3D-printed Permeable Trailing Edges for Broadband Noise Abatement

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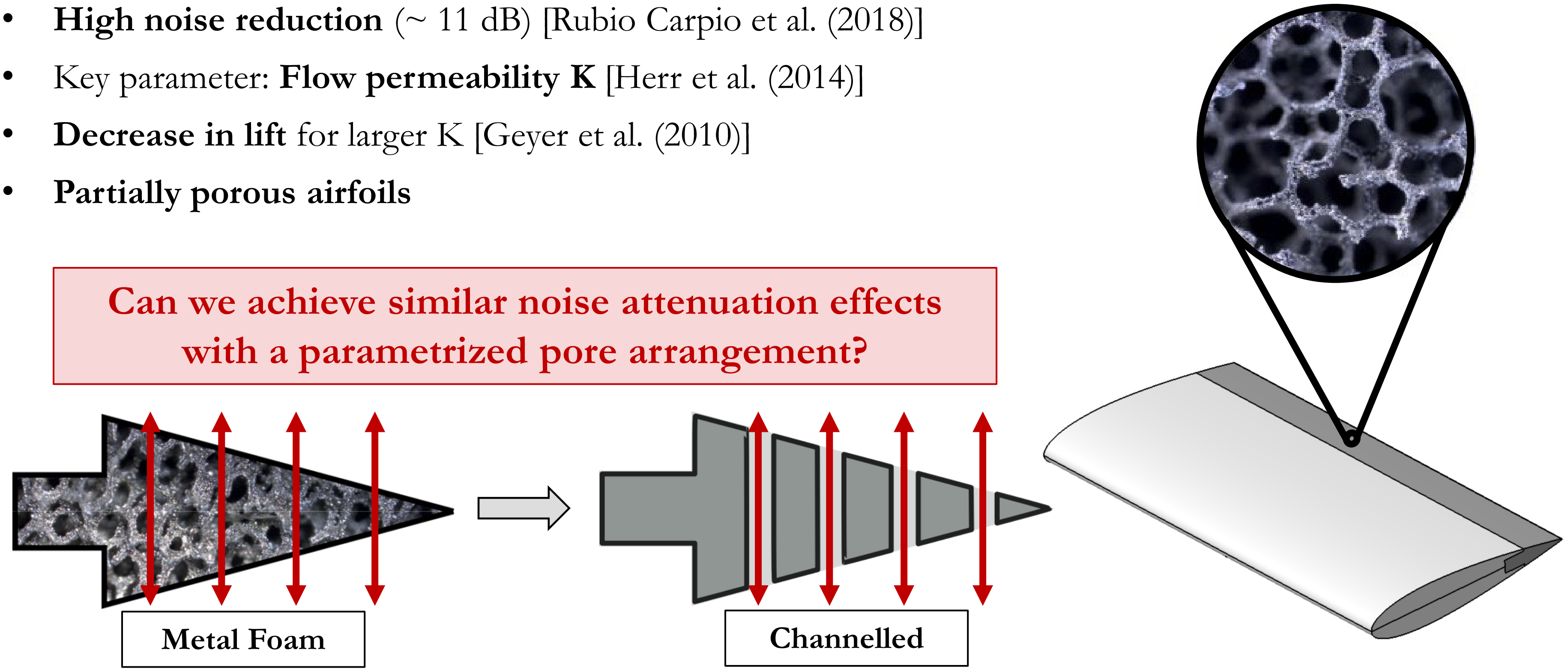
Roma Tre University, Rome, Italy

23rd Workshop of the Aeroacoustics Specialists Committee of the CEAS, 26-27 September 2019

Permeable Materials for Noise Reduction

- **High noise reduction** (~ 11 dB) [Rubio Carpio et al. (2018)]
- Key parameter: **Flow permeability K** [Herr et al. (2014)]
- **Decrease in lift** for larger K [Geyer et al. (2010)]
- **Partially porous airfoils**

Can we achieve similar noise attenuation effects with a parametrized pore arrangement?

