PHYSICAL EFFECTS OF POROUS MATERIALS IN FLOW-INDUCED NOISE MITIGATION

R. Zamponi[1], S. Satcunanathan[2], S. Moreau[3], M. Meinke[2], W. Schröder[2], C. Schram[1]

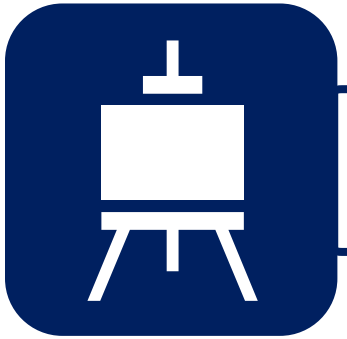
1 von KARMAN INSTITUTE FOR FLUID DYNAMICS

2 RWTH AACHEN UNIVERSITY

3 UNIVERSITÉ DE SHERBROOKE

ENODISE/DJINN/INVENTOR Joint Workshop

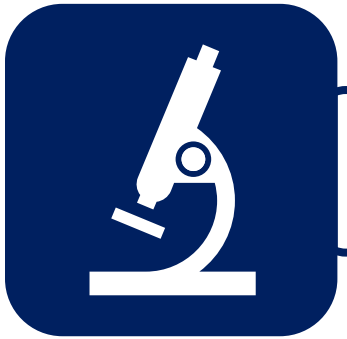
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Framework: flow-induced noise reduction by porosity

Physical problem from the analogy point of view





Physical effects of porosity on airfoil-noise sources

Guidelines for effective porous-treatment design



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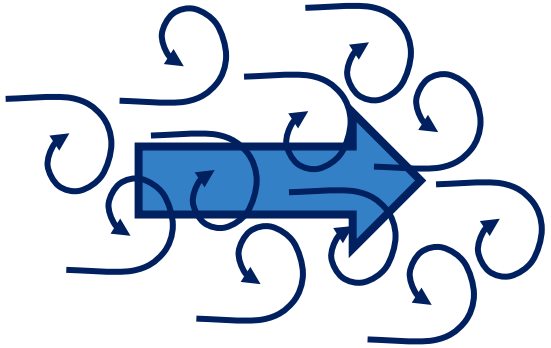
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BASIC AIRFOIL BROADBAND-NOISE MECHANISMS





Turbulence-interaction noise (TIN):
usually large scale,
correlated with incident turbulence

Turbulent-boundary-layer (TBL) noise:
usually small scale,
not correlated with incident turbulence

Context

TIN contributing to **aeroacoustic noise** for several applications

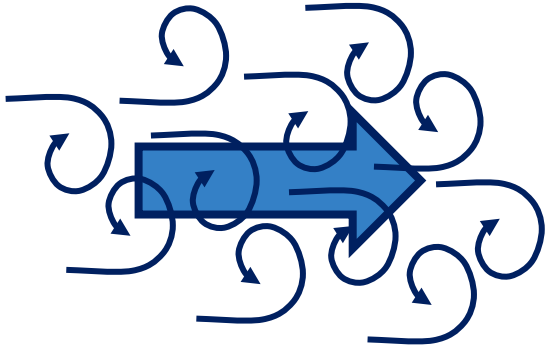
Problem

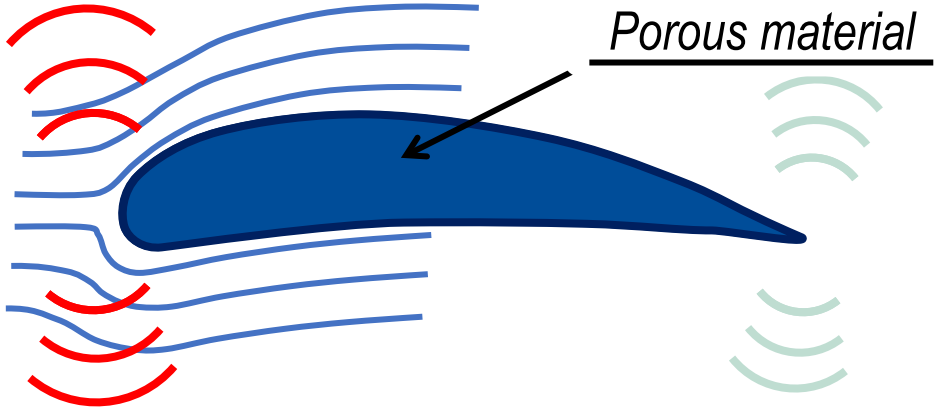
Turbulence related to **installation elements** difficult to control

Solution

Making airfoil surface **less sensitive** to turbulence

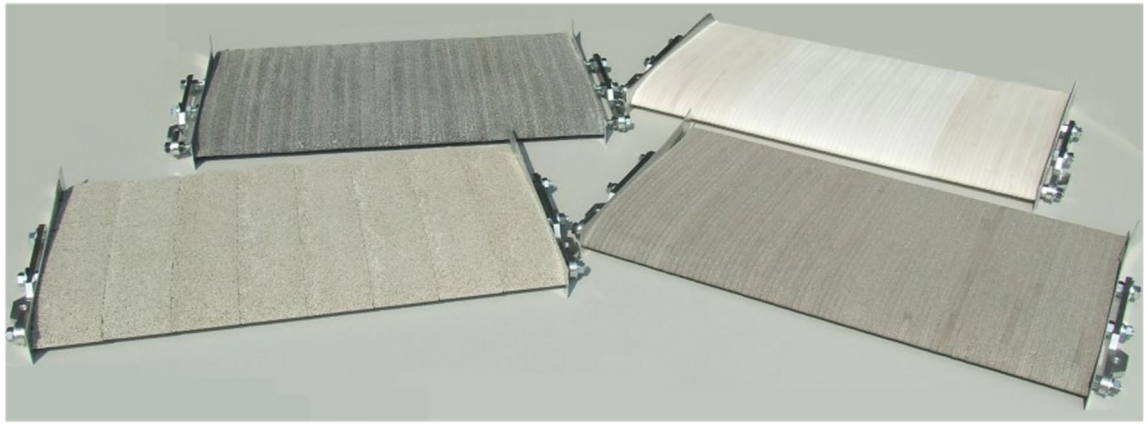
How do we reduce it?





The integration of **porous materials** into the **airfoil structure** is a **promising strategy** to reduce TIN [1]

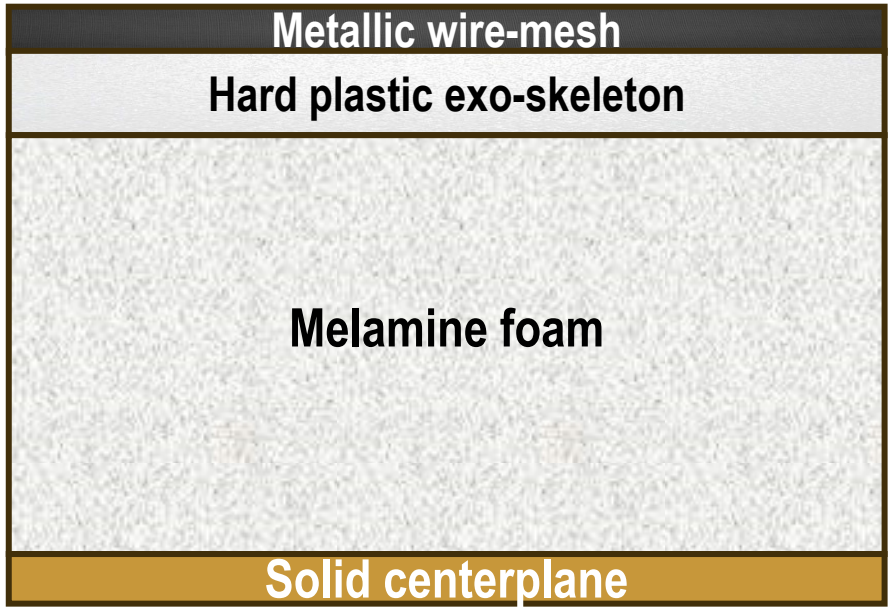




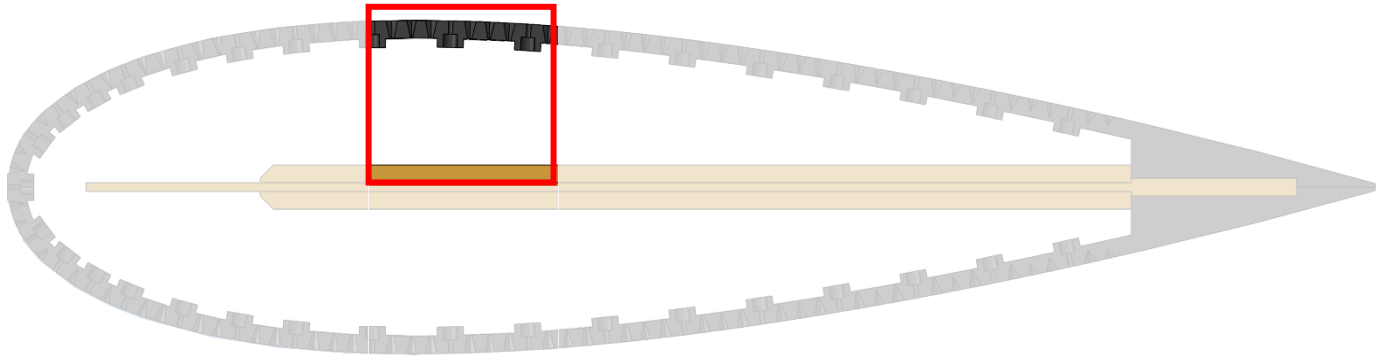
[1] Geyer et al., *17th AIAA/CAES*, 2011

[2] Roger and Moreau, *INTER-NOISE*, 2016

VKI POROUS AIRFOIL



NACA-0024 profile



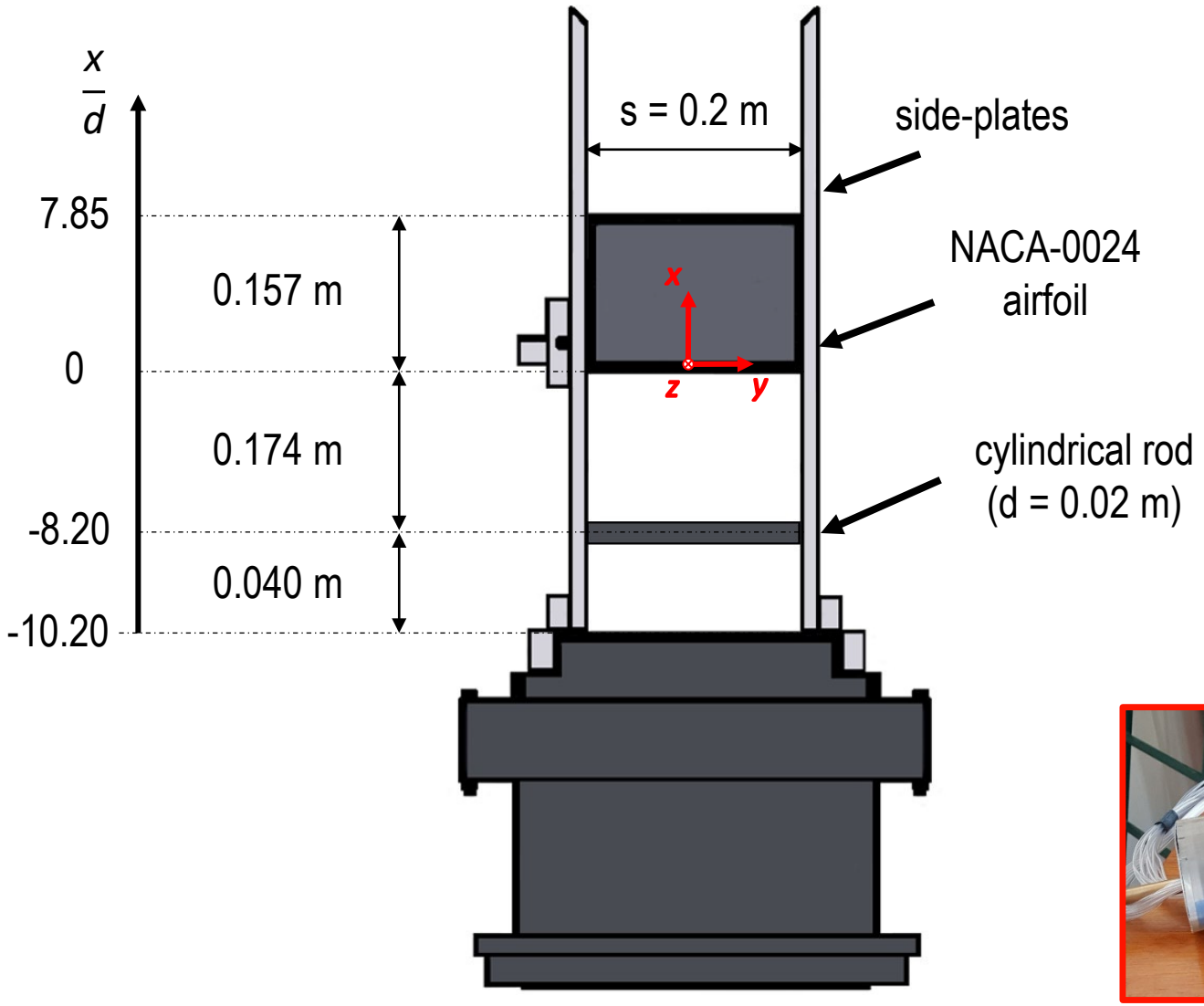
Determination of melamine foam parameters according to the JCAL model [1-3]

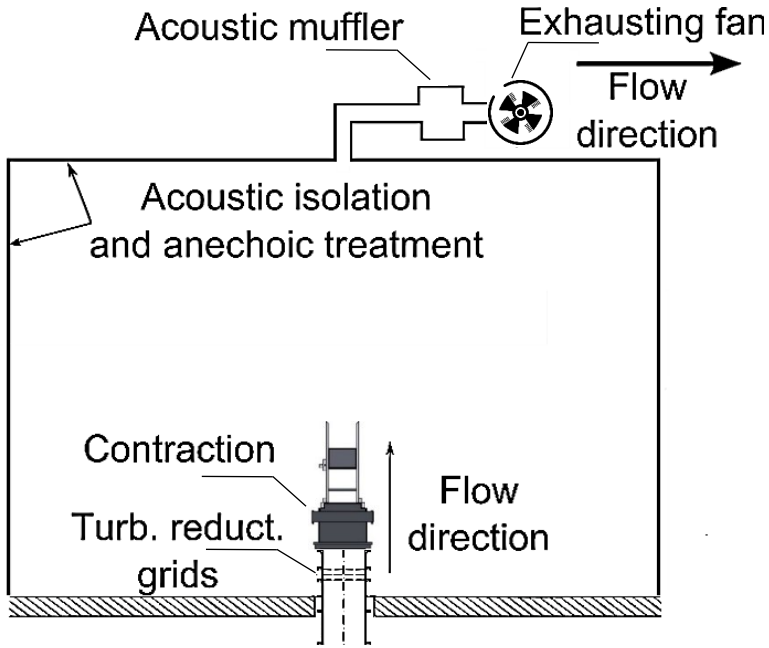
Material	ϕ [%]	σ [Pa s m^{-2}]	α_∞ [-]	Λ [m]	Λ' [m]	k' [m^2]
Melamine foam	98.6	8,683	1.02	1.344×10^{-4}	1.942×10^{-4}	2.305×10^{-9}
Exo-skeleton	80.0	~ 0	~	~	~	~
Wire-mesh	60.8	~ 0	~	~	~	~

LAUM

[1] Johnson et al., *JFM*, 1987 **[2]** Champoux and Allard, *JAP*, 1991 **[3]** Lafarge et al., *JASA*, 1997

