Etude aéroacoustique d'un canal avec obstacle(s) - Application à la production de fricatives

Yo FUJISO

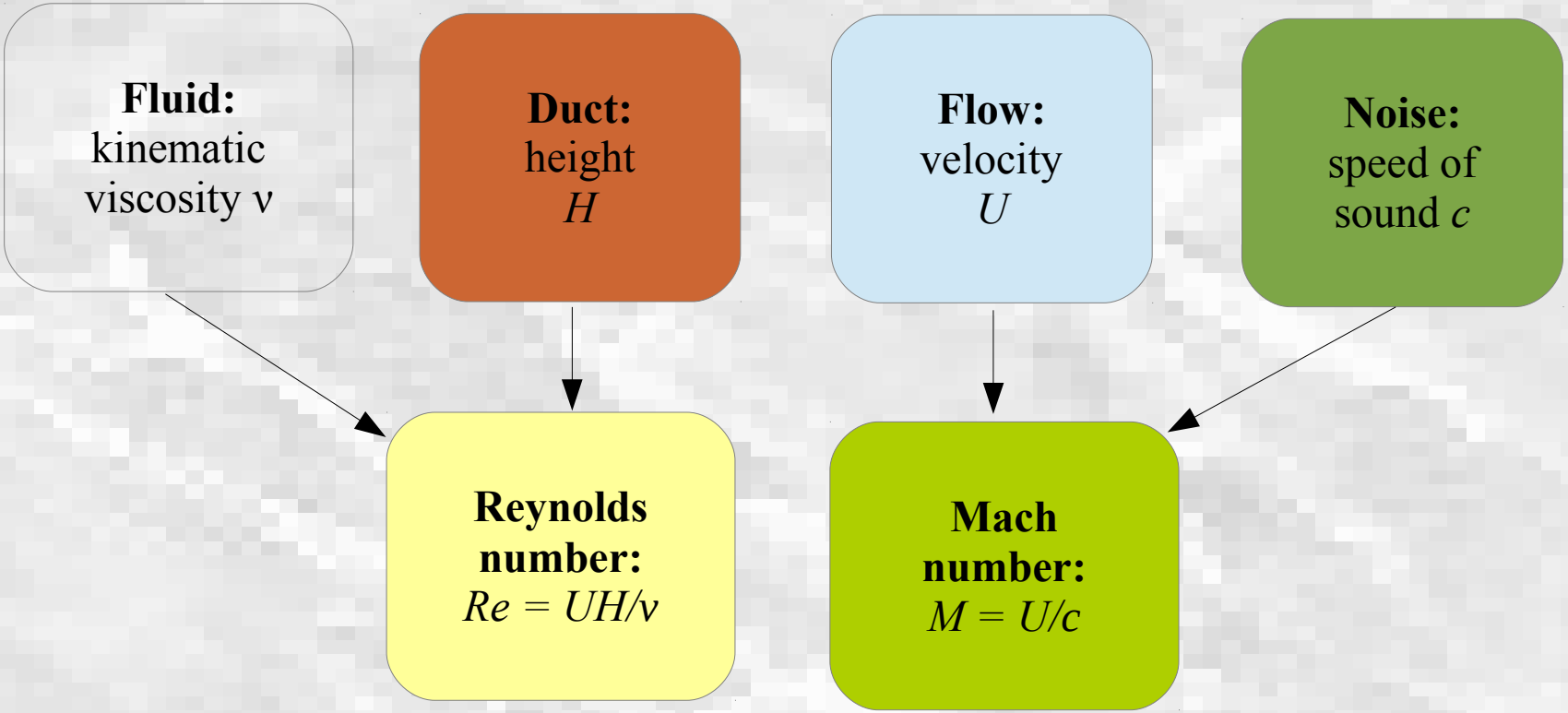
GIPSA-lab, Département Parole & Cognition

Equipe GAMA (Gestes phonatoires, Analyse & Modélisation Acoustique)

Supervisor: Annemie VAN HIRTUM

February 14th, 2014

Duct aeroacoustics?