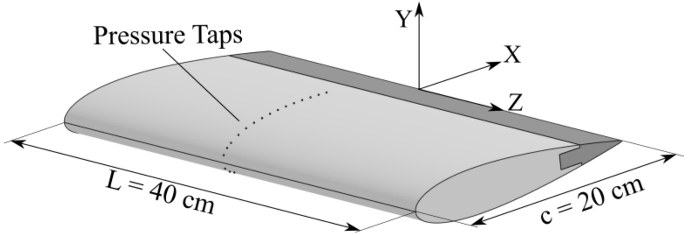


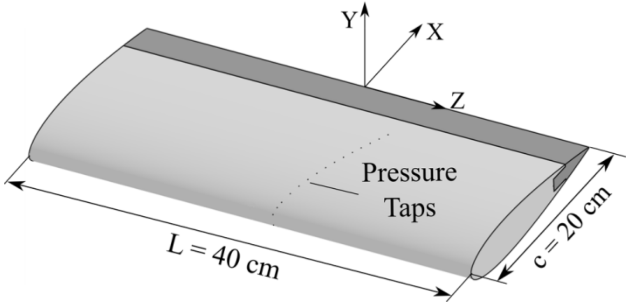
Experimental Set-Up

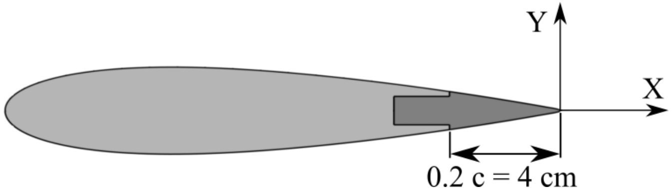
TU Delft CEAS

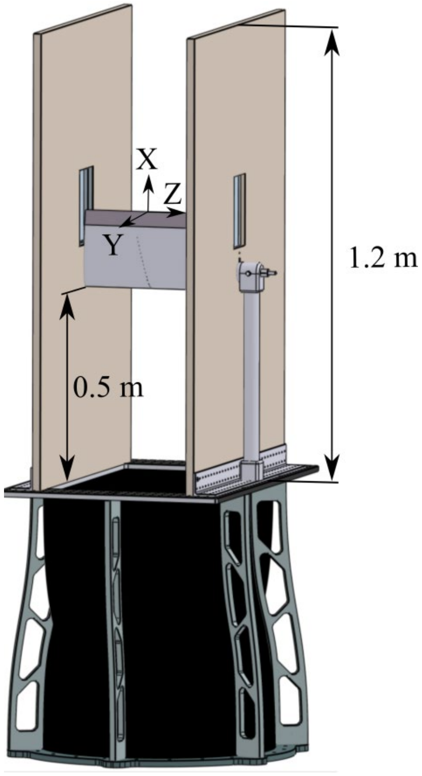
Model

- NACA 0018 airfoil: c = 20 cm; airfoil span: L = 40 cm
- Exchangeable permeable inserts: 20% of the airfoil
- Turbulent boundary layer transition: 20% of the chord
- Outlet section: 40x70 cm^2
- Free-stream velocity: U_∞ = 12.5 … 34 m/s
- Re_c: 140,000 … 380,000
- Free-stream turbulence: 0.05%





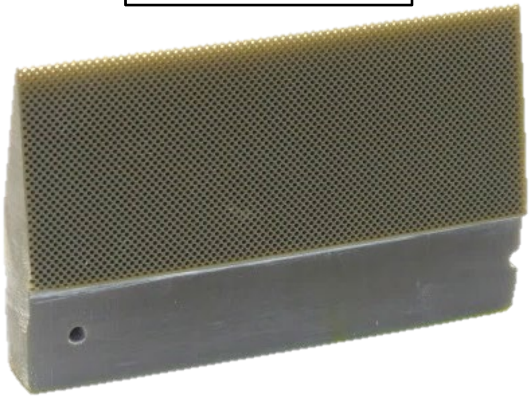


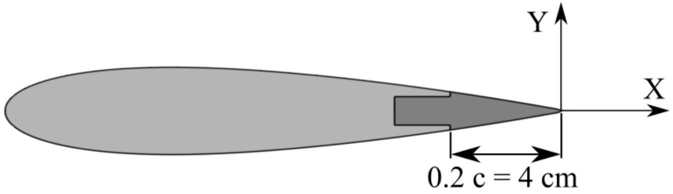


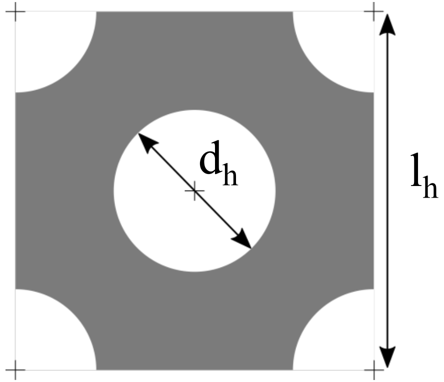
3D-printed Perforated Inserts

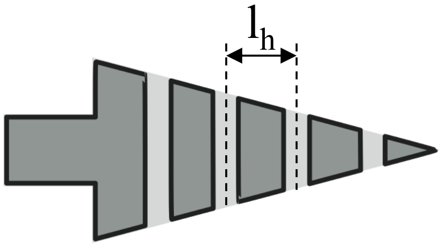
- EnvisionTEC's Perfactory 4 Standard
  - Resolution: 25 µm
  - Material: HTM 140 V2 (light-activated resin)
- Perforated inserts (x4) :
  - Span: 10 cm
  - Fixed hole diameter: d_h = 0.8 mm
  - Varying hole spacing: l_h = 1.5, …, 5 mm

l_h = 1.5 mm









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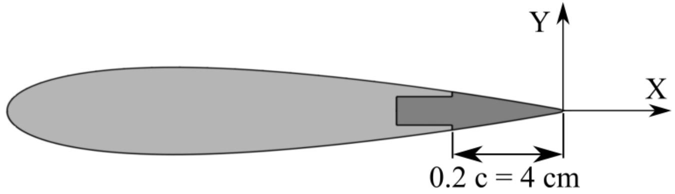
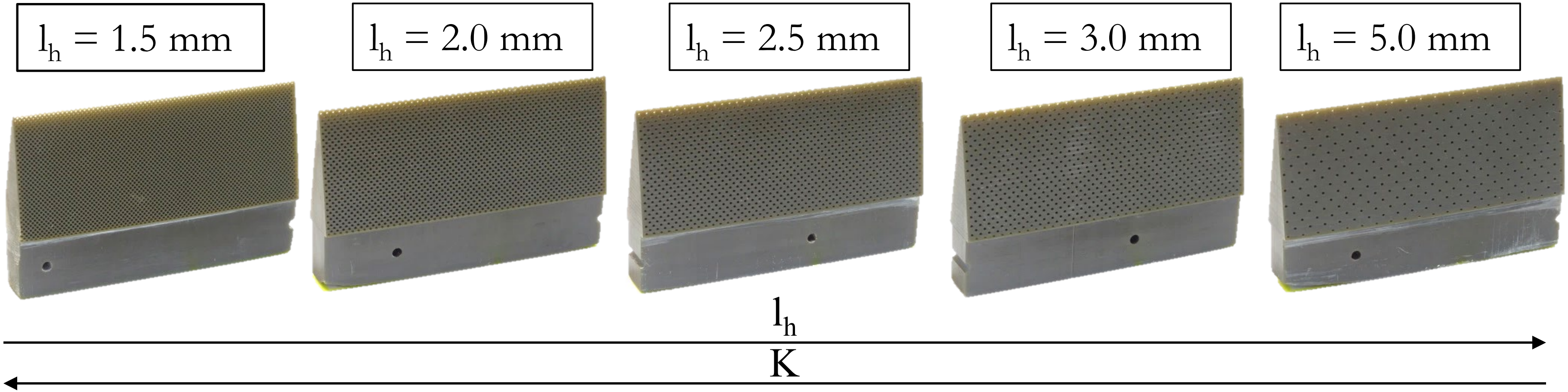