THE ROD-AIRFOIL CONFIGURATION





Solid airfoil



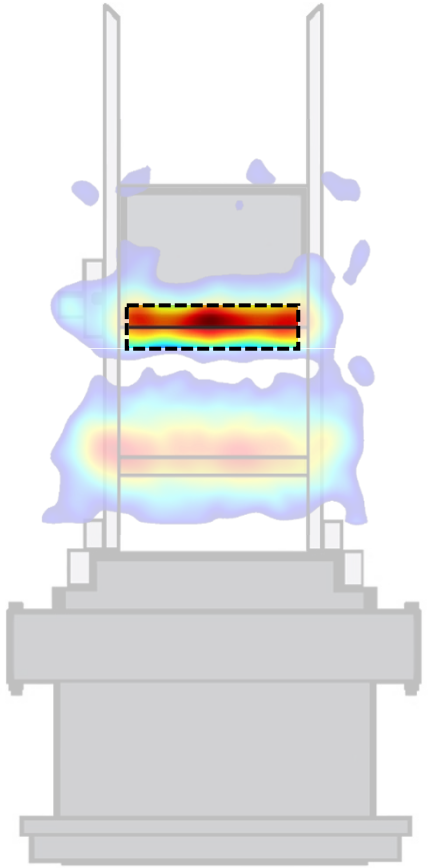
Porous airfoil



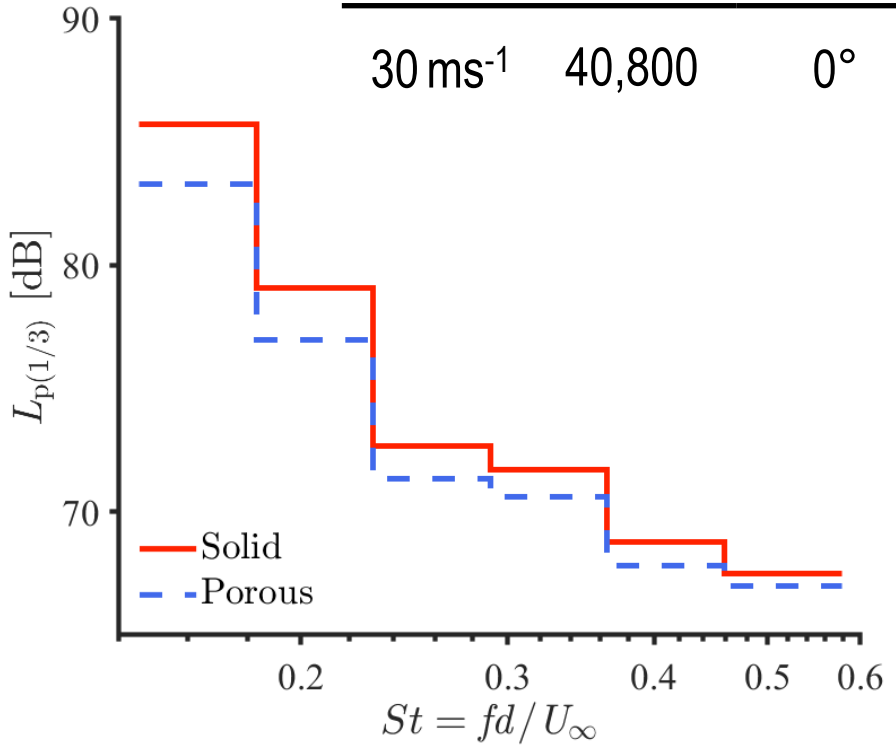
[1] Jacob et al., *TCFD*, 2005 **[2]** Zamponi et al., *25th AIAA/CAES*, 2019

ISOLATION OF NOISE-SOURCE DISTRIBUTIONS

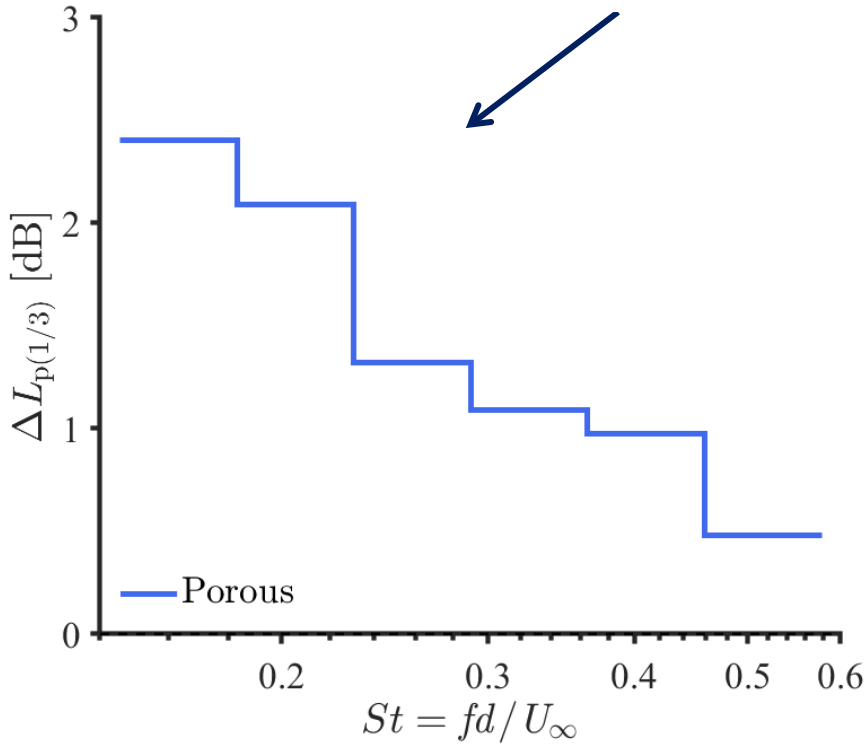
Acoustic beamforming proved to be effective in **isolating** noise-source contributions and showed a **TIN reduction** at low frequencies[1]



U_∞	Re_d	AoA
30 ms^{-1}	40,800	0°



What is the origin of the noise reduction?



[1] Zamponi et al., *JSV*, 2020

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Framework: flow-induced noise reduction by porosity

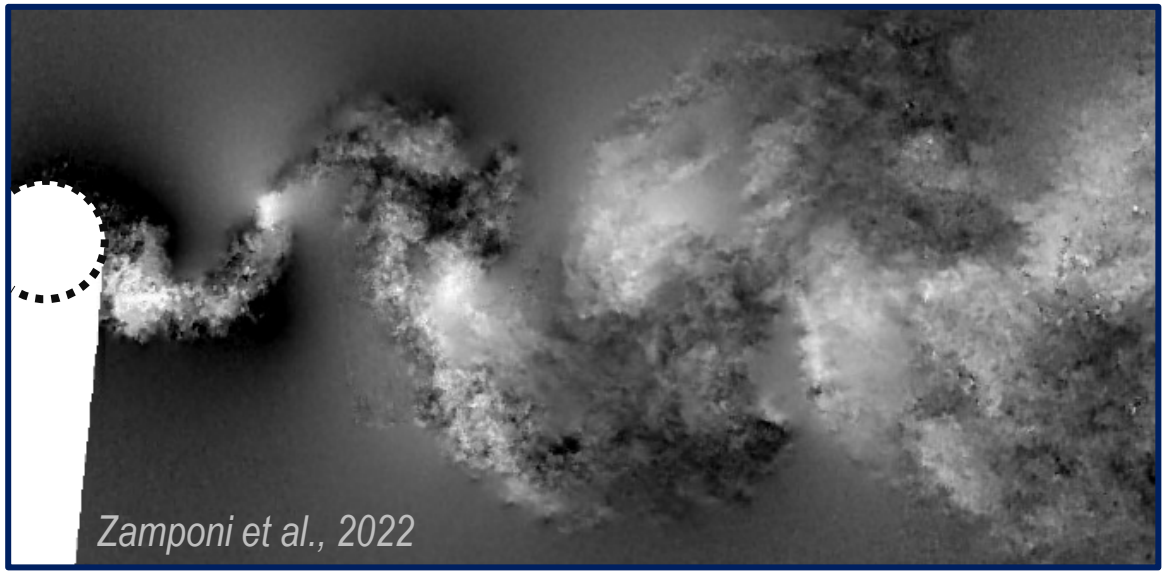
Physical problem from the analogy point of view

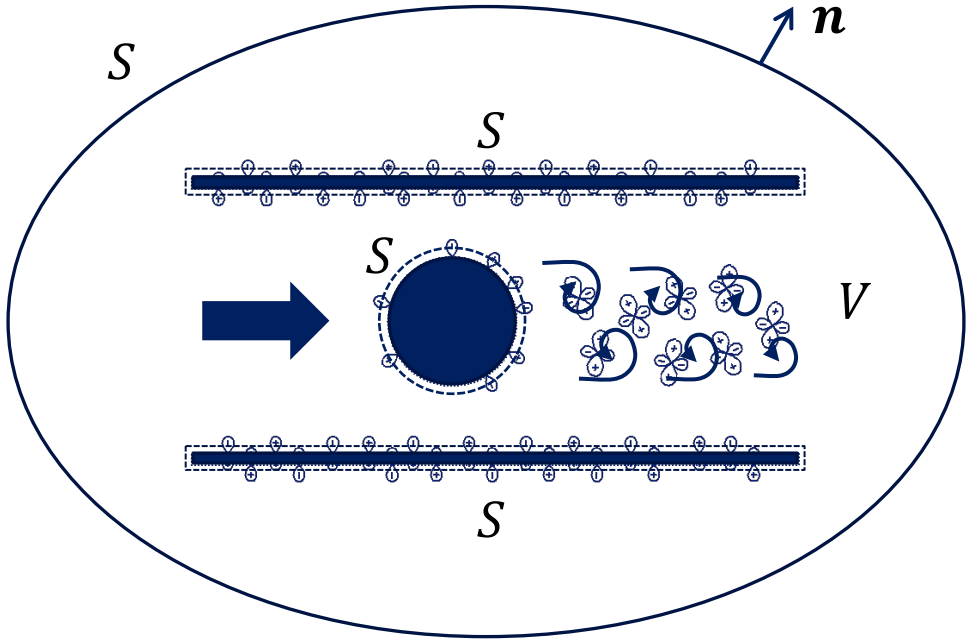
Physical effects of porosity on airfoil-noise sources

Guidelines for effective porous-treatment design

SOUND GENERATION FROM THE ANALOGY VIEWPOINT

Real physical mechanisms substituted by equivalent sources in **aeroacoustic analogies**[1]





*Sound field produced by a solid body immersed in an inflow is modelled by surface distributions of **dipoles** and volume distributions of **quadrupoles** in a medium at rest*[2]

How is sound generation affected when the surface is porous?

[1] Lighthill, *Proc. of the Royal Society of London*, 1952 **[2]** Curle, *Proc.of the Royal Society of London*, 1955

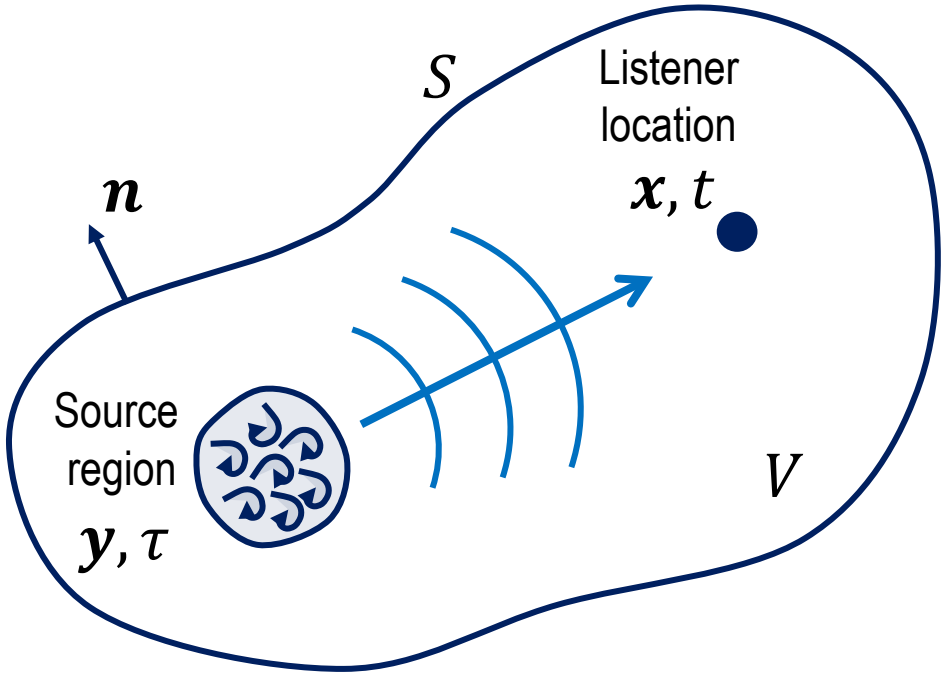
A STEP BACK: LIGHTHILL'S ANALOGY

Density perturbations in a medium at rest described by **Lighthill's aeroacoustic analogy**[1]:

$$\frac{\partial^2 \rho'}{\partial t^2} - c_0^2 \frac{\partial \rho'}{\partial x_i^2} = \frac{\partial^2 T_{ij}}{\partial x_i x_j}$$

$\rho' = \rho - \rho_0$: density $\quad p = p - p_0$: pressure

$u_i' = u_i$: velocity $\quad c_0 = \sqrt{(\partial p/\partial \rho)_s}$: speed of sound



Lighthill's stress tensor

$$T_{ij} = \rho u_i u_j - \tau_{ij} + (p' - c_0^2 \rho')$$

High Reynolds numbers

Incompressible and isentropic fluid

Exact… and perfectly useless! *(cit. Prof. Schram)*

[1] Lighthill, *Proc. of the Royal Society of London*, 1952

TOWARDS CURLE'S ANALOGY

In the presence of a stationary surface S, an integral solution to Lighthill's analogy can be found using the **Green's function** approach

$$c_0^2 \rho' = p^* = \underbrace{\int_{-\infty}^{t} \iiint_V \frac{\partial^2 T_{ij}}{\partial y_i \partial y_j} G \, dV \, d\tau}_{\text{Incident field}} + \underbrace{c_0^2 \int_{-\infty}^{t} \iint_S \left(\rho' \frac{\partial G}{\partial y_i} - G \frac{\partial \rho'}{\partial y_i} \right) n_i \, dS \, d\tau}_{\text{Scattered field}}$$

By integrating the incident-field term by parts the incident-field term, using the divergence theorem, and imposing the momentum conservation law[1]:

$$p^* = \int_{-\infty}^{t} \iiint_V T_{ij} \frac{\partial^2 G}{\partial y_i \partial y_j} \, dV \, d\tau + c_0^2 \int_{-\infty}^{t} \iint_S \left[G \frac{\partial \rho u_i}{\partial \tau} + (p' \delta_{ij} + \rho u_i u_j) \frac{\partial G}{\partial y_i} \right] n_i \, dS \, d\tau$$

[1] Curle, *Proceedings of the Royal Society of London*, 1955

SOUND GENERATION BY A POROUS BODY

Curle's solution to Lighthill's analogy is finally derived using **free-field Green's function**[1]

Porosity generates two additional equivalent sources, a **monopole** related to the unsteady-flow penetration and a **dipole** linked to the non-zero Reynolds stresses at the surface

$$p^* = \frac{\partial^2}{\partial x_i \partial x_j} \iiint_V \left[\frac{T_{ij}}{4\pi||\boldsymbol{x}-\boldsymbol{y}||}\right]_{\tau=t_e} dV - \frac{\partial}{\partial x_i} \iint_S \left[\frac{p'\delta_{ij} + \rho u_i u_j}{4\pi||\boldsymbol{x}-\boldsymbol{y}||}\right]_{\tau=t_e} n_j dS + \iint_S \left[\frac{\partial \rho u_j}{\partial \tau} \frac{1}{4\pi||\boldsymbol{x}-\boldsymbol{y}||}\right]_{\tau=t_e} n_j dS$$

Quadrupole term:
sound production
of the flow
$I_r \propto M^8$ in free field

Dipole term:
unsteady force exerted
by the body
$I_r \propto M^6$ in free field

Monopole term:
unsteady transpiration velocity
at the surface
$I_r \propto M^4$ in free field

[1] Curle, *Proceedings of the Royal Society of London*, 1955

CURLE'S DIPOLAR SOURCES

With the assumption of **geometric far field** and **source compactness**:

$$p^* \simeq \frac{x_i x_j}{4\pi|\vec{x}|^3 c_0^2}\frac{\partial^2}{\partial t^2}\left[\iiint_V T_{ij}\,dV\right]_{\tau=t_e} - \frac{x_j}{4\pi|\vec{x}|^2 c_0}\frac{\partial}{\partial t}\left[\iint_S \left(p'\delta_{ij} + \rho u_i u_j\right) n_j\,dS\right]_{\tau=t_e} + \frac{1}{4\pi|\vec{x}|}\frac{\partial}{\partial t}\left[\iint_S \rho u_j\, n_j\,dS\right]_{\tau=t_e}$$

Low Mach numbers

Unsteady-pressure term

Reynolds-stresses term

Continuity equation

Research questions addressed in this lecture:

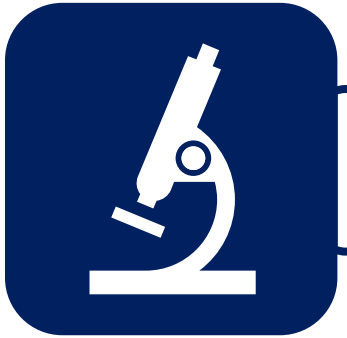
What is the effect of porosity on unsteady-pressure term?