Flow classification according to Reynolds number

$Re \leq 10^2$

e.g.
- Stokes flows
- geophysical flows
(glaciers)

$10^2 \leq Re \leq 10^4$

e.g.
- biological airflows
(respiration,
speech production...)

Gap in literature?

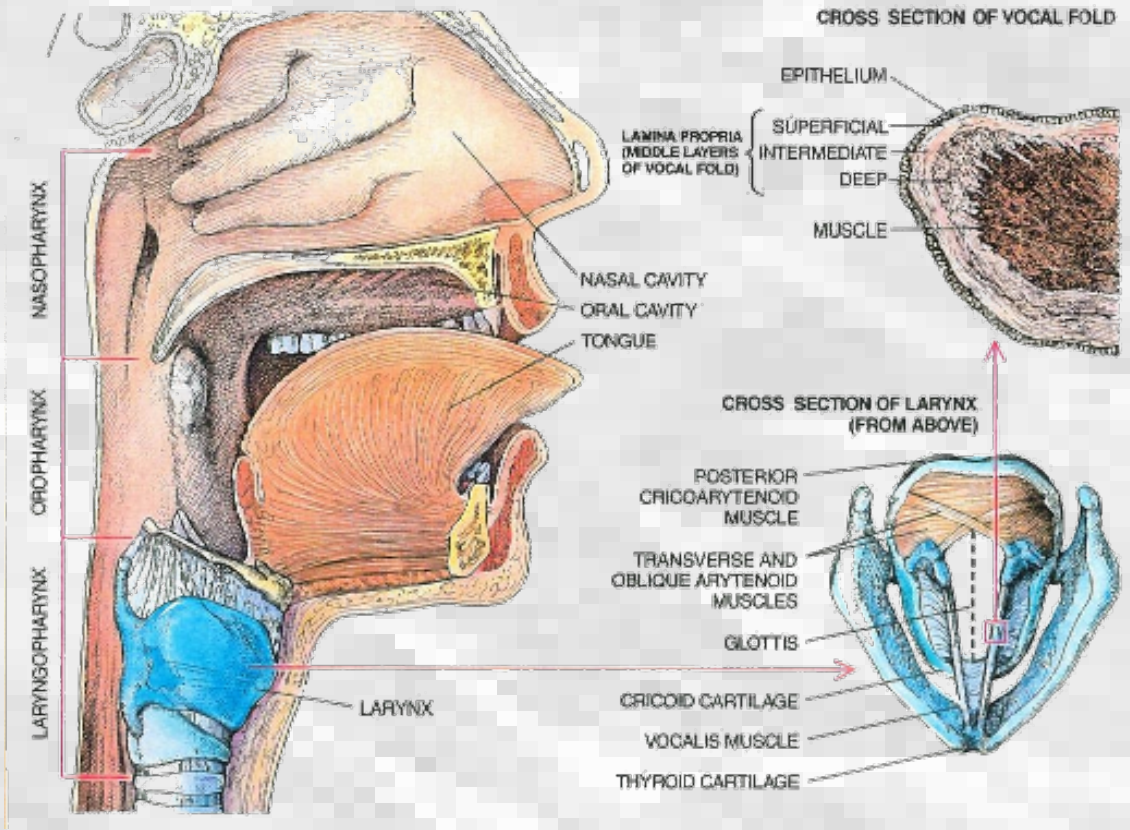
$10^4 \leq Re$

e.g.
- industrial flows
(aircrafts, trains...)
- wind flows
(hurricanes...)

