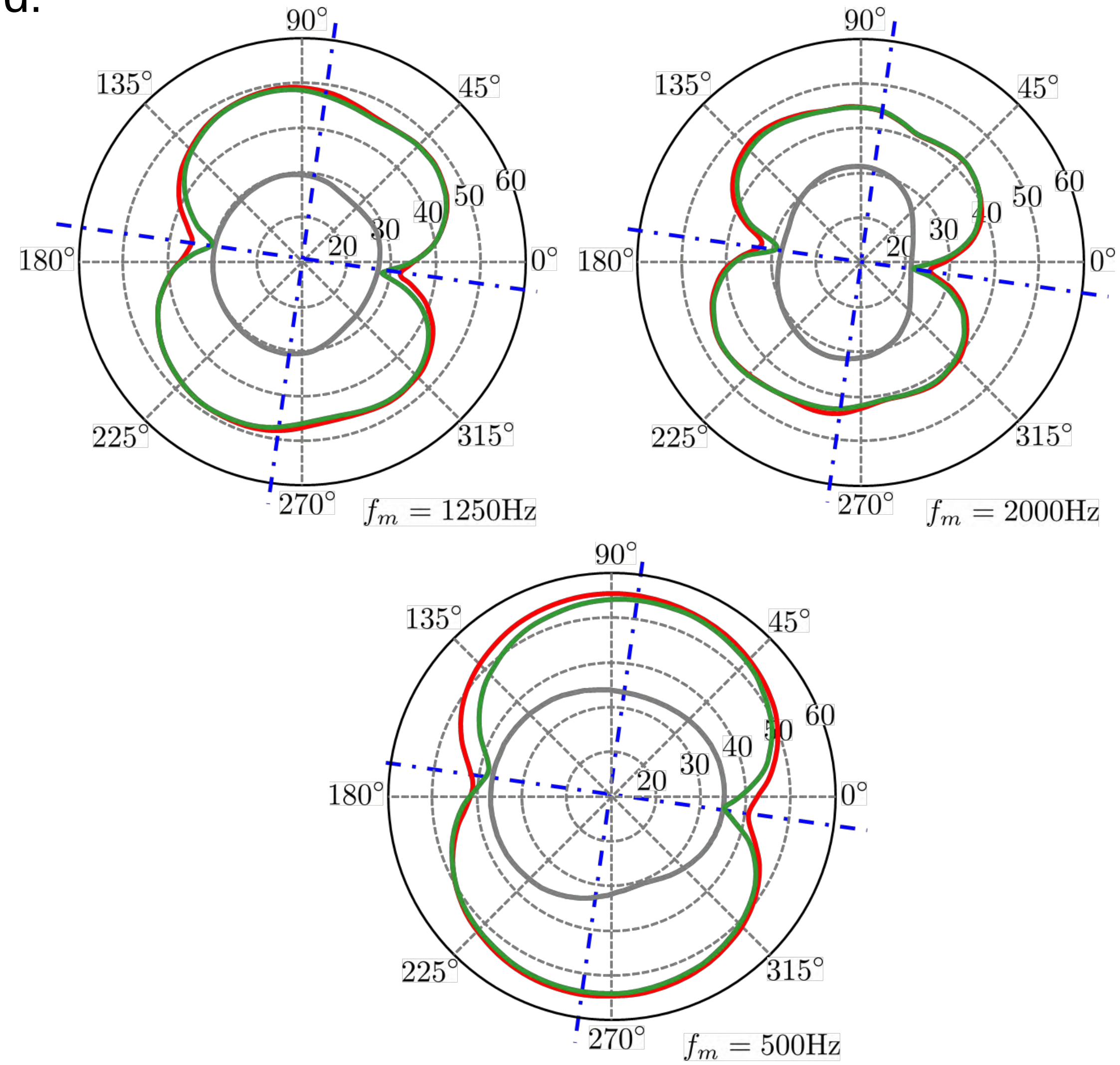
$$\hat{p}(\boldsymbol{x}) = \hat{p}_f + \frac{1}{4\pi}\int_{\partial V_B} \exp(-ikr)(ikr+1)\frac{\boldsymbol{e}_r\cdot\boldsymbol{n}}{r^2}\hat{p}_S(\boldsymbol{\xi})\, dS(\xi)$$

$$\hat{p}_S(\boldsymbol{x}) = \hat{q} + \frac{1}{4\pi}\int_{\partial V_B} \exp(-ikr)(ikr+1)\frac{\boldsymbol{e}_r\cdot\boldsymbol{n}}{r^2}\hat{p}_S(\boldsymbol{\xi})\, dS(\xi)$$