What is the impact of the Reynolds-stresses term on far-field noise?

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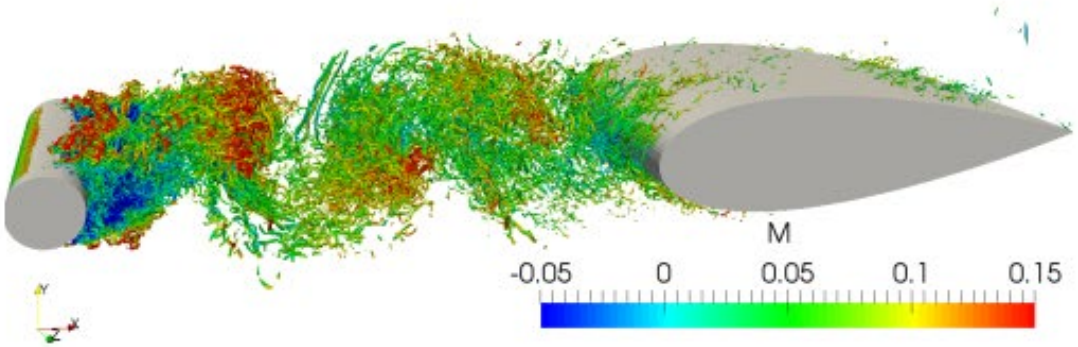
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ROD-AIRFOIL LES DATASET

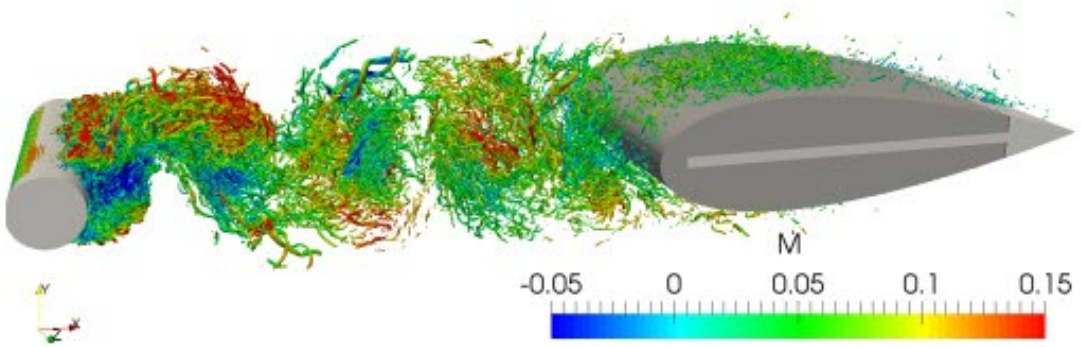
The VKI experimental setup has been **numerically simulated** by RWTH with a **direct hybrid CFD/CAA method** [1-2]

$\epsilon_{LES/CAA}$ [−]	Da_{LES} [−]	Da_{CAA} [−]	$c_{F,LES}$	$c_{F,CAA}$
0.99	$5.3 \cdot 10^{-6}$	$2.1 \cdot 10^{-6}$	0	0

Darcy-Forchheimer model parameters characterizing the melamine foam calibrated with experimental data [3]



Solid airfoil



Porous airfoil

[1] Zamponi et al., *JSV*, 2020

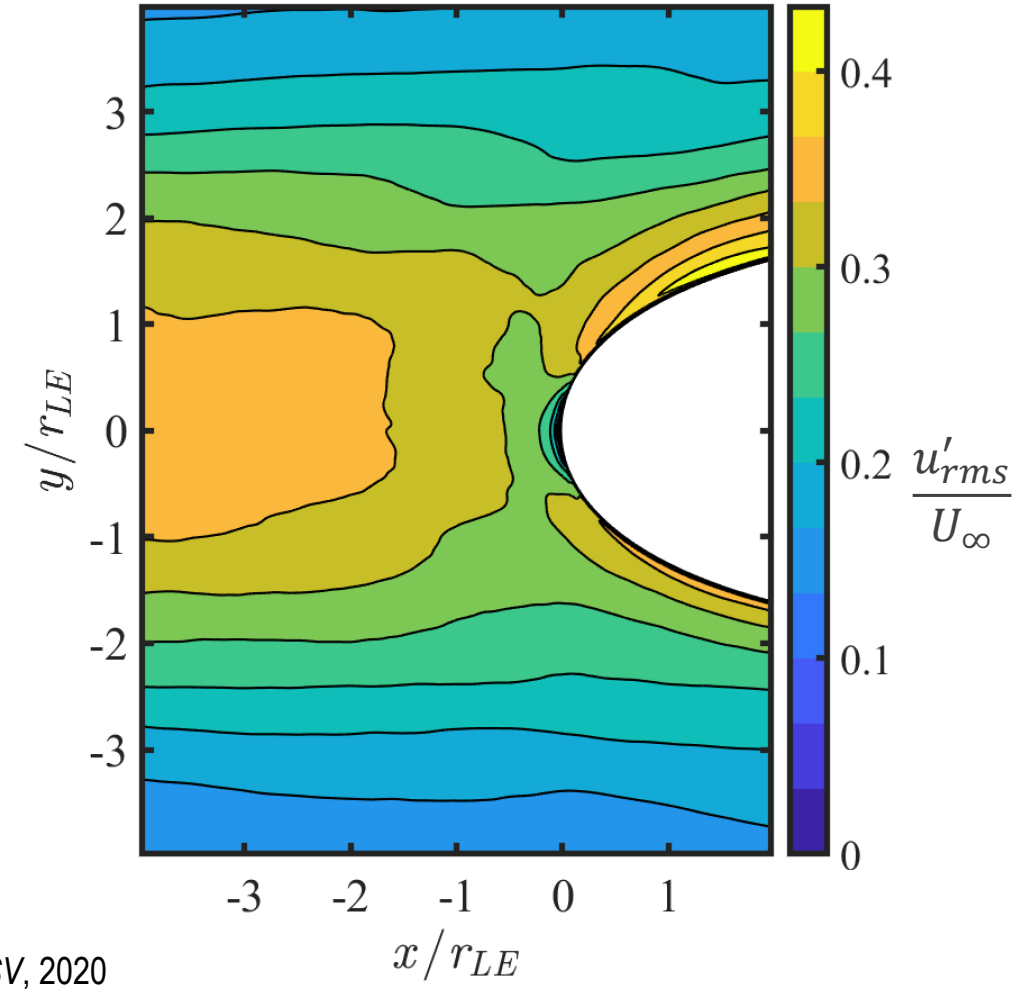
[2] Satcunanathan et al., *25th AIAA/CAES*, 2019

[3] 3 Satcunanathan et al., INTER-NOISE, 2019

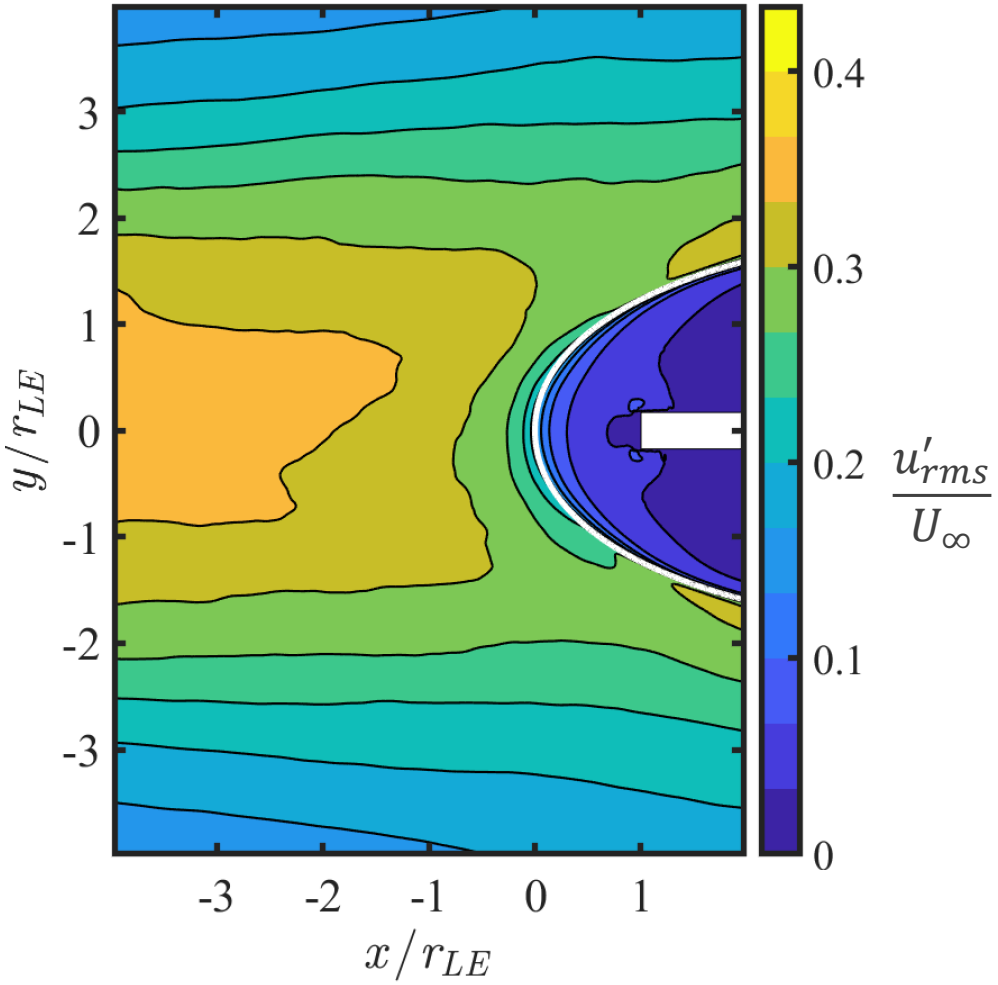
UNSTEADY-FLOW ALTERATIONS

Porosity affects the flow field by **reducing** the **momentum transfer** between the velocity components