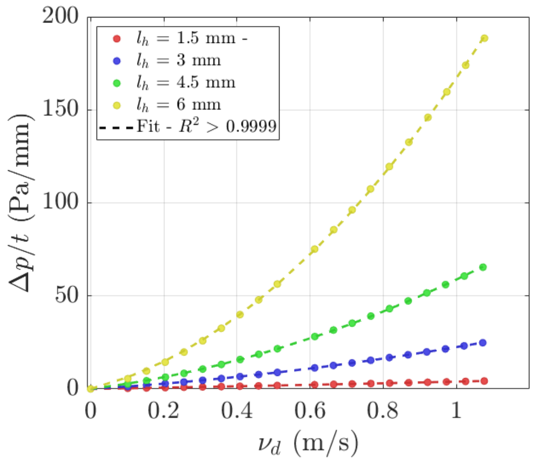
Permeability Characterization

- Perforated samples:
  - t = 1 cm; diameter of 5.5 cm
  - l_h = 1.5, …, 6 mm

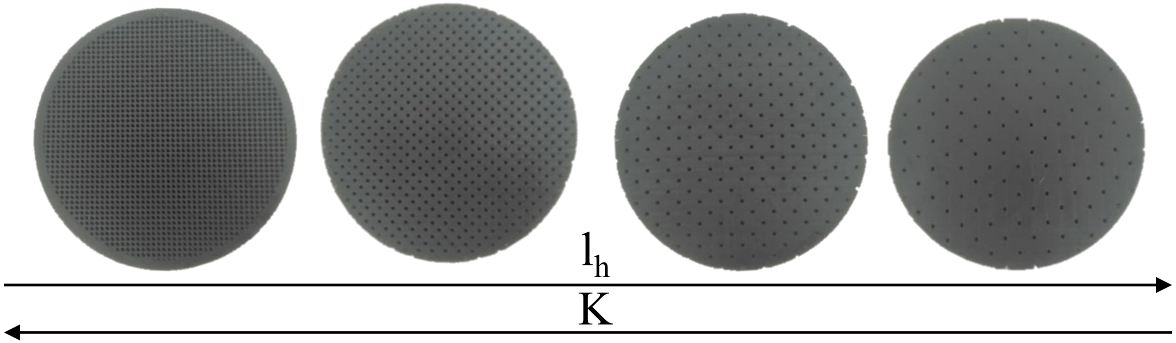
Hazen-Dupuit-Darcy Law:

$$\frac{\Delta p}{t} = \frac{\mu}{K} v_d + \rho C v_d^2$$ [Ingham (1998)]

Δp: pressure drop across the metal foam sample (Pa)
μ: dynamic viscosity (Pa s)
ρ: density (kg/m^3)
v_d: velocity (m/s)
t: thickness of the sample (m)

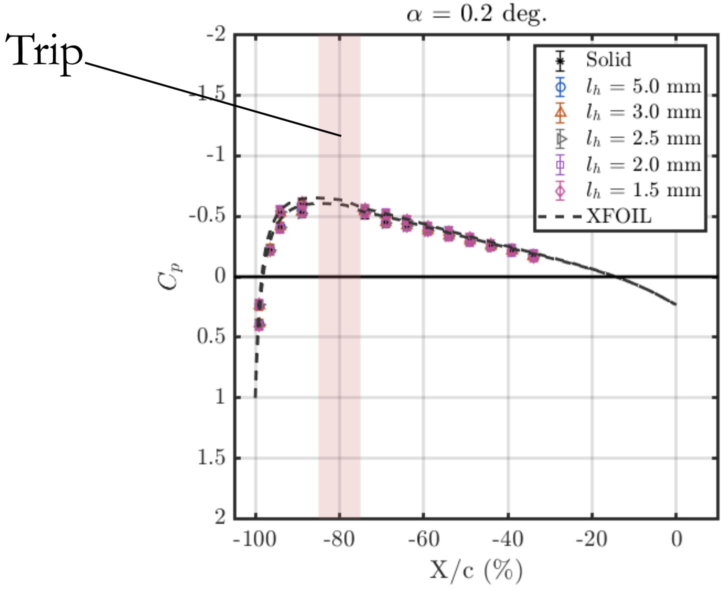


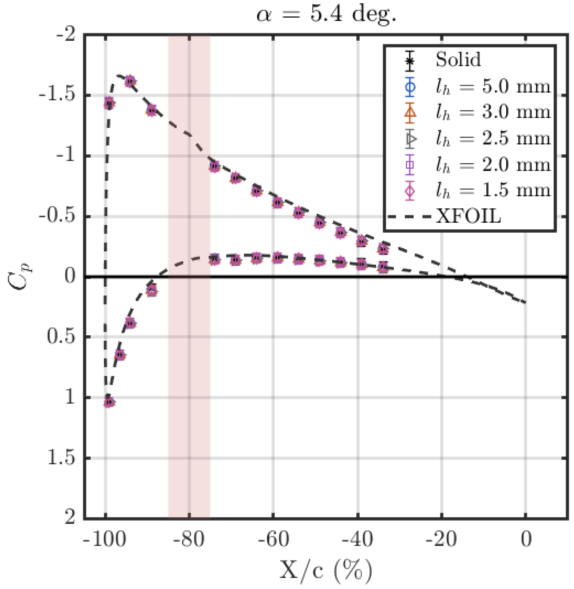
l_h (mm)	K (m^2) (x10^{10})
1.5	50
2	28
2.5	18
3	13
5	5