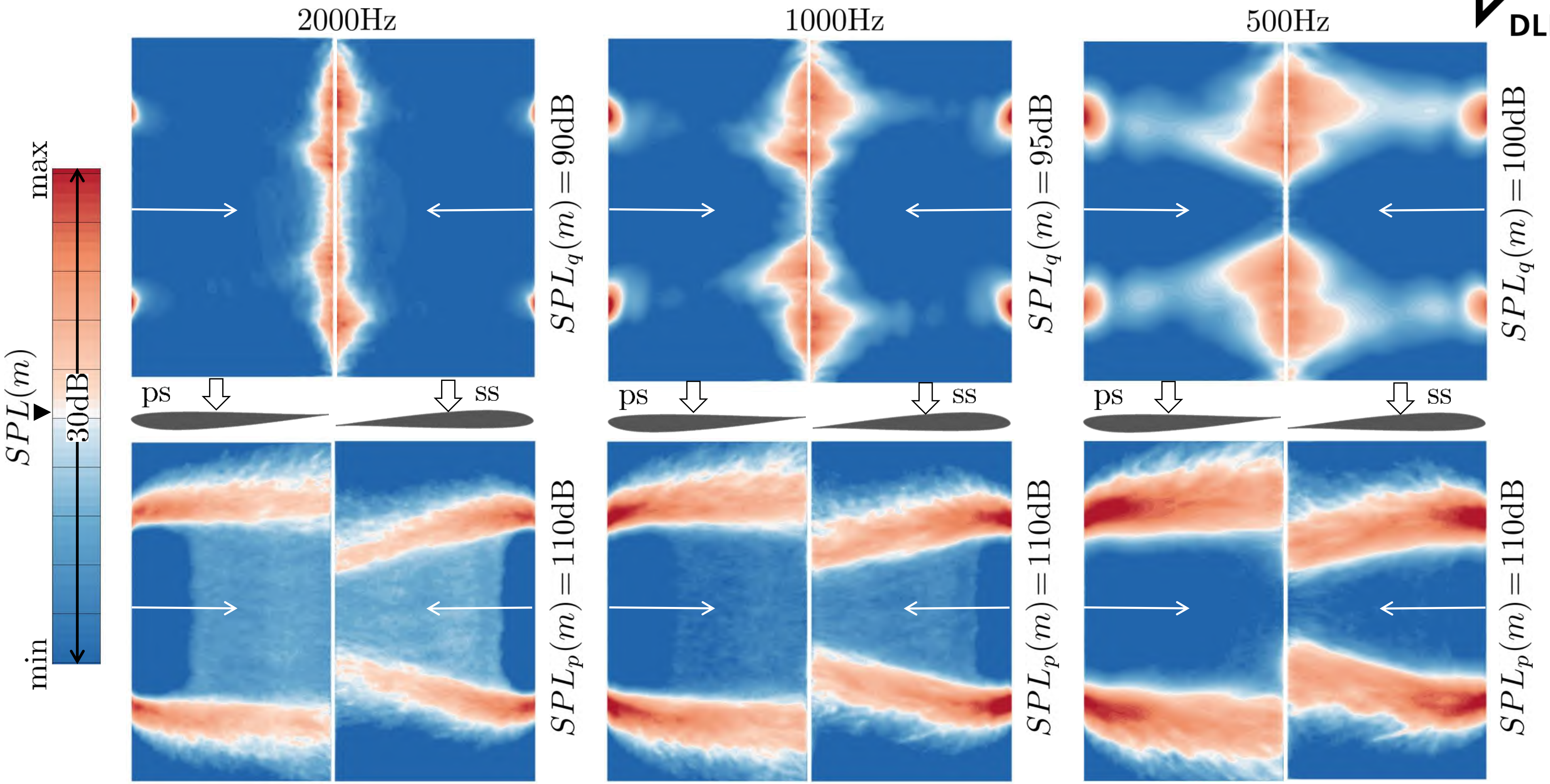
Does $\hat{p}_S$ carry the source information of the original surface pressure $\hat{p}$?