Solid airfoil



Porous airfoil

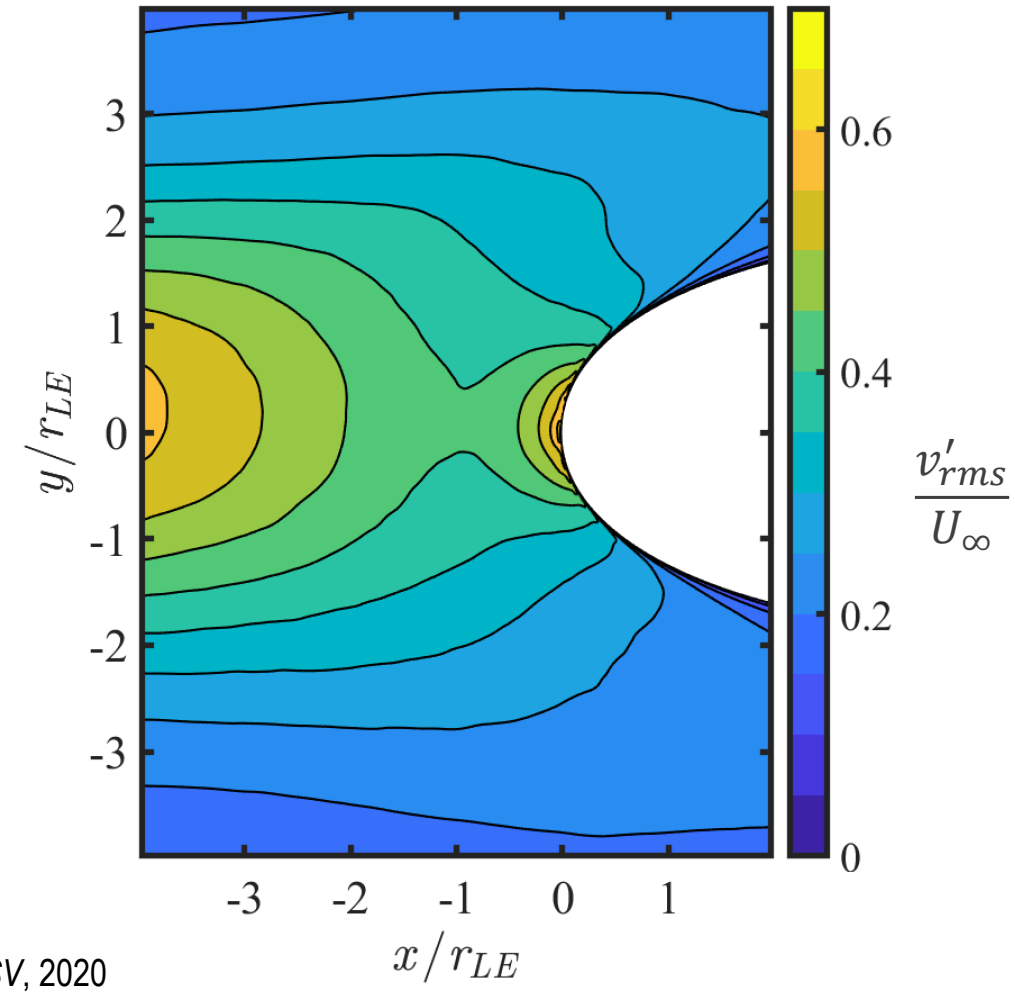


[1] Zamponi et al., *JSV*, 2020

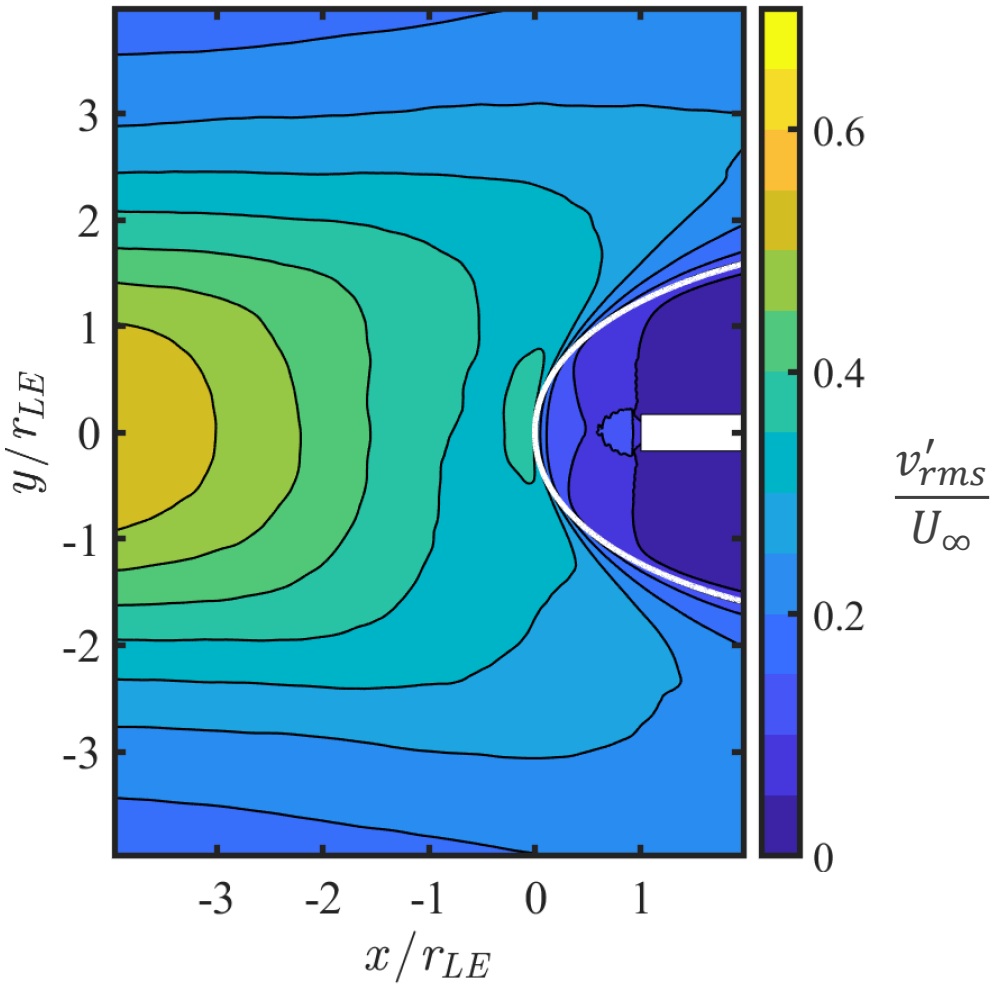
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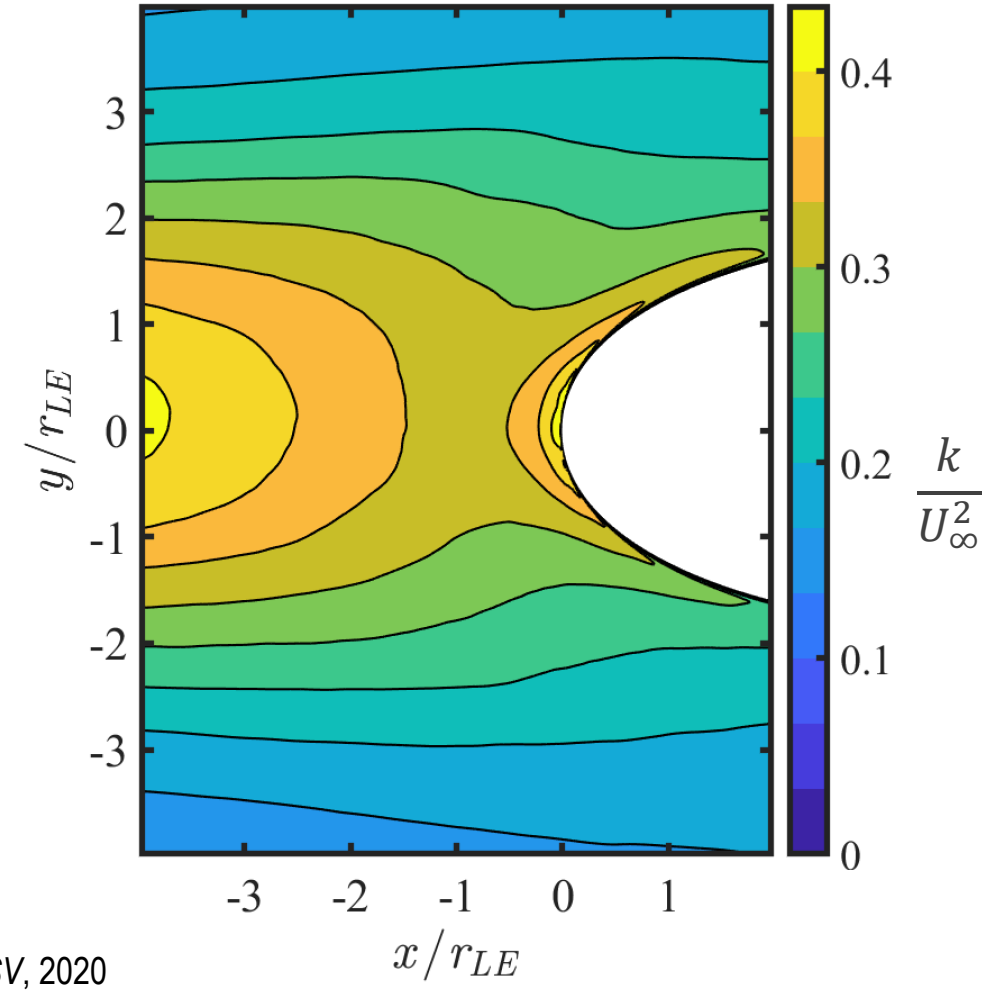


[1] Zamponi et al., *JSV*, 2020

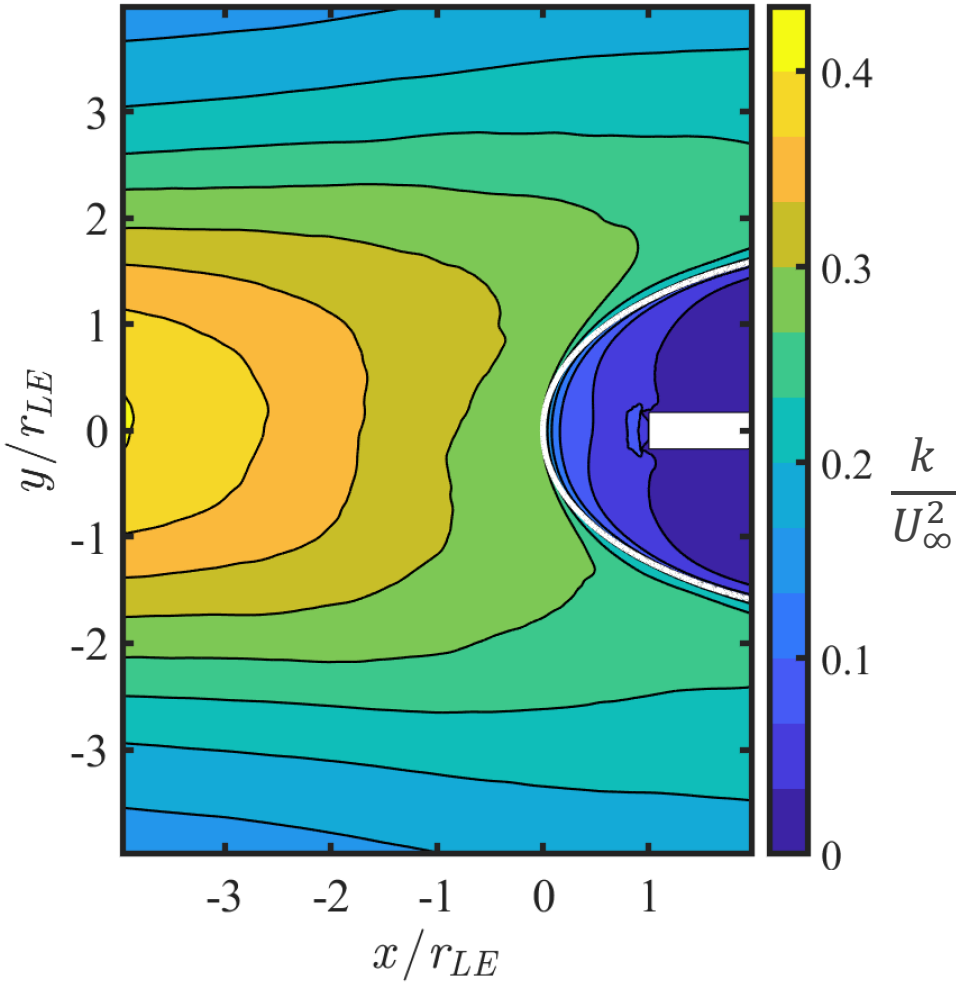
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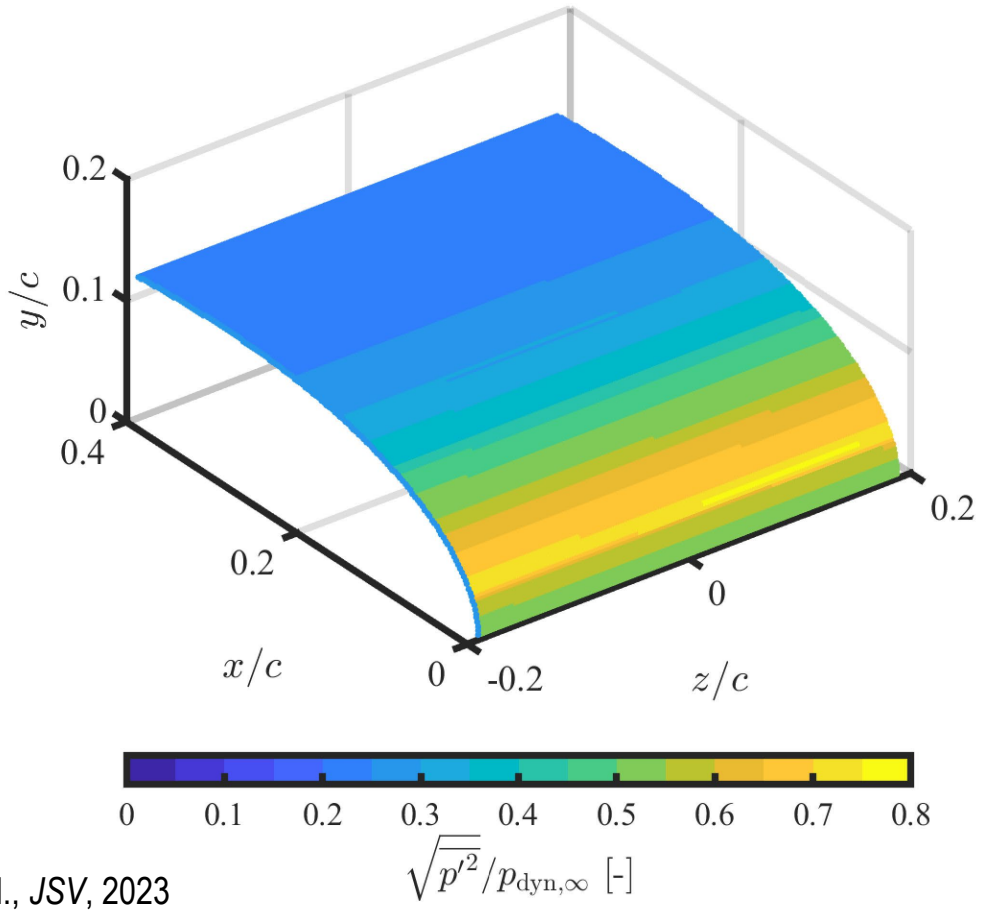


[1] Zamponi et al., *JSV*, 2020

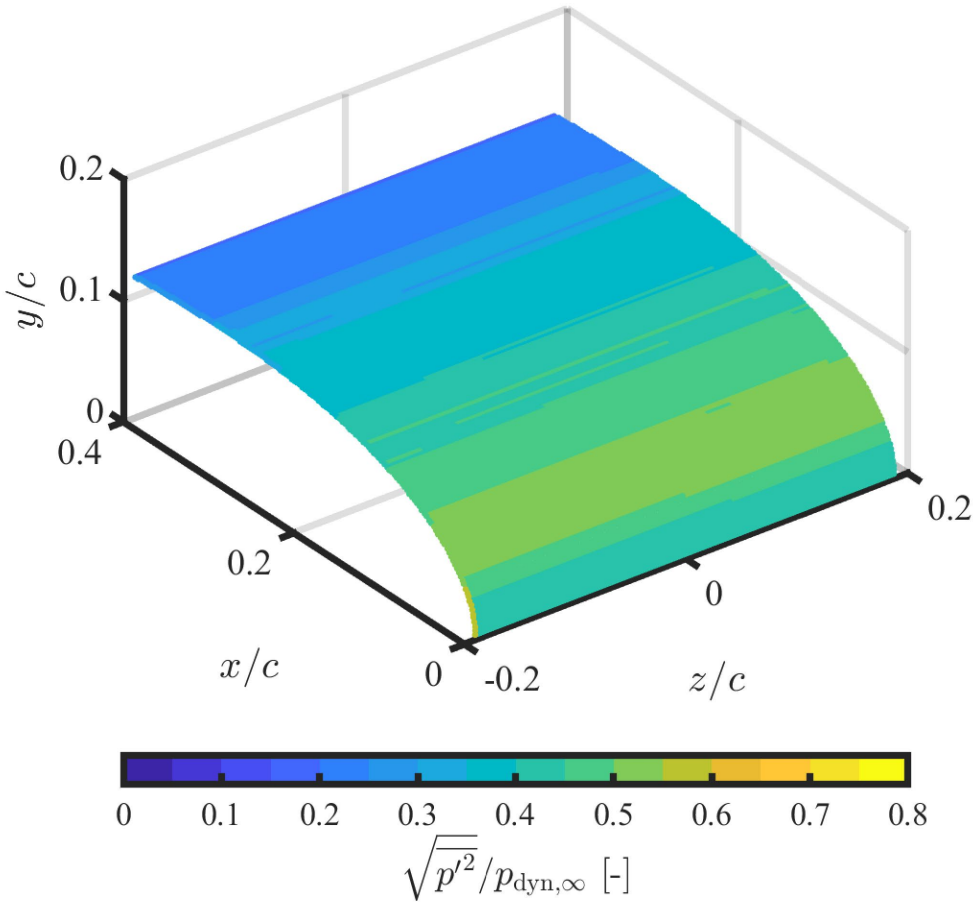
STUDY OF CURLE'S DIPOLAR SOURCES - p'

Effect of porosity resulting in **attenuation** of **r.m.s.** surface-pressure-fluctuations **peak**

Solid airfoil



Porous airfoil

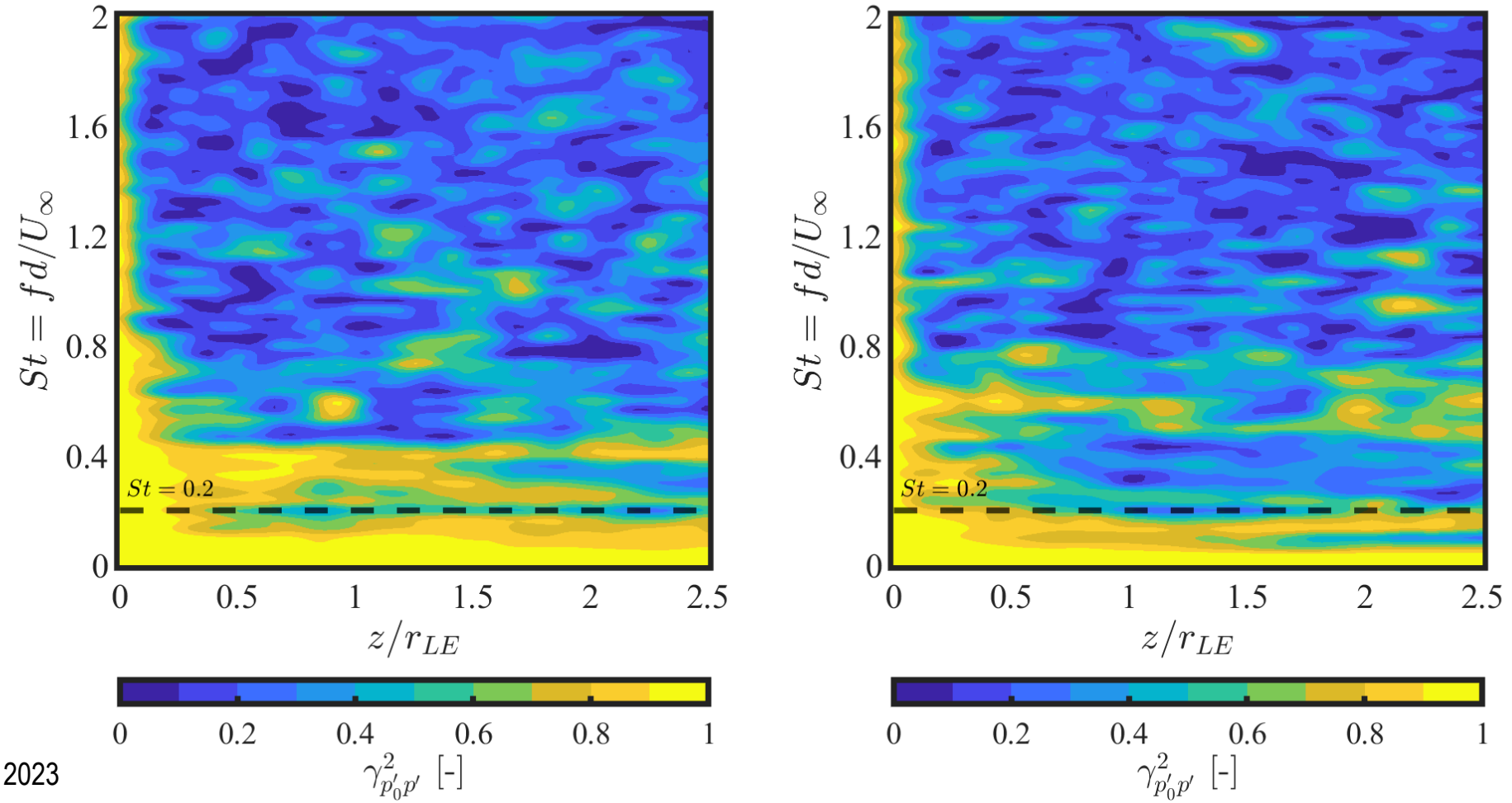


[1] Zamponi et al., *JSV*, 2023

STUDY OF CURLE'S DIPOLAR SOURCES - p'