Experimental Set-up

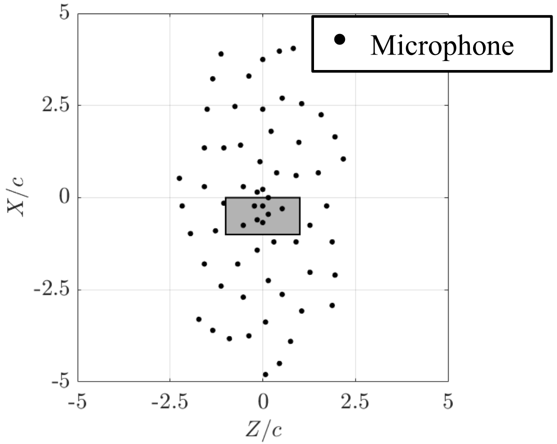
- Honeywell TruStability pressure sensors: range: -2.5 to 2.5 kPa; accuracy: ±0.25% FS
- Wind tunnel angle of attack: α_t = 0 and 8 deg.
- Effective angle of attack: α = 0.2 and 5.4 deg. (XFOIL)

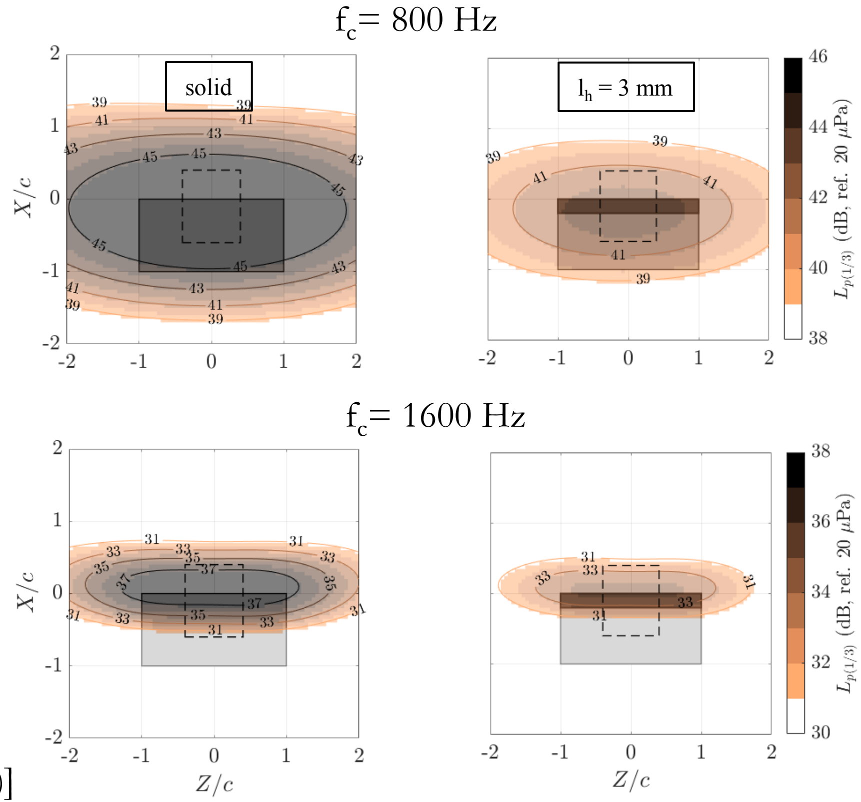




- No change in measured pressure distribution due to perforated inserts

Experimental Set-up





Hardware, acquisition parameters & data-processing:

- (64x) G.R.A.S. 40PH. free-field microphones: D = 2 m
- Distance array-trailing edge: 1 m
- Acquisition frequency: f_s = 50 kHz
- Acquisition period: T = 20 s
- Acoustic camera looking at suction side
- Adapted Underbrink design [Underbrink (2001)]
- Conventional frequency domain beamforming [Mueller (2002)]
- Source Power Integration [Sarradj et al. (2017)]

A-Tunnel

Results & Discussion

Results

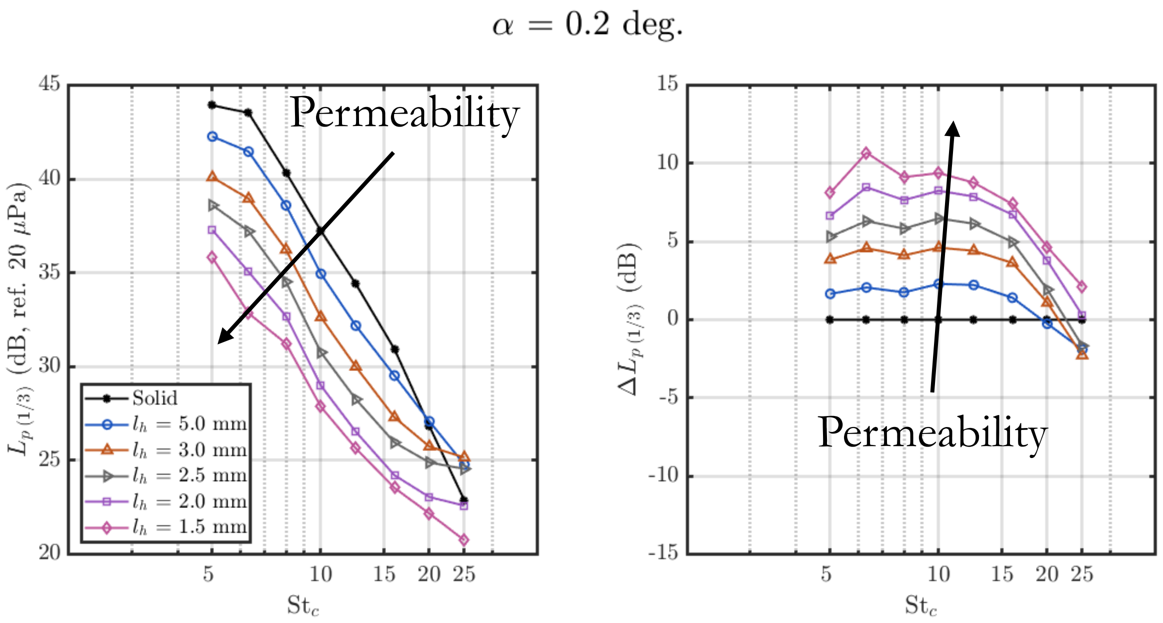
Broadband Noise Abatement with Channelled Inserts