→ Use $\hat{p}_S$ instead of $\hat{p}$ in FW-H and propagate to farfield:

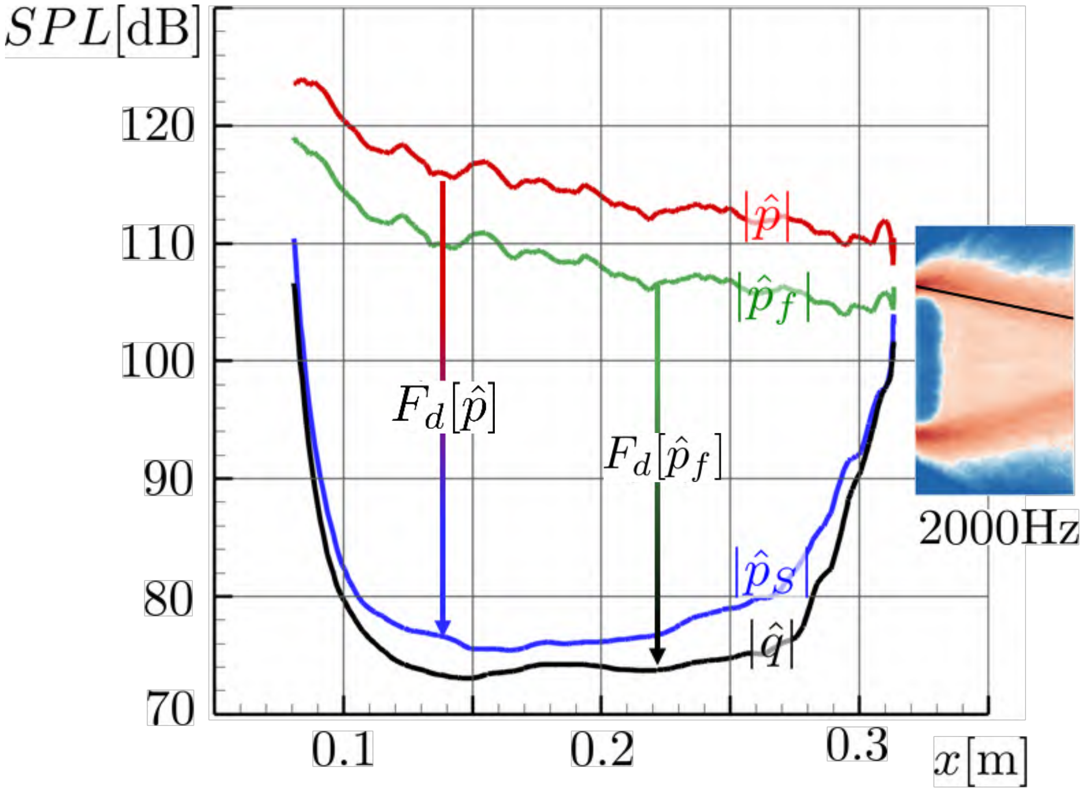




Results: acoustic surface source quantity $\hat{q}$

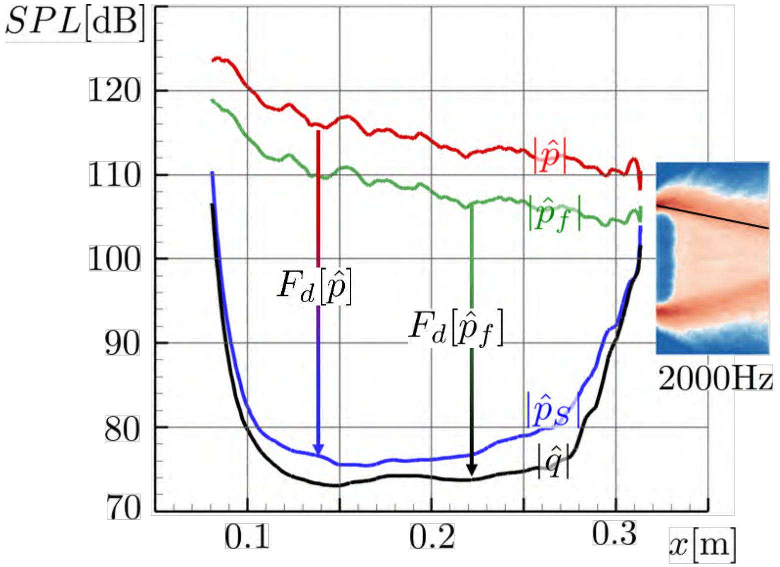


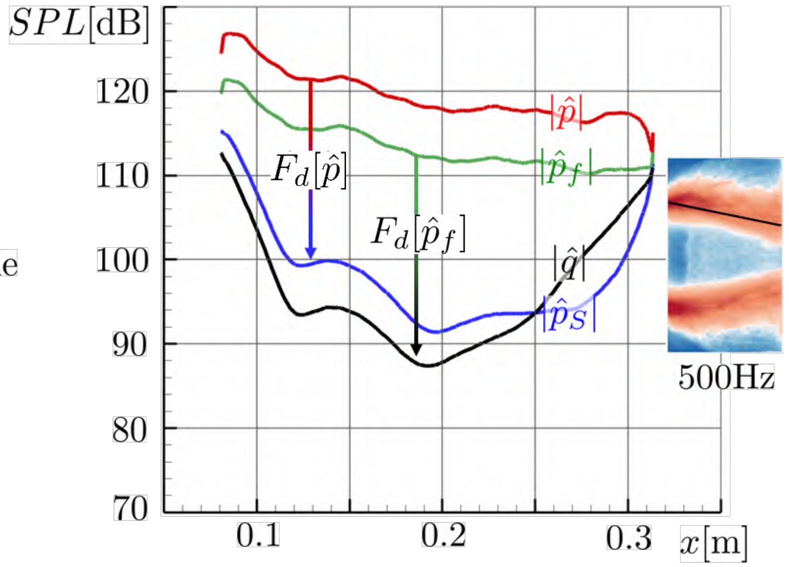