Limited effect of porosity on spanwise **spatial coherence** of surface-pressure fluctuations

Solid airfoil $x/r_{LE} = 0$ ***Porous airfoil***

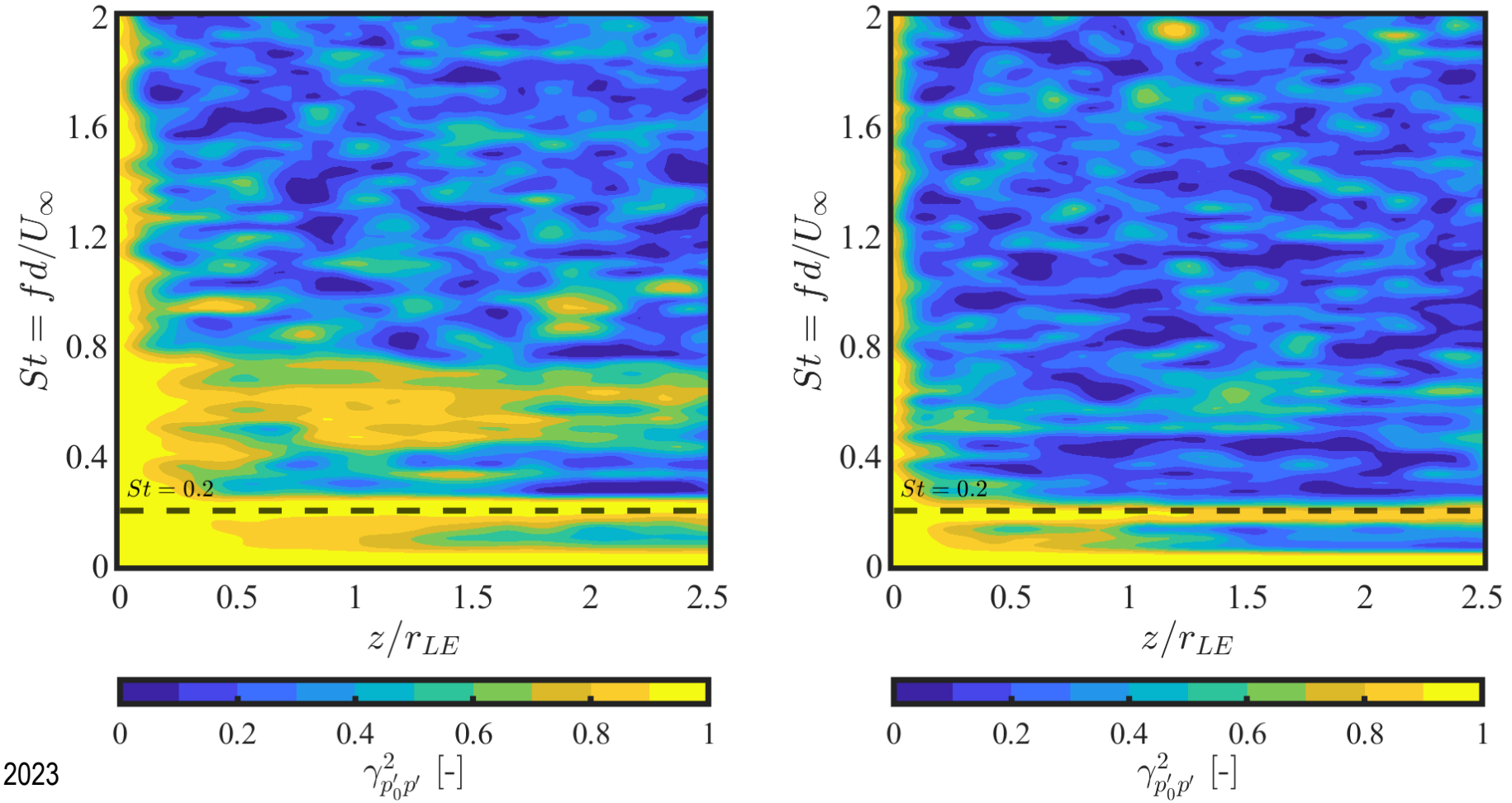


[1] Zamponi et al., *JSV*, 2023

STUDY OF CURLE'S DIPOLAR SOURCES - p'

Limited effect of porosity on spanwise **spatial coherence** of surface-pressure fluctuations

Solid airfoil $x/r_{LE} = 0.47$ ***Porous airfoil***

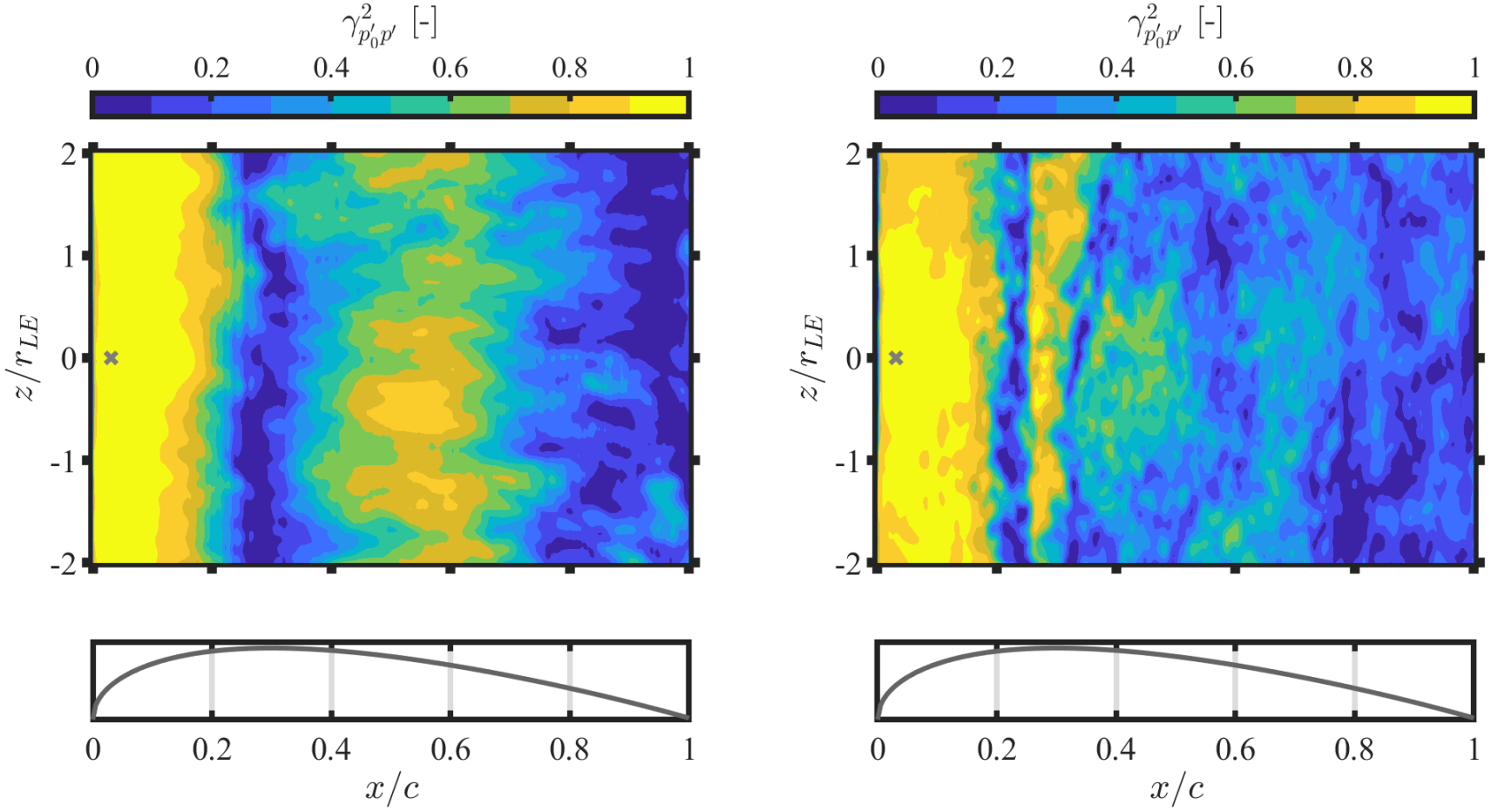


[1] Zamponi et al., *JSV*, 2023

STUDY OF CURLE'S DIPOLAR SOURCES - p'

Limited effect of porosity on **spatial coherence** of surface-pressure fluctuations

Solid airfoil $St = 0.2$ ***Porous airfoil***

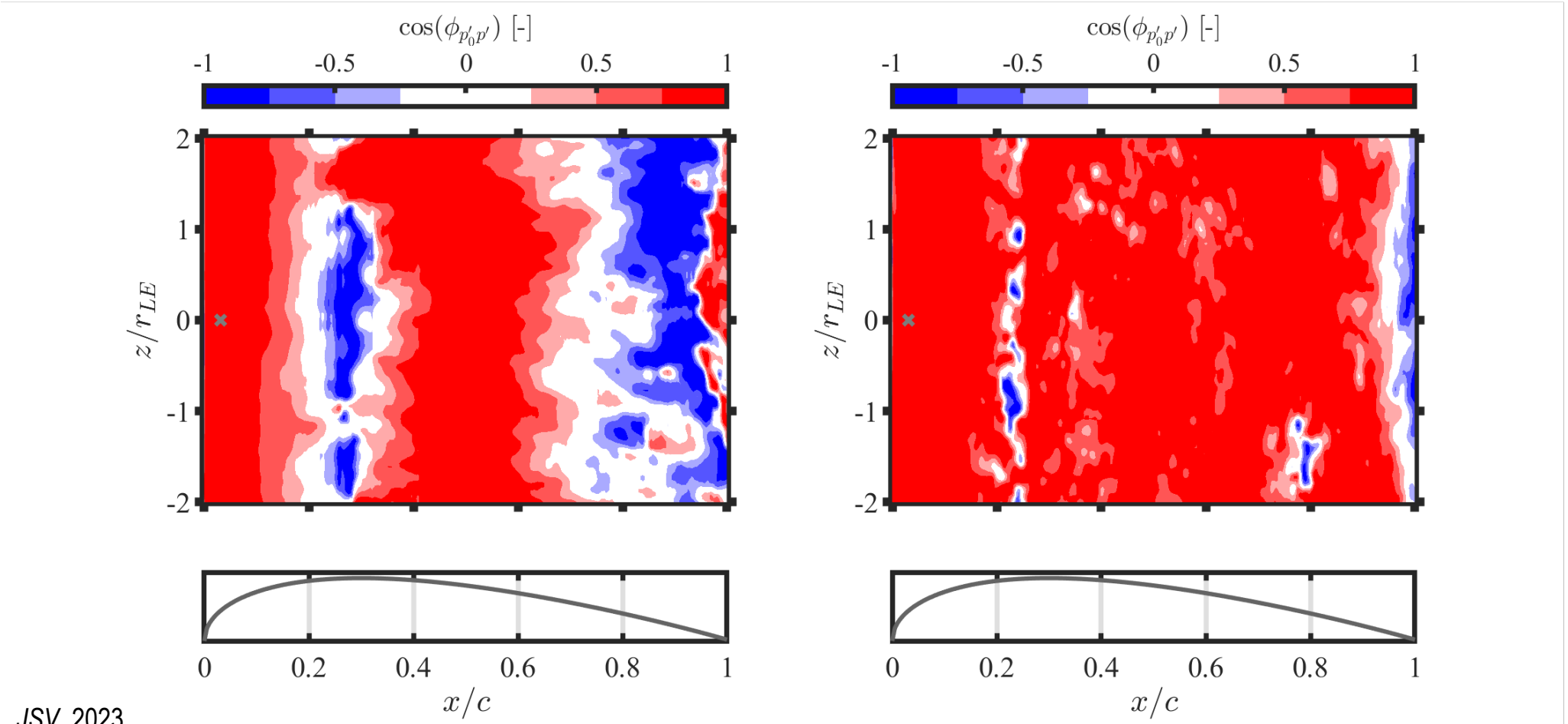


[1] Zamponi et al., *JSV*, 2023

STUDY OF CURLE'S DIPOLAR SOURCES - p'

Limited effect of porosity on **phase difference** of surface-pressure fluctuations

Solid airfoil $St = 0.2$ ***Porous airfoil***

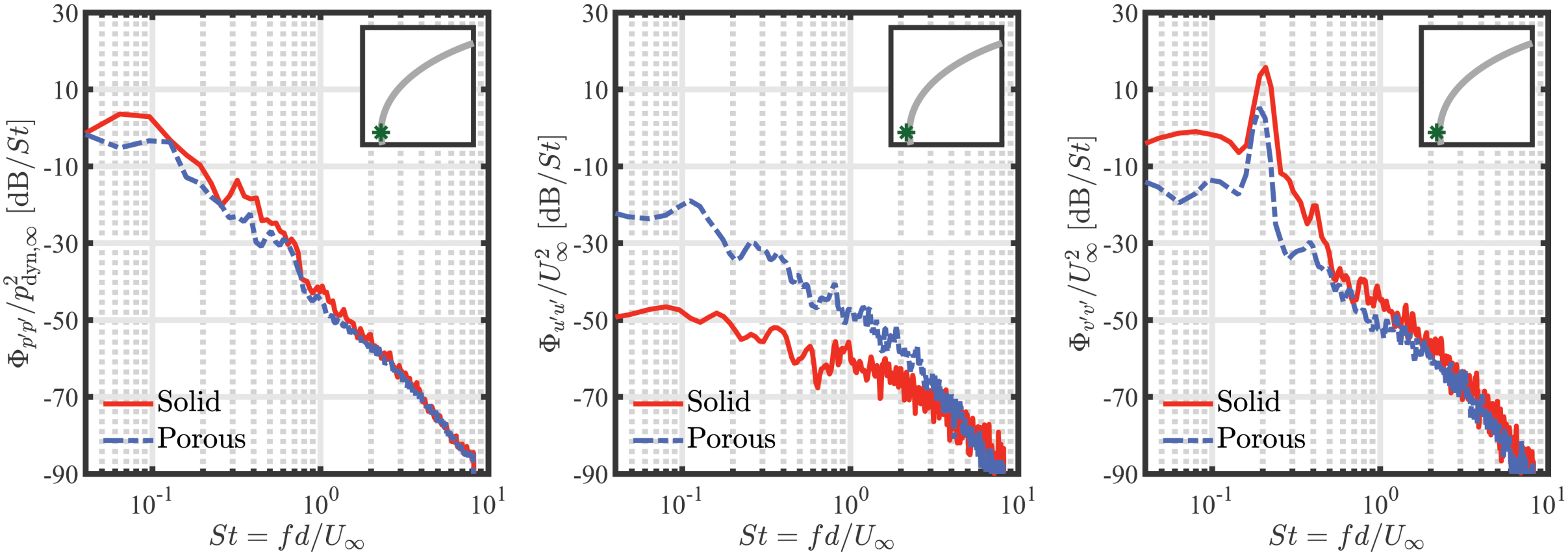


[1] Zamponi et al., *JSV*, 2023

STUDY OF CURLE'S DIPOLAR SOURCES - p'

Surface-pressure fluctuations spectra indicating **attenuation** in **turbulence distortion** as one of the dominant **noise-reduction mechanisms** for TIN