- Sound Pressure Level at approximately no incidence, U = 20 m/s

$$\mathrm{St_c} = \frac{f\,c}{U_\infty}$$

$$\mathrm{L}_p = 10\log_{10}\frac{\overline{p^2}}{{p_0}^2}$$

p: far-field ac. pressure (Pa)
p_0: reference pressure (Pa)
f: frequency (Hz)
U_∞: free-stream velocity (m/s)
c: chord (m)



Results

Broadband Noise Abatement with Channelled Inserts

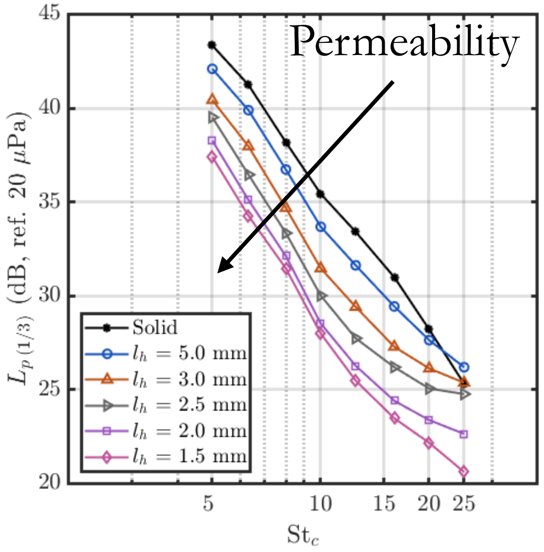
- Sound Pressure Level at a lifting condition, U = 20 m/s

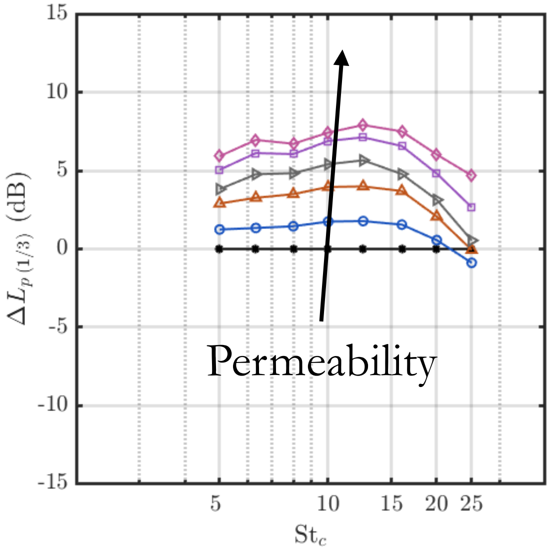
$$\mathrm{St_c} = \frac{f\ c}{U_\infty}$$

$$\mathrm{L}_p = 10\log_{10}\frac{\overline{p^2}}{{p_0}^2}$$

p: far-field ac. pressure (Pa)
p_0: reference pressure (Pa)
f: frequency (Hz)
U_∞: free-stream velocity (m/s)
c: chord (m)

α = 5.4 deg.