Results: all pressure quantities along shearlayer signature



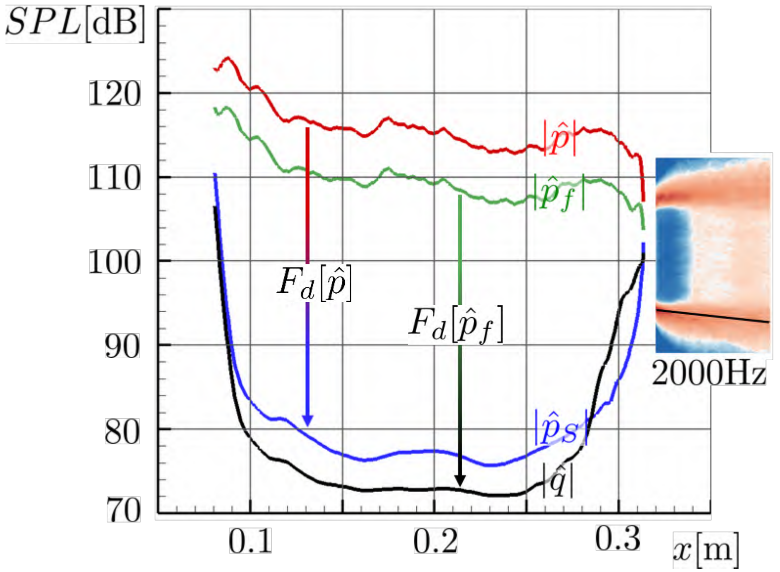
$$F_d[(\hat{.})] = \frac{1}{2\pi} \oint_{\partial V_B} \exp(-ikr)(ikr+1)\frac{\boldsymbol{e}_r \cdot \boldsymbol{n}}{r^2}(\hat{.})\; dS(\xi)$$