$x/r_{LE} = 0$



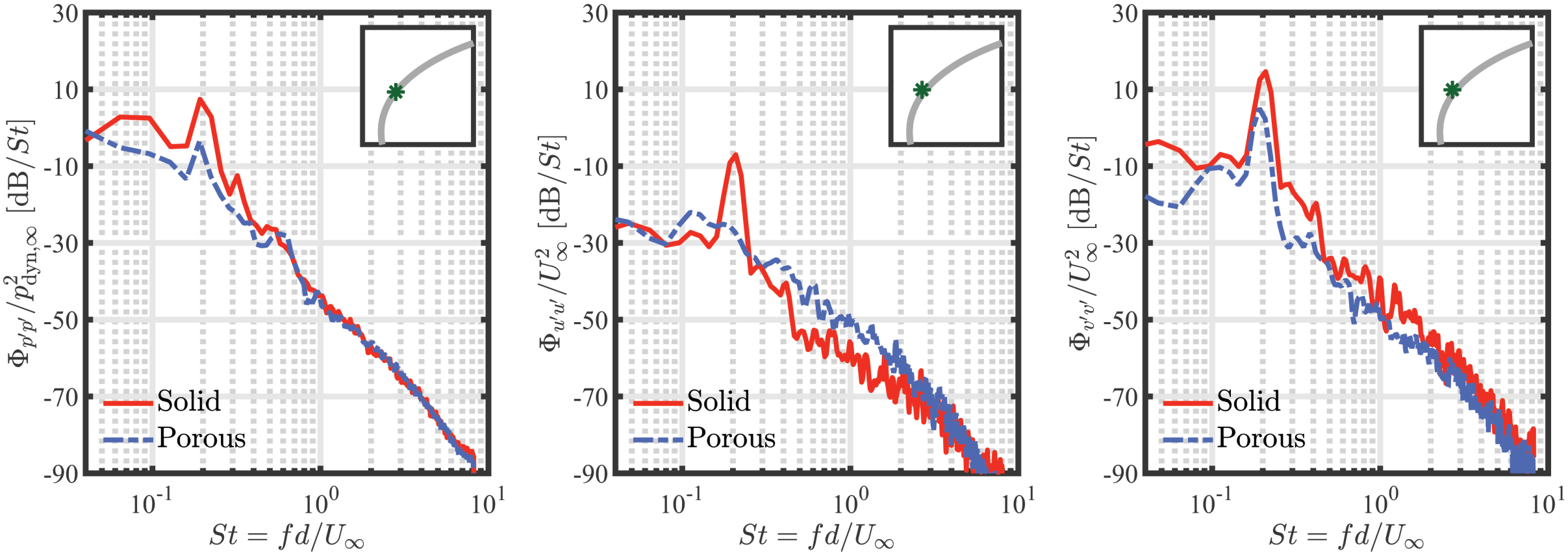
[1] Zamponi et al., *JFM*, 2021

[2] Zamponi et al., *JSV*, 2023

STUDY OF CURLE'S DIPOLAR SOURCES - p'

Surface-pressure fluctuations spectra indicating **attenuation** in **turbulence distortion** as one of the dominant **noise-reduction mechanisms** for TIN

$x/r_{LE} = 0.24$



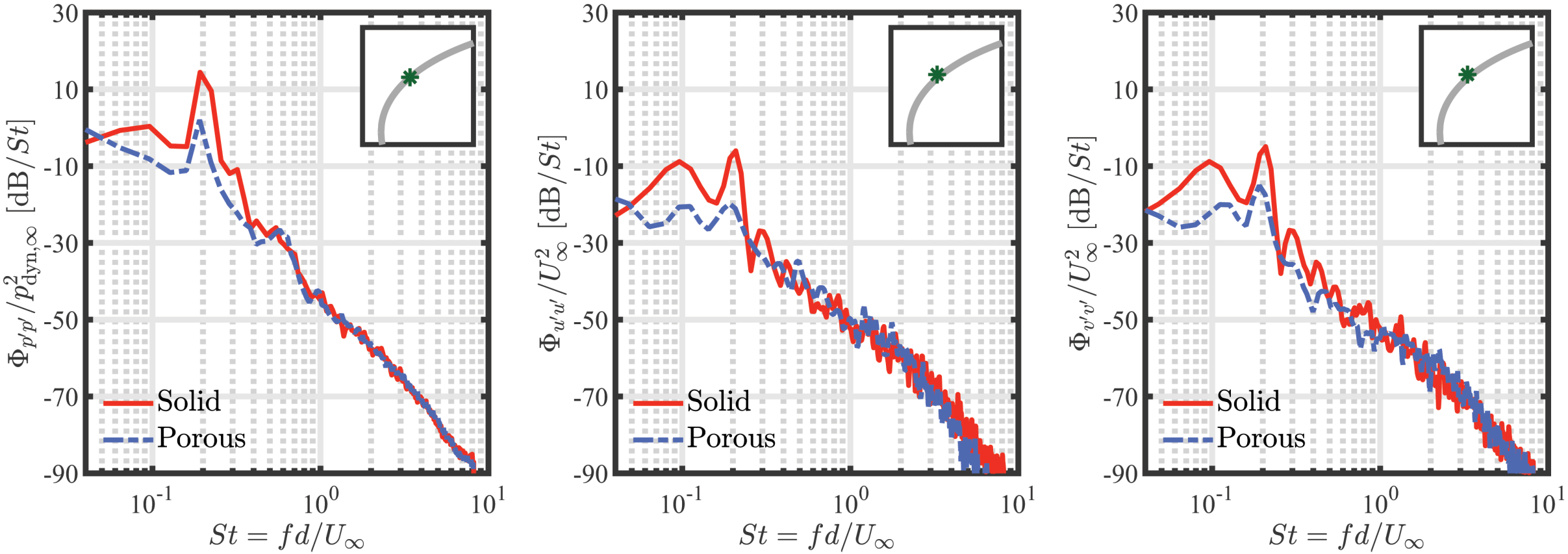
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[2] Zamponi et al., *JSV*, 2023

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Surface-pressure fluctuations spectra indicating **attenuation** in **turbulence distortion** as one of the dominant **noise-reduction mechanisms** for TIN

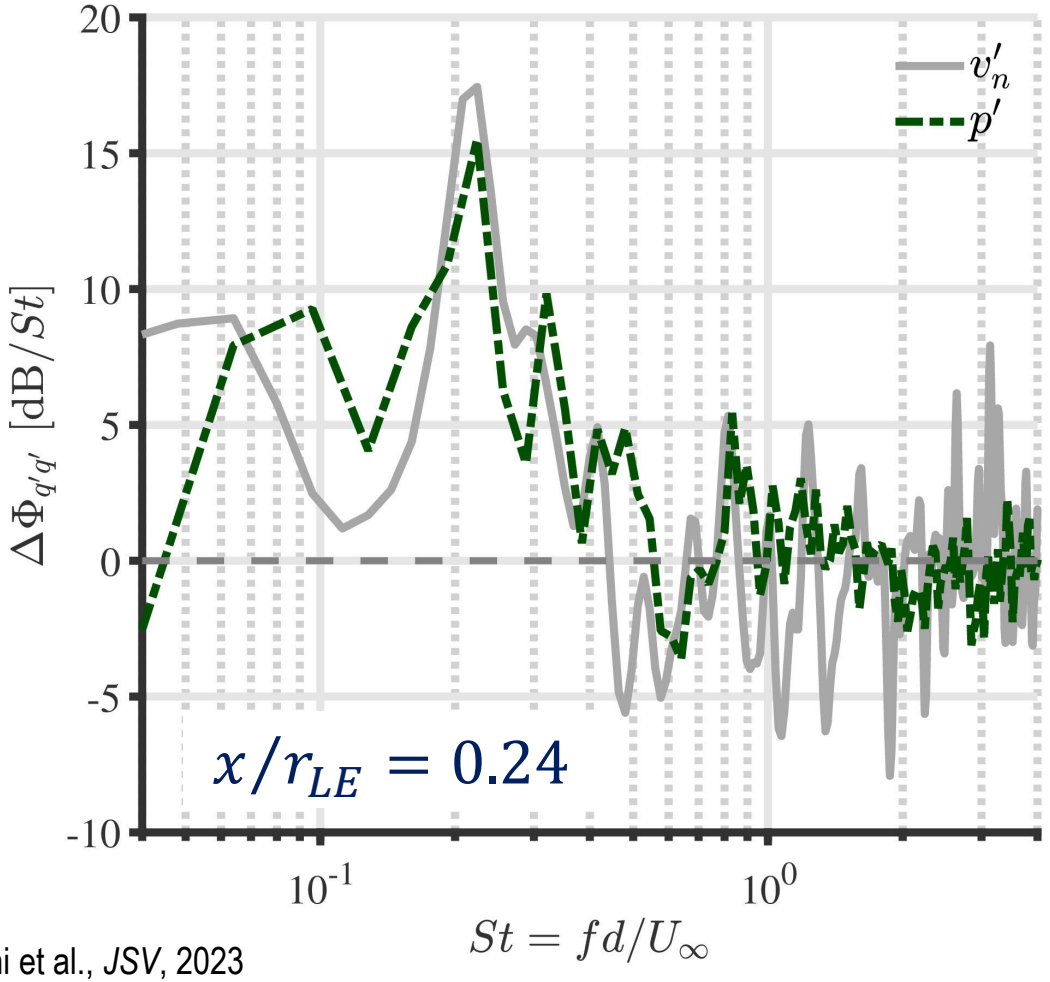
$x/r_{LE} = 0.47$

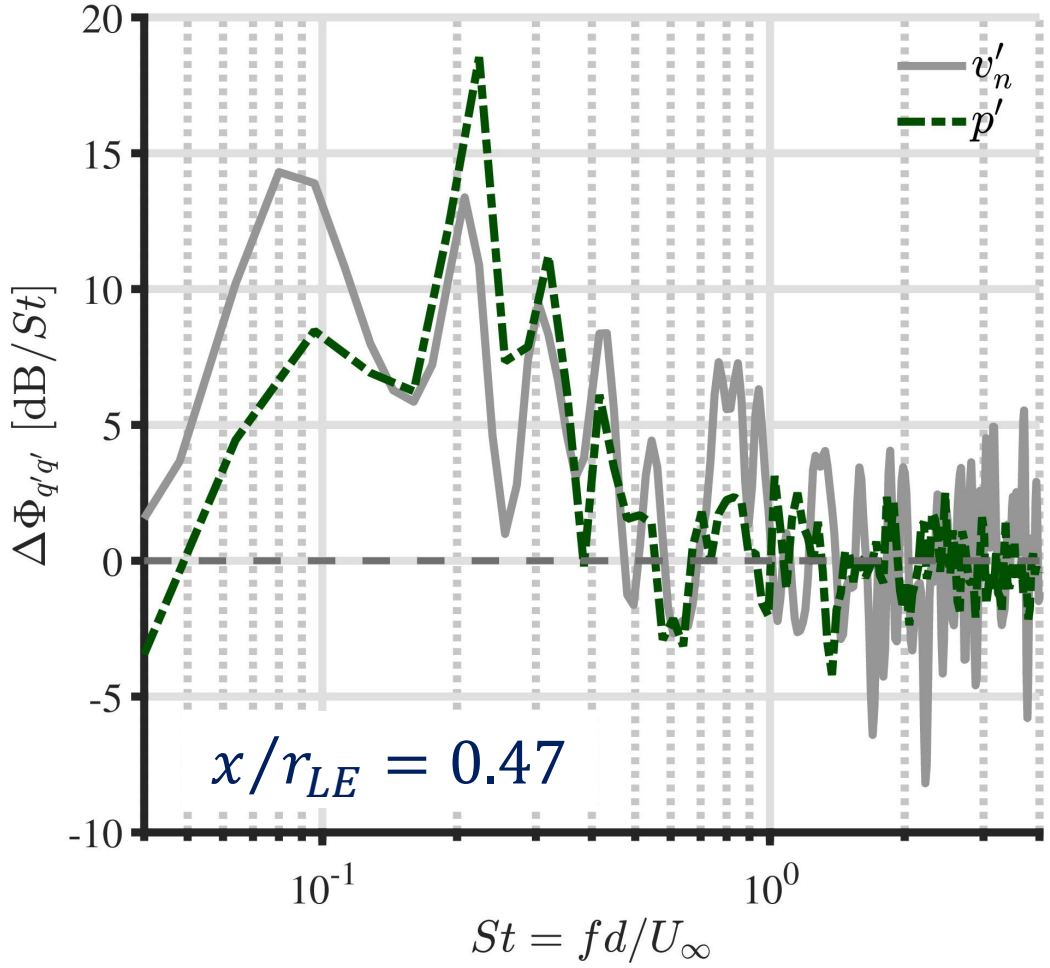


[1] Zamponi et al., *JFM*, 2021 **[2]** Zamponi et al., *JSV*, 2023

STUDY OF CURLE'S DIPOLAR SOURCES - p'

Surface-pressure fluctuations spectra indicating **attenuation** in **turbulence distortion** as one of the dominant **noise-reduction mechanisms** for TI noise