Low Mach numbers
(M<0.3)
→ **incompressible flows**

low — **Reynolds number** — high

laminar — **transition** — **turbulent**



Upper airways, vocal tract [Sataloff 1992]

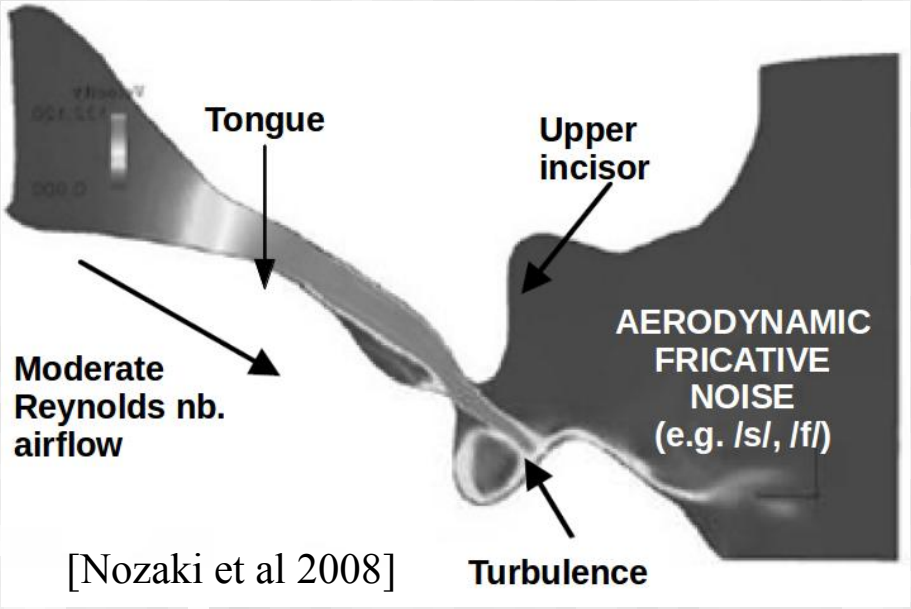
Human speech production:

Airflow → Re=O(10^4) & M<0.3
(from *in-vivo* observations)

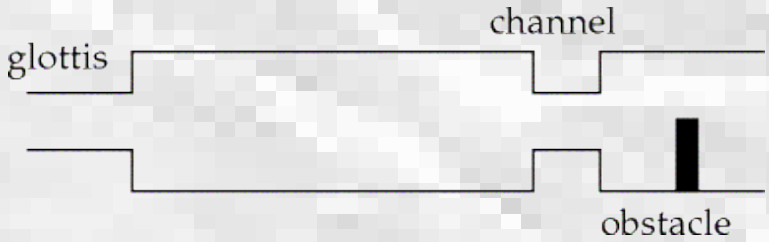
Various speech sounds:

* **Voiced sounds** e.g. vowels → vibration of vocal folds

* **Unvoiced (or voiceless) sounds** e.g. unv. stops, unv. fricatives
→ no vibration of vocal folds
→ various sound sources



[Nozaki et al 2008]



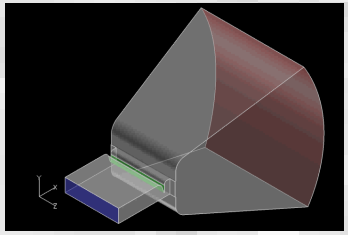
[Shadle 1985-1991; Ramsay 2006]

Unvoiced fricative consonants:
/f/ ('fanfare'), /s/ ('scie'), /ʃ/ ('chat')

System: upstream duct + downstream obstacle

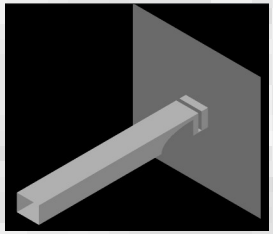
Source: turbulent jet interacting with **surface/obstacle**

Approach:
→ *In-vitro* geometries

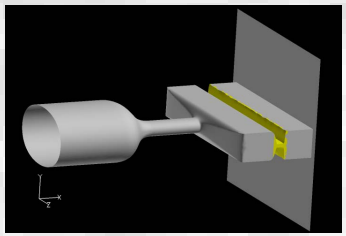


Incisor & free field
[Cisonni et al 2013]

Tongue & incisor
[Van Hirtum et al 2011]