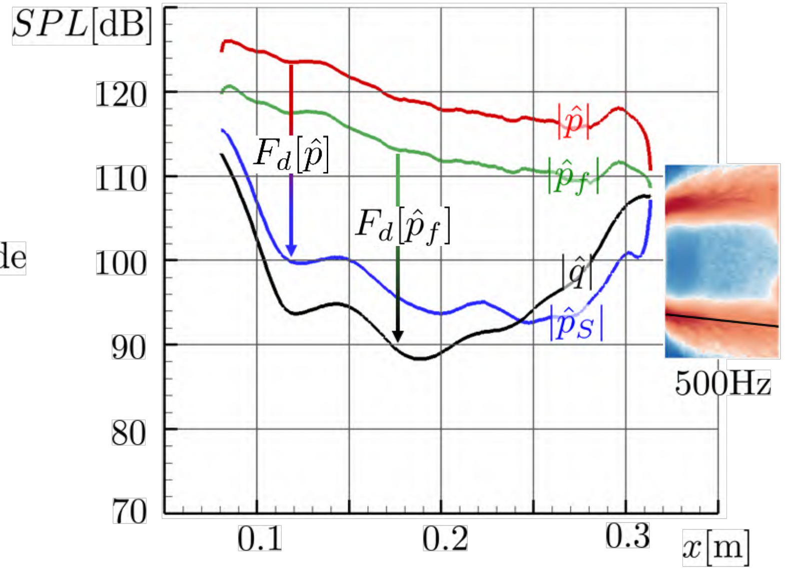
Results: all pressure quantities along shearlayer signature