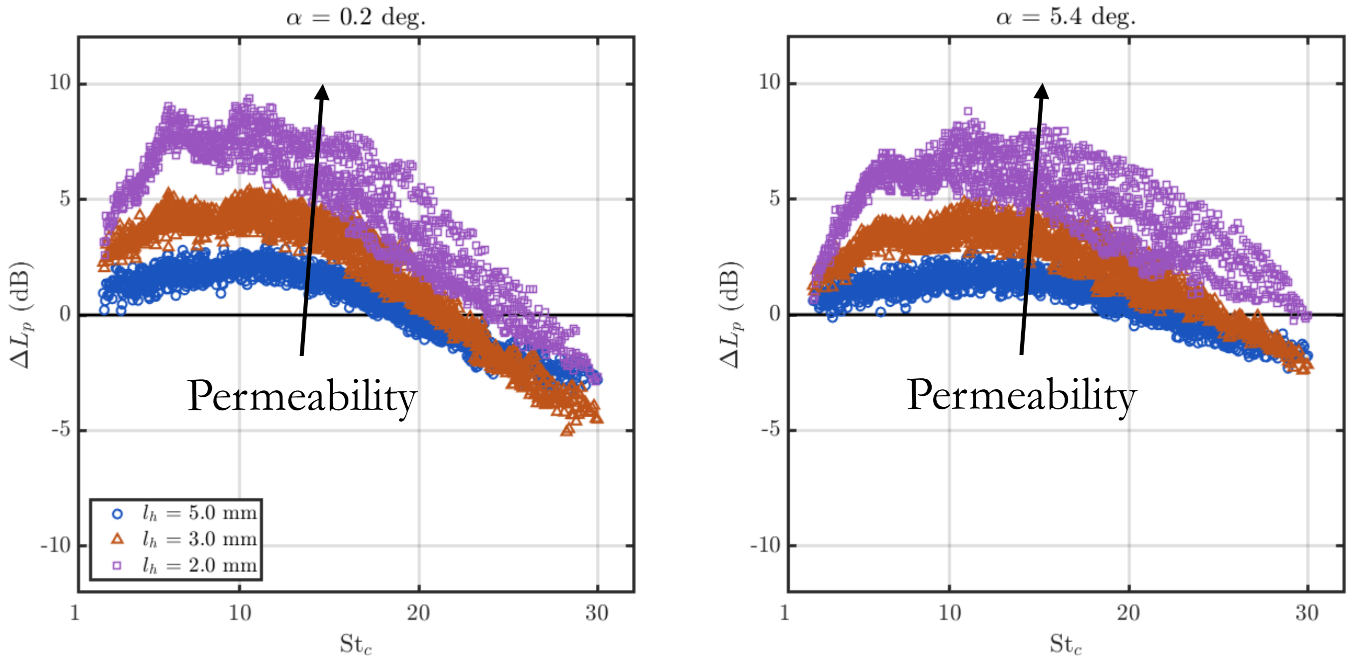




Results

Broadband Noise Abatement with Channelled Inserts

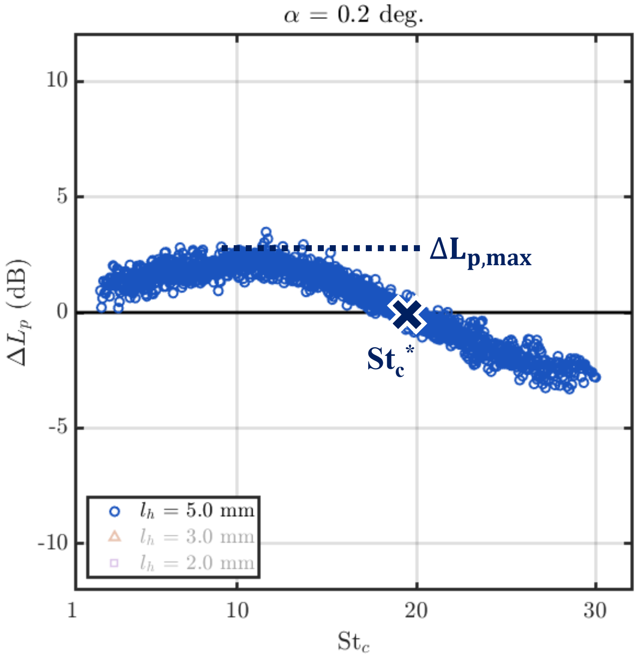
- Collapse of noise attenuation data measured at U_∞ = 12.5, 15, 20, 25, 30, 34 m/s with a simple Strouhal number relationship



Results

Broadband Noise Abatement with Channelled Inserts

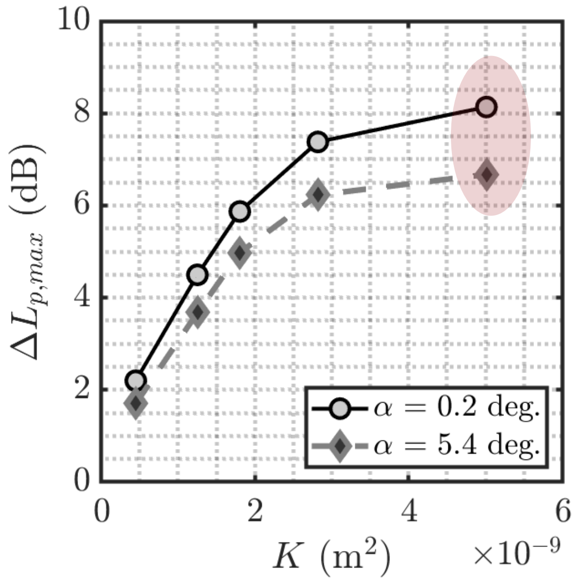
- Collapse of noise attenuation data measured at U_∞ = 12.5, 15, 20, 25, 30, 34 m/s with a simple Strouhal number relationship
- Computation of maximum noise reduction $\Delta L_{p,max}$ and cross-over Strouhal number St_c^*

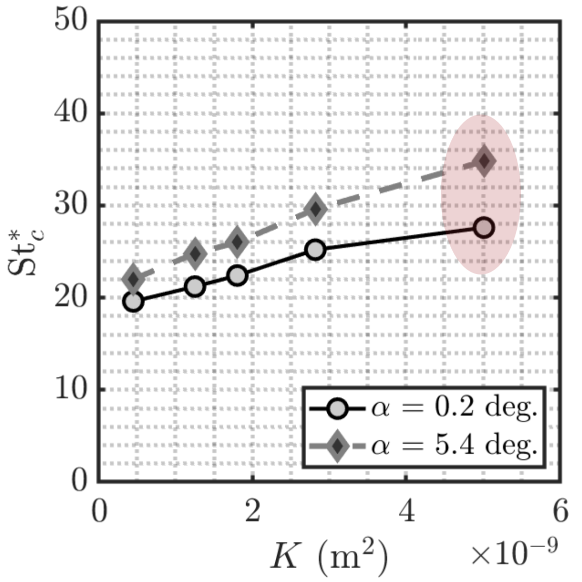


Results

Broadband Noise Abatement with Channelled Inserts

- Variation of maximum noise reduction $\Delta L_{p,max}$ and cross-over Strouhal number St_c^* with permeability K .