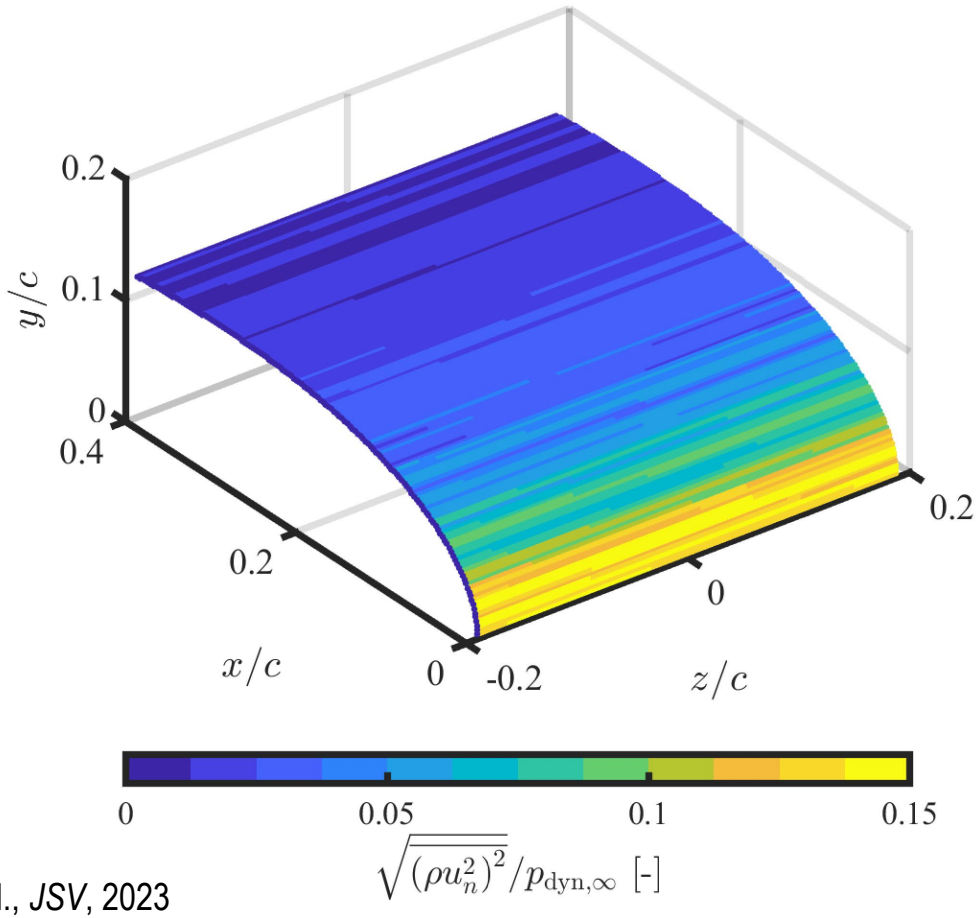


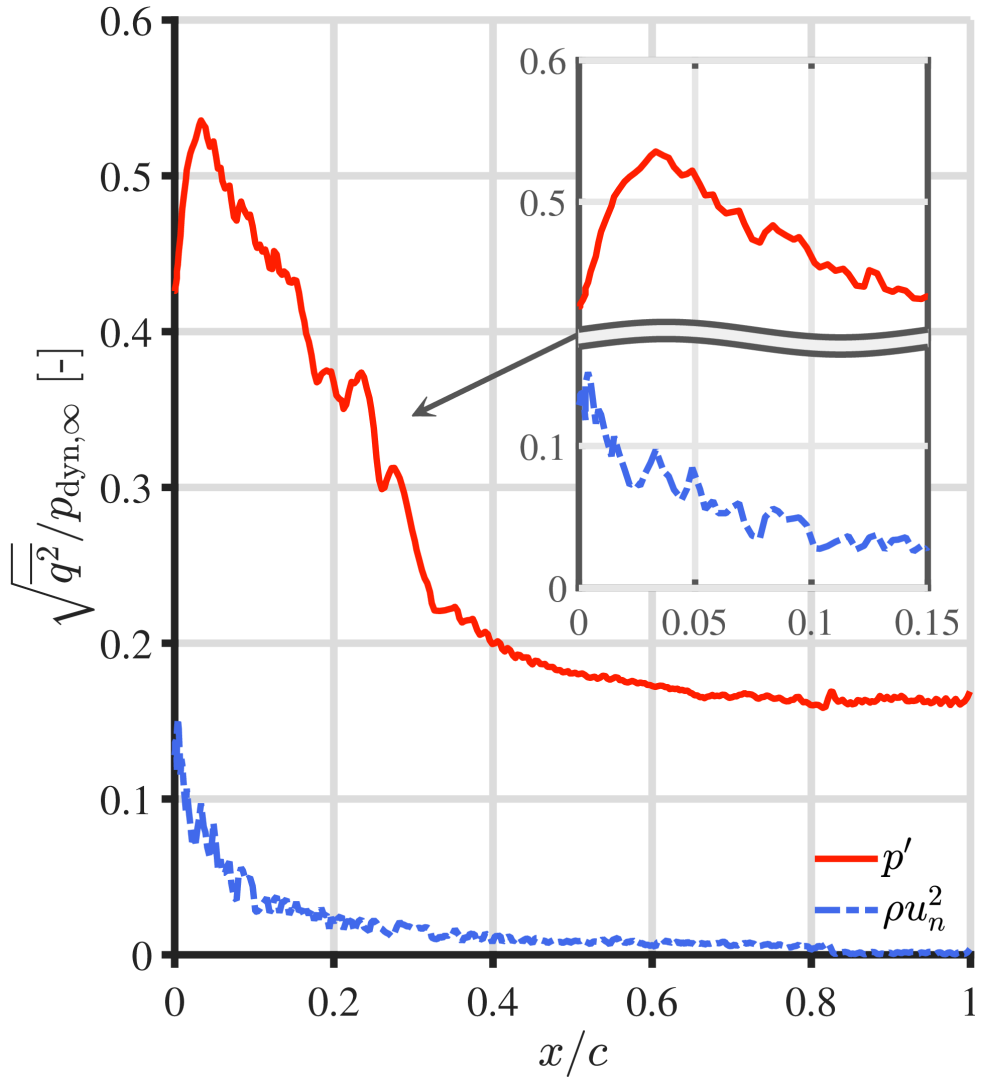
[1] Zamponi et al., *JSV*, 2023

STUDY OF CURLE'S DIPOLAR SOURCES - ρu_n^2

Amplitude of Reynolds-stresses term **considerably smaller** than that of unsteady-pressure term

Porous airfoil

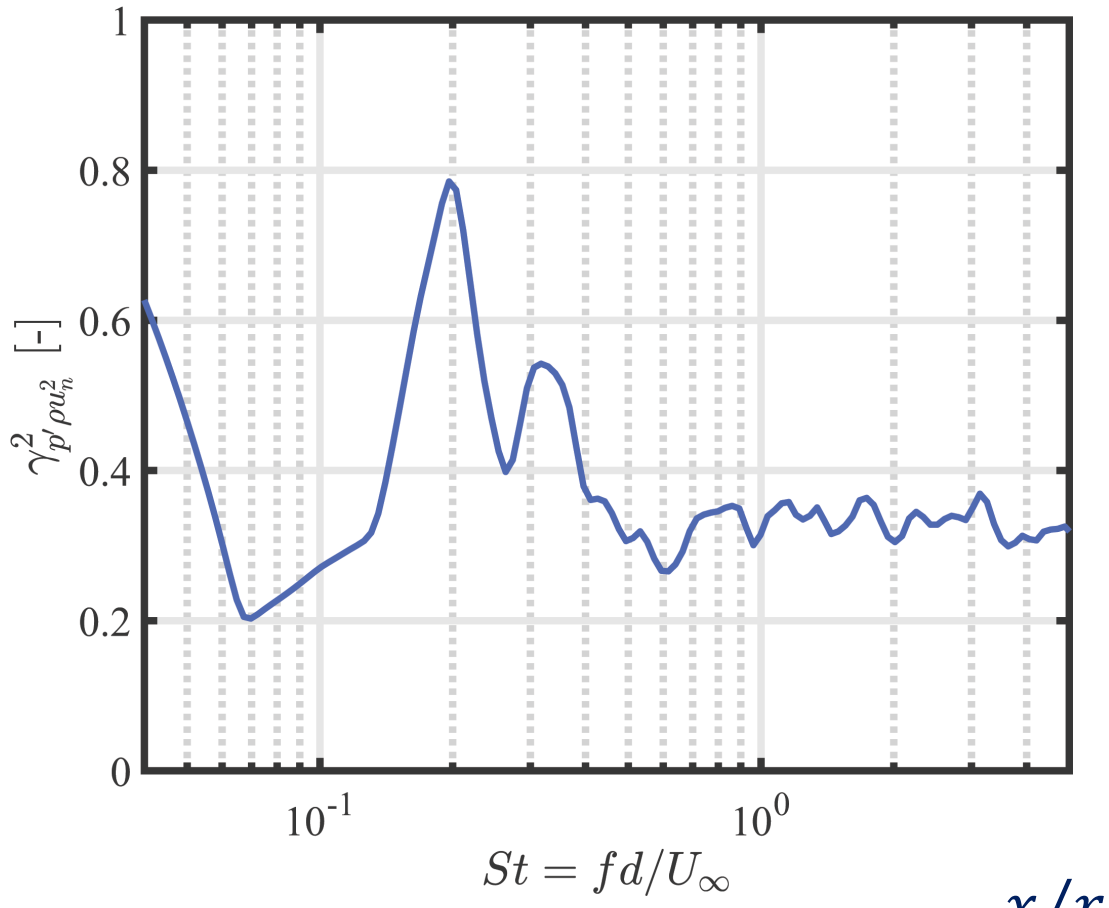


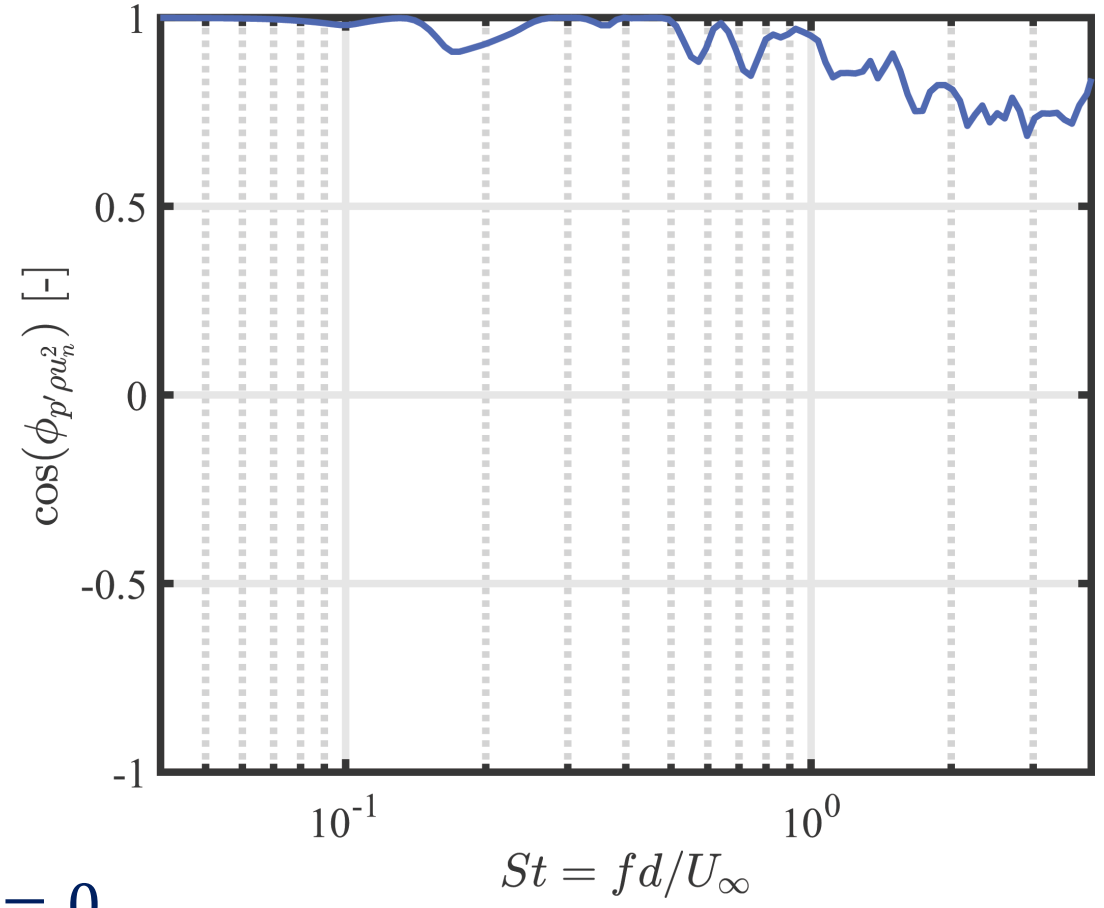


[1] Zamponi et al., *JSV*, 2023

STUDY OF CURLE'S DIPOLAR SOURCES - TERMS CORRELATION

Cross-coherence of unsteady-pressure term and Reynolds-stresses term in porous airfoil **not negligible**: potential **constructive phase interference**



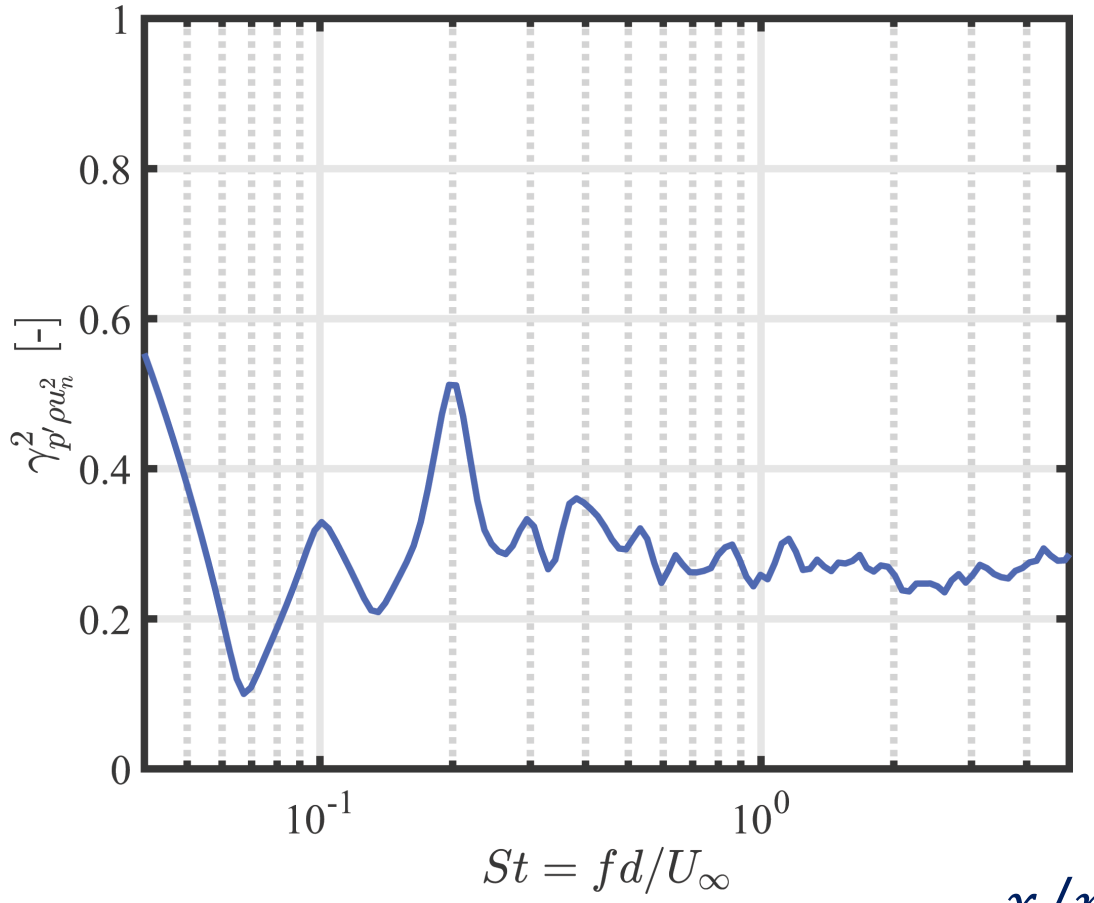


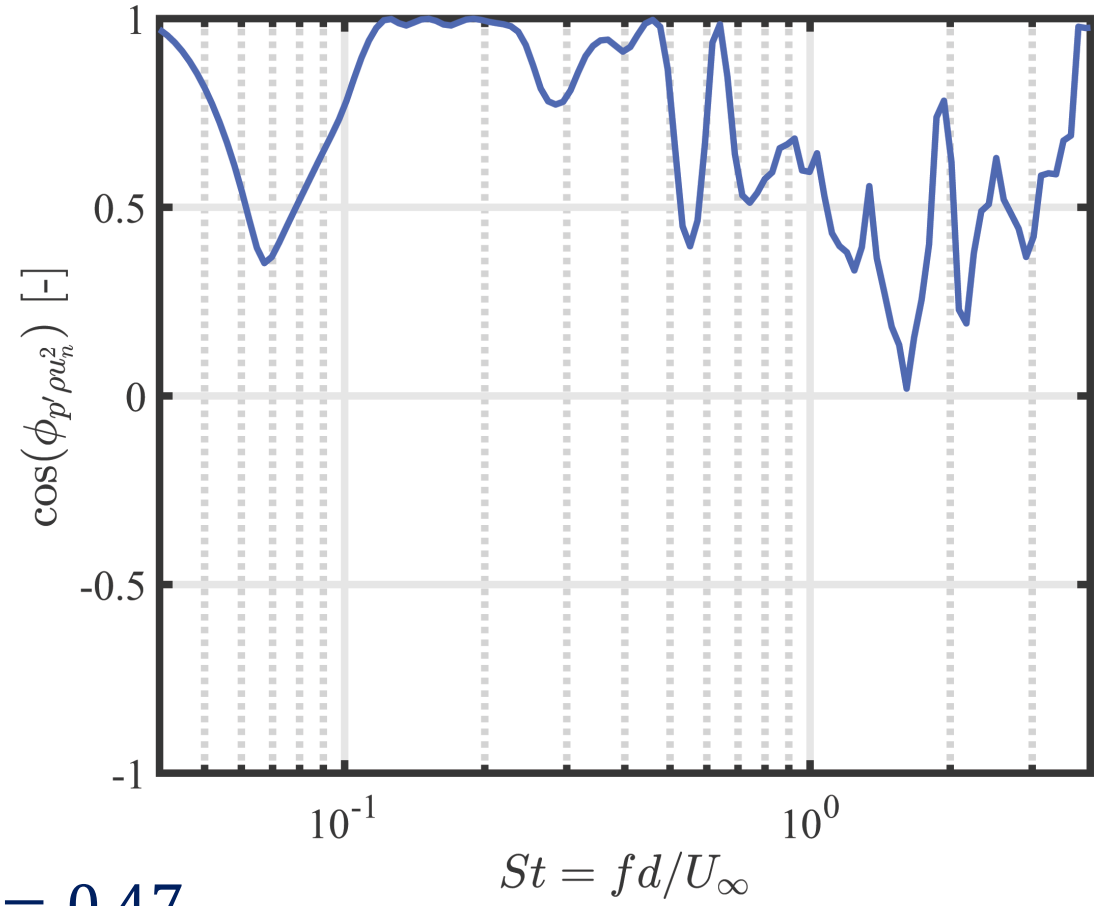
$x/r_{LE} = 0$

[1] Zamponi et al., *JSV*, 2023

STUDY OF CURLE'S DIPOLAR SOURCES - TERMS CORRELATION

Cross-coherence of unsteady-pressure term and Reynolds-stresses term in porous airfoil **not negligible**: potential **constructive phase interference**