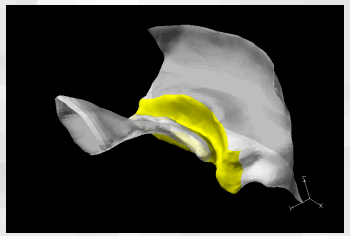


Increasing geometrical complexity

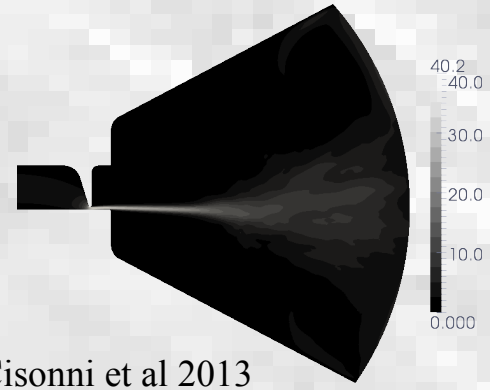


Tongue & incisor
[Van Hirtum et al 2009]

Human oral cavity
[Nozaki 2010]

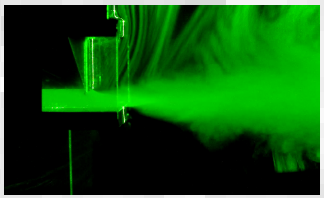


Re=4000, uniform inlet velocity profile



Cisonni et al 2013

≠



Grandchamp 2009

→ Influence of **initial conditions**? (IC)

Previous studies:
* Reynolds number *Re* = 4000 (exp.+sim.)
* Constriction degree (exp.+sim.)
* Uniform inlet velocity profile (sim.)

This thesis

Unvoiced fricative production

Flow initial conditions?

Reynolds numbers *Re*?

Obstacle(s) geometry?