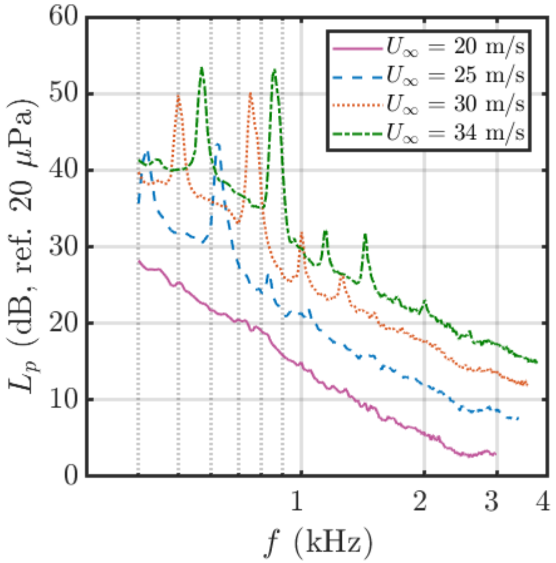


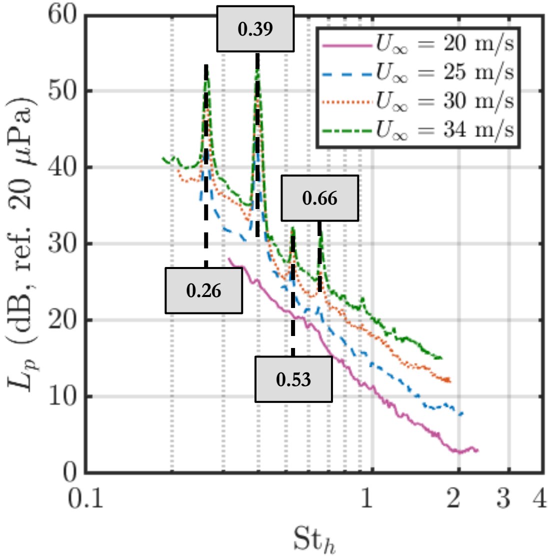


Results

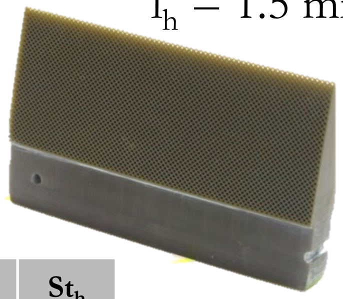
Tonal Noise at Channelled Inserts

- Appearance of tonal noise for the most permeable perforated insert (l_h = 1.5 mm).



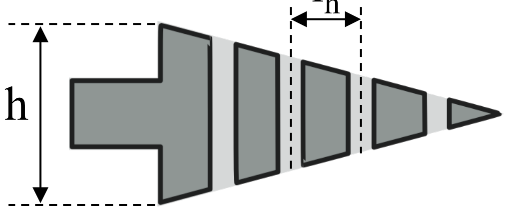


l_h = 1.5 mm



	St_h
FT	0.13
H_1	0.26
H_2	0.39
H_3	0.52
H_4	0.65

$$St_h = \frac{f\,h}{U_\infty}$$

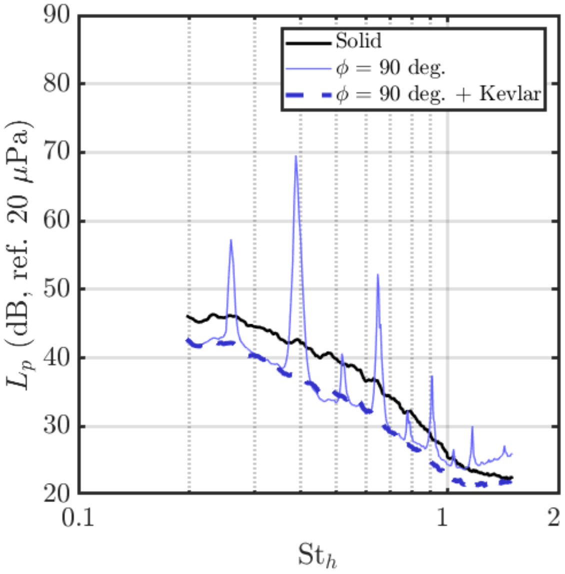


- Strouhal number based on the airfoil thickness at the root of the insert (h = 15.7 mm) for the fundamental tone (= 0.13) is in line with airfoil blunt trailing-edge noise (~0.11).

Results

Tonal Noise at Channelled Inserts

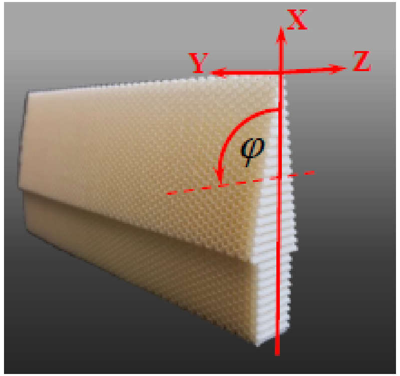
- Another way is to cover the inserts with Kevlar.
- Far-field acoustic spectra for α = 0 deg. and U_∞ = 40 m/s



Material	d_h (mm)	K (m^2) (x10^{10})
HTM 140 V2	0.8	50
PLA	1.2	233
PLA + Kevlar*	1.2	72

*Kevlar 49T965 fabric, weight-to-area ratio of 61 g/m^2, density of 1,45 g/m^3, thickness of 0,12 mm.

	St_h
FT	0.13
H_1	0.26
H_2	0.39
H_3	0.52
H_4	0.65
H_5	0.78
H_6	0.91



3D-printed permeable TE insert, φ = 90°

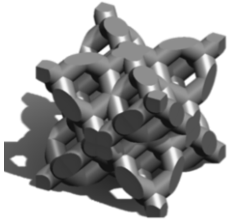
[S. Luesutthiviboon et al. (2019), Int. Jour. Aeroac., submitted]