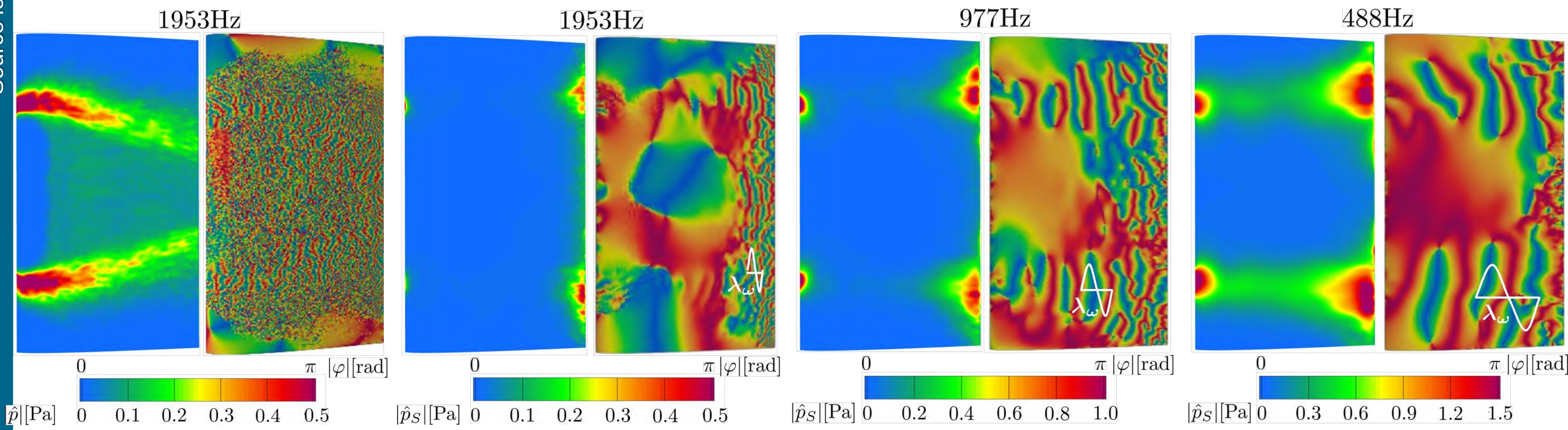
suction side





pressure side

Results: more observations: phase



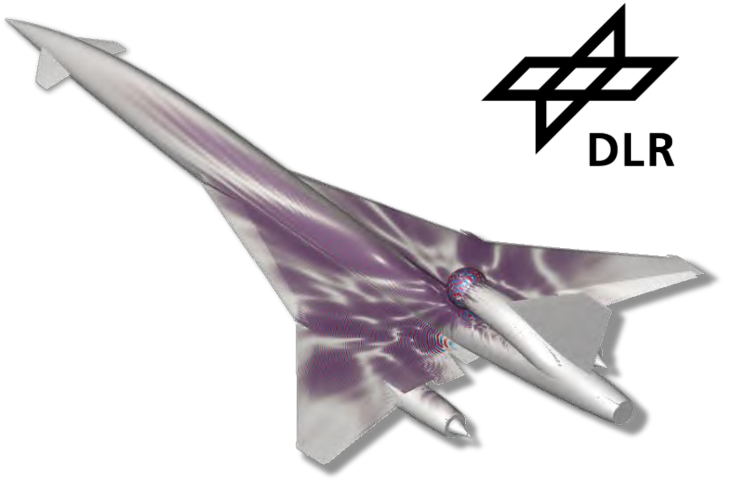
phase of $\hat{p}$:

- dominating in all locations with turbulence
- isotropic

phase of $\hat{p}_S$:

- anisotropic scales || edge
- structures scale like $\lambda_\omega = M\lambda \Rightarrow$ vortical
- vortical scales dominating in strip || edge
- strip || edge narrows with frequency
- large structures related to sound dominating

Conclusions

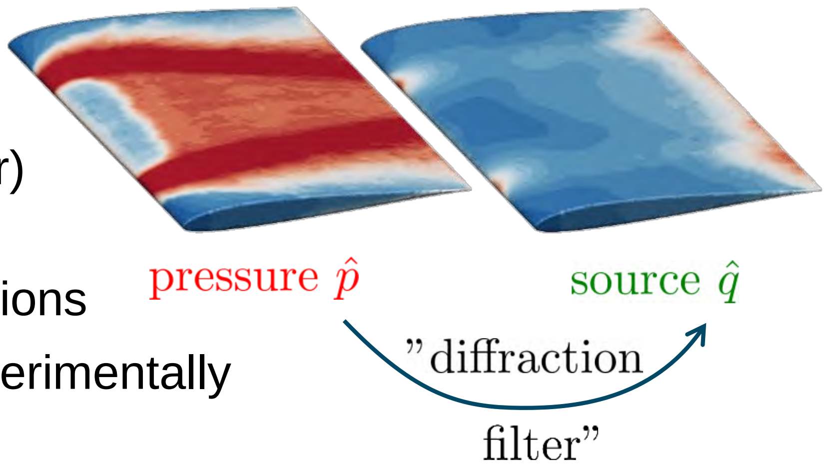


Radiation subject to acoustic installation and locally nonuniform flow

- volume resolving and BEM approaches may be strongly coupled
- enables very small 3D CAA domains by perfect NRBCs (even in nearfield)
- very efficient for highly complex installation problems

Direct use of FW-H/Kirchhoff integrals for source localization on surfaces subject to turbulence

- surface source quantity $\hat{q}$ is derived enabling source localization/identification w/o beamforming
- source localization is first principles based on the hypothesis, that reflection does not generate sound
- derived source quantity $\hat{q}$
  * shows super resolution (no acoustic wavelength restriction), dominated by incompressible dynamics
  * is objective (not depending on observer, nor acoustic installation)
  * forms natural basis for aeroacoustic cost function (optimisation)
  * enables source localisation in complex installation conditions
  * may be used to express surface sound intensity vectors (→ sound power)
  * follows from diffraction filtering of acoustic surface pressure
- related acoustic surface pressure $\hat{p}_S$ free of spurious quadrupole contributions
- given flush surface mounted Mems technology $\hat{q}$ could be determined experimentally



Thank you !