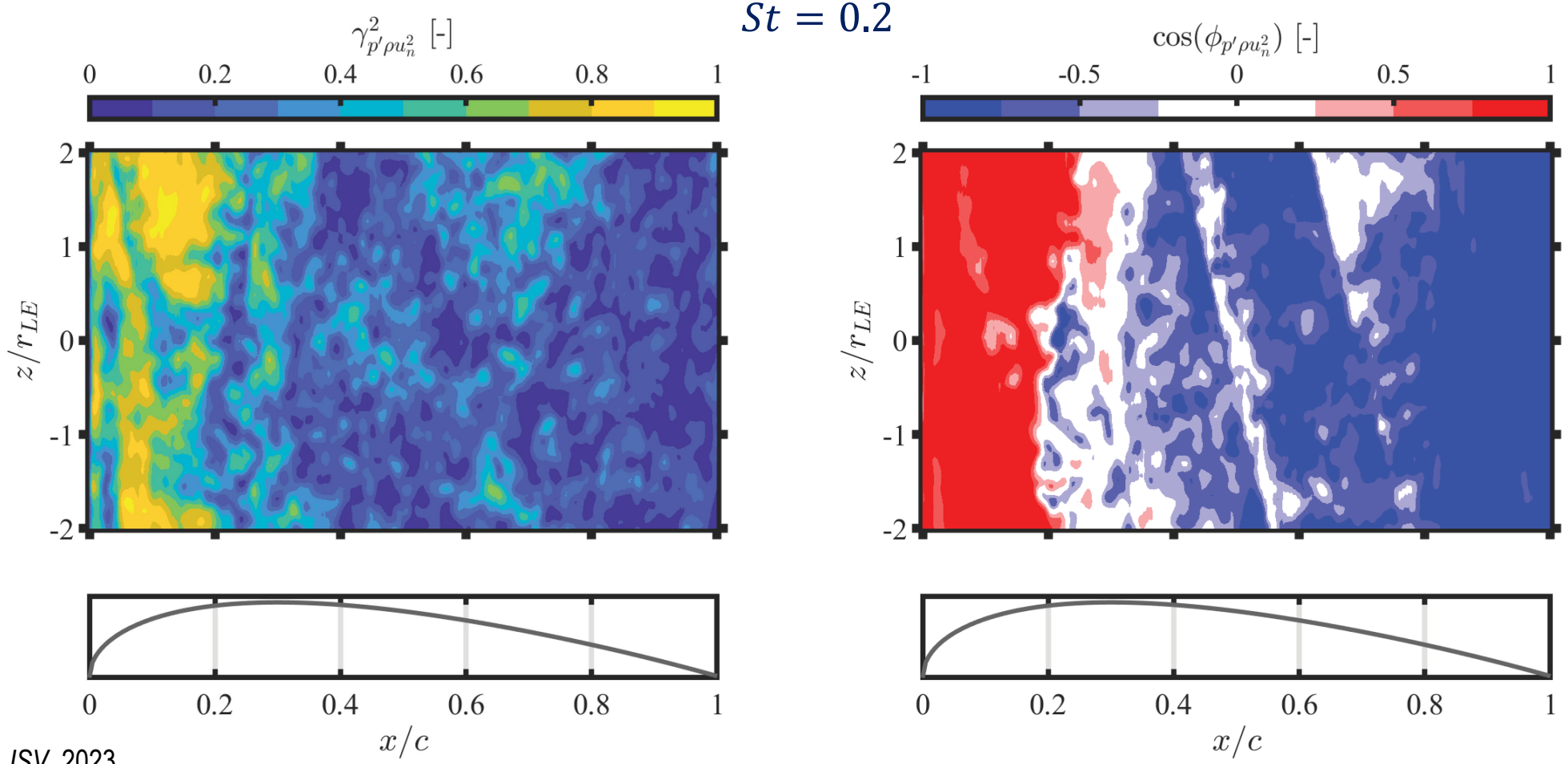
$x/r_{LE} = 0.47$

[1] Zamponi et al., *JSV*, 2023

STUDY OF CURLE'S DIPOLAR SOURCES - TERMS CORRELATION

Cross-coherence of unsteady-pressure term and Reynolds-stresses term in porous airfoil **not negligible**: potential **constructive phase interference**

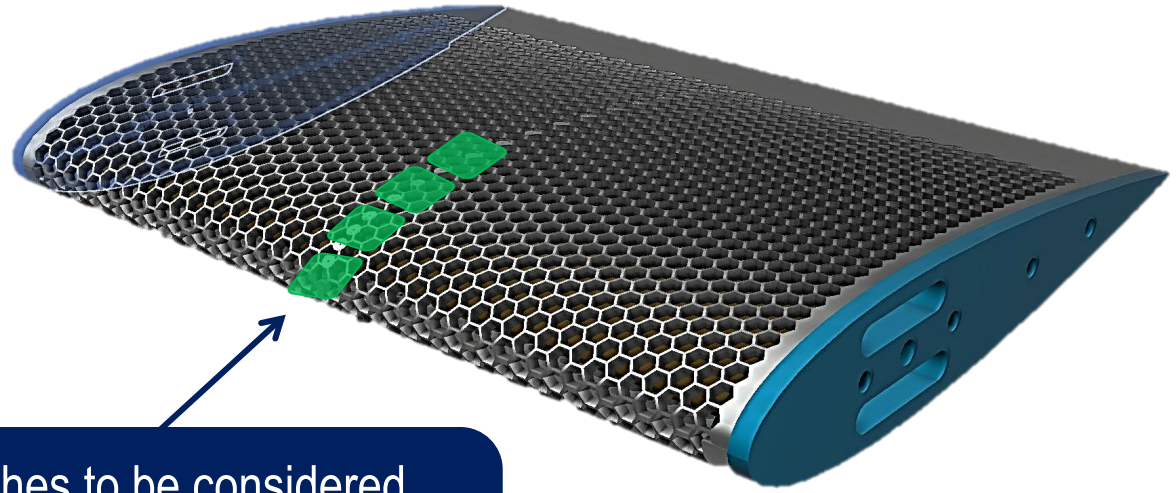
$St = 0.2$



CONTRIBUTION OF CURLE'S DIPOLAR SOURCES TO FAR-FIELD NOISE

Integration of Curle's dipolar sources performed following a **strip approach** by evaluating **chordwise-varying patches** on the airfoil surface

$$p^* \backsimeq -\frac{x_j}{4\pi|\vec{x}|^2 c_0}\frac{\partial}{\partial t}\left[\iint_S \left(p'\delta_{ij} + \rho u_i u_j\right) n_j dS\right]_{\tau=t_e}$$



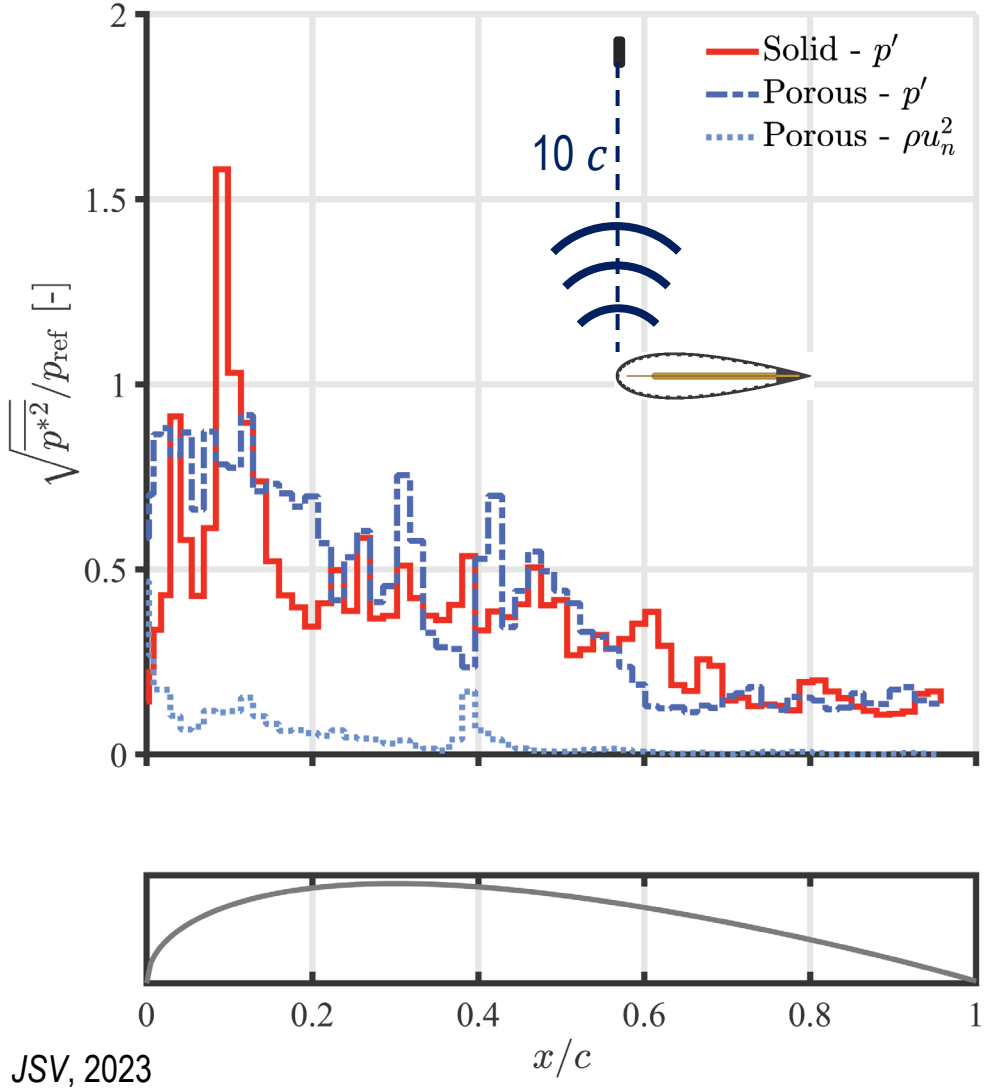
Patches to be considered acoustically **compact** in frequency range of interest

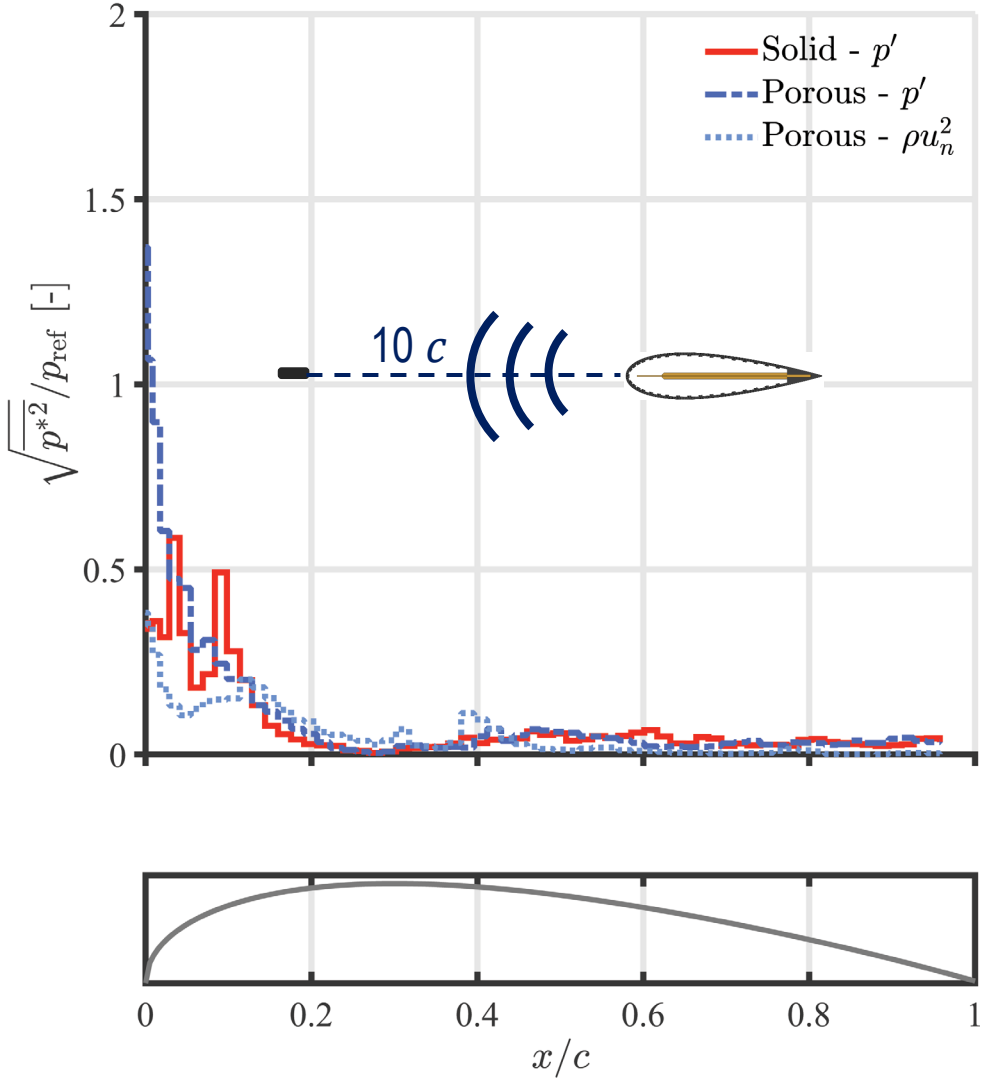
Focus points of the study:

- Evaluate the **local contribution** of dipolar sources to the far-field noise
- Suggest the **orientation** of the **Reynolds-stresses** dipolar **term**
- Investigate the **mutual interference** between patches in the far-field noise
- Reveal the **directivity pattern** of the TIN radiated by the airfoil

CONTRIBUTION OF CURLE'S DIPOLAR SOURCES TO FAR-FIELD NOISE

Different contributions of Curle's dipolar sources to p^* depending on **listener location**





[1] Zamponi et al., *JSV*, 2023

TABLE OF CONTENTS

Framework: flow-induced noise reduction by porosity

Physical problem from the analogy point of view

Physical effects of porosity on airfoil-noise sources

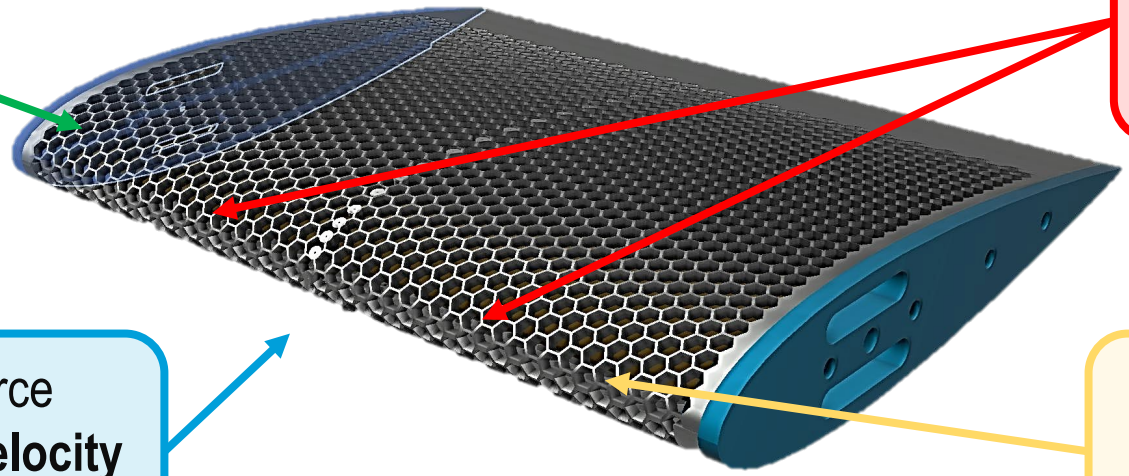
Guidelines for effective porous-treatment design



FOCUS POINTS FOR POROUS-AIRFOIL DESIGN

Largest pressure fluctuations located **downstream** of the LE

Spanwise-uniform porosity not effective in breaking **spatial coherence**



Additional noise source produced by **non-zero velocity** at the porous surface

Important role played by **attenuation** of turbulence **distortion**

Towards a spanwise-varying porosity located in the region of largest pressure fluctuations

THANK YOU FOR YOUR ATTENTION