Preliminary Results

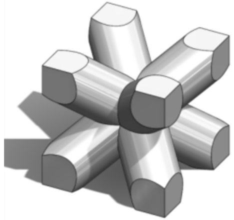
3D-Printed Porous Media

- Far-field acoustic spectra for $\alpha = 0$ deg. and $U_\infty = 40$ m/s

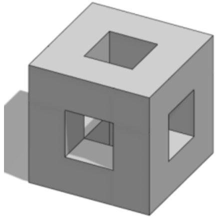
Diamond

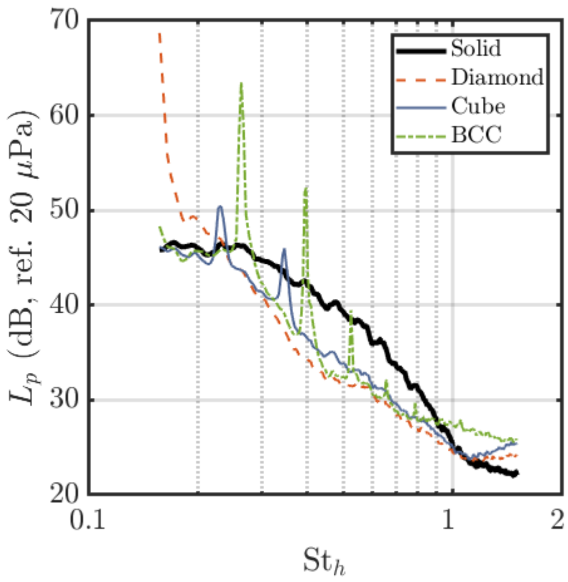


BCC



Cubic





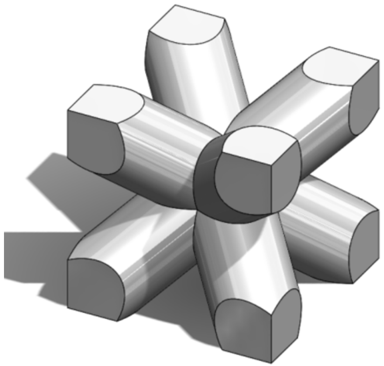
Material	**Shape**	***K*** **(m²) (x10¹⁰)**
HTM 140 V2	Channelled	50
PLA	Diamond	160
PLA	BCC	153
PLA	Cube	158

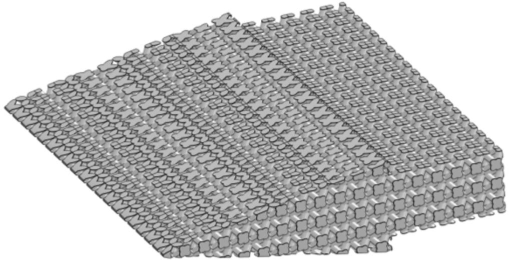
	St_h		
	Diamond	**Cube**	***BCC***
FT	<u>0.15</u>	<u>0.12</u>	<u>0.13</u>
H_1	-	0.23	0.26
H_2	-	0.35	0.39
H_3	-	0.47	0.53

[R. Hedayati et al. (2020)]

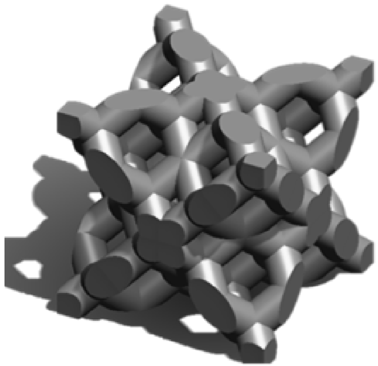
Ongoing Work

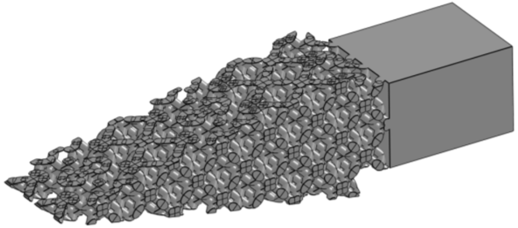
BCC



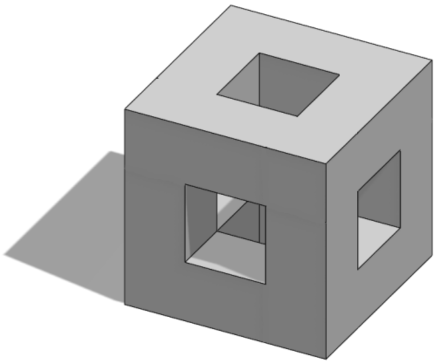


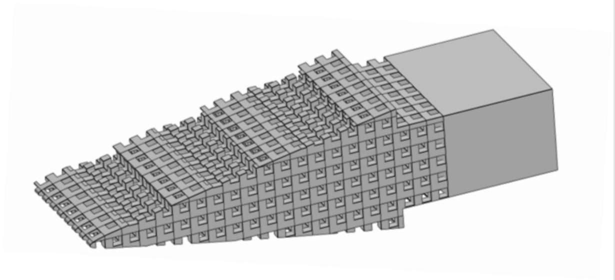
Diamond





Cubic





[R. Hedayati et al. (2020)]

Conclusions

Conclusions

- Perforated inserts mimic the behaviour of other permeable treatments with more complex micro-structure.
- Perforated inserts yield up to 11 dB noise attenuation at $\alpha = 0.2$ deg., and up to 9 dB at $\alpha = 5.4$ deg. for increasing flow permeability.
- Noise attenuation w.r.t. the baseline configuration collapses with a simple chord-based Strouhal number relationship.
- The maximum noise attenuation and the cross-over Strouhal number can be empirically correlated to the permeability.
- For inserts with very high permeability, a tonal noise appears at a Strouhal number based on the thickness of the solid-permeable junction ranging from 0.13 to 0.15; the exact value depends on the pore arrangement.
- The tonal noise can be modified by employing treatments with a streamwise permeability gradient or by covering the inserts with Kevlar.

References

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- *A. Rubio Carpio, F. Avallone, D. Ragni, M. Snellen, S. van der Zwaag;* **3D-printed Perforated Trailing Edges for Broadband Noise Abatement**; 25th AIAA/CEAS Aeroacoustics Conference; AIAA 2019-2458; https://doi.org/10.2514/6.2019-2458

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- *A. Rubio Carpio, F. Avallone, D. Ragni, M. Snellen, S. van der Zwaag*; **3D-printed Permeable Trailing Edges for Broadband Noise Abatement;** AIAA Journal; To be submitted

Thank you for your attention!

TUDelft CEAS

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