Aeroacoustic analysis

* Experiments
* Simulations

Outline

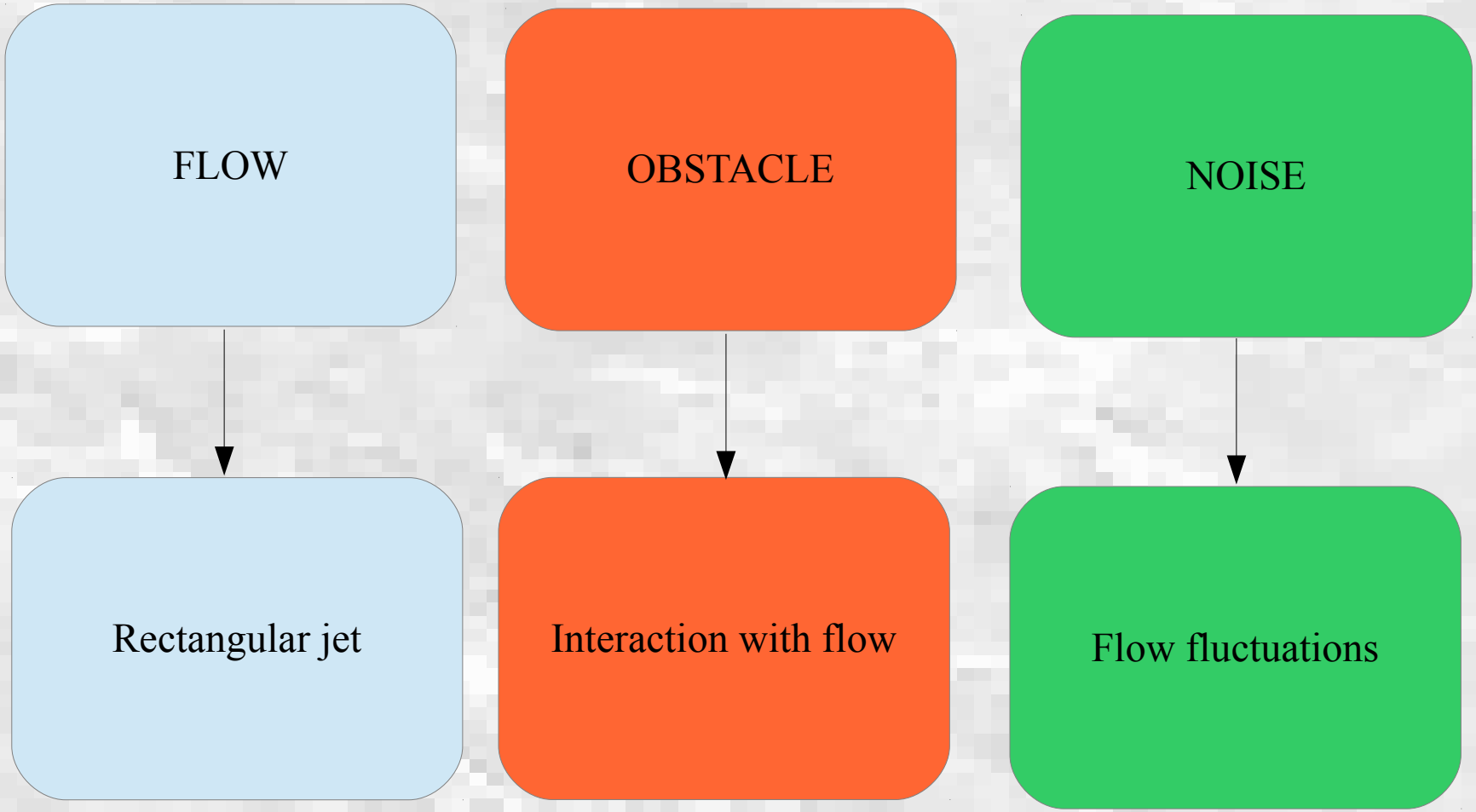
I. Introduction

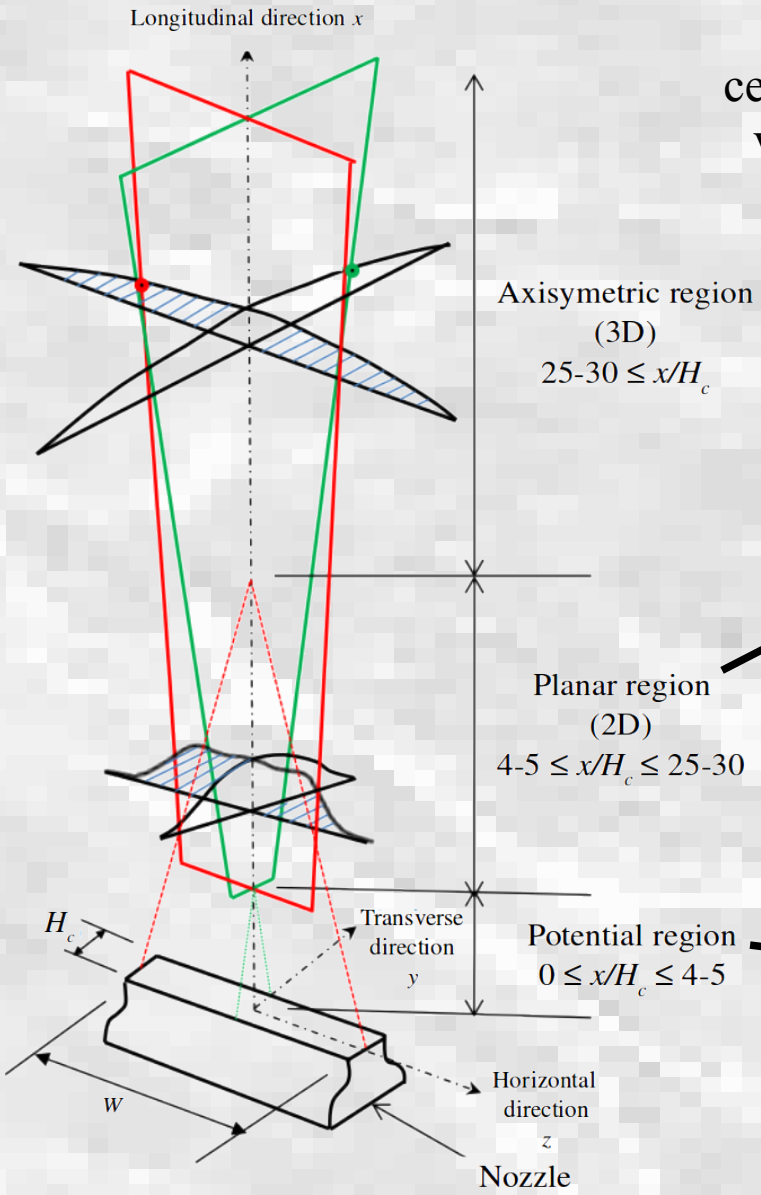
II. Theory
- Jet
- Obstacle
- Noise

III. Method

IV. Results

V. Conclusion


FLOW
OBSTACLE
NOISE
Rectangular jet
Interaction with flow
Flow fluctuations



center bulk velocity

center bulk velocity at x=0

'Square' decay law

$$\left(\frac{U_{dc}}{U_c}\right)^2 = K_u\left(\frac{x}{H_c} + \frac{x_{01}}{H_c}\right)$$

Strouhal number

$$St = \frac{f H_c}{U_{dc}}$$

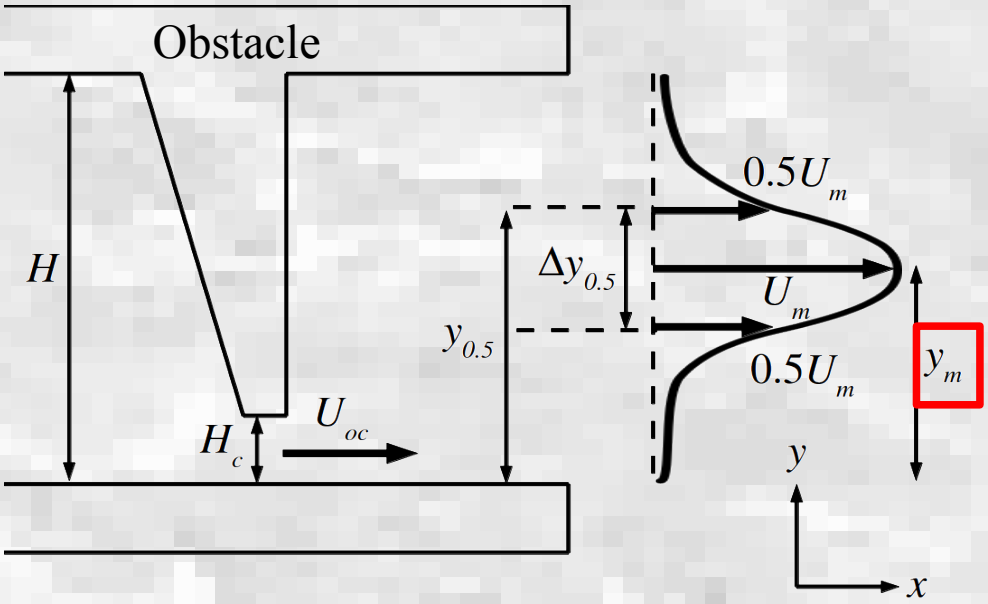
Vortex shedding

St~0.3 (typically)

Potential core length

$$x_{pc} = x\Big|_{U_c=0.95U_0}$$

'Hybrid' jet parameters (obstacle)



Reynolds decomposition for velocity field:

$$u(t) = \bar{U} + \tilde{u}(t)$$

Mean velocity

Fluctuating velocity

Turbulence intensity

$$Tu = \frac{u'}{\bar{U}}$$

RMS velocity (2^{nd} order moment)

Bulk Reynolds number

$$Re_d = \frac{U_d h}{\nu} = \frac{Q}{W\nu} \quad (h \in \{H; H_c\})$$

Width of rect. duct

Constriction degree

$$\frac{H_c}{H}$$

Aspect ratio

$$AR = \frac{W}{H_c}$$

Conservation of momentum → **Navier-Stokes equation**

$$\rho\left(\frac{\partial\vec{u}}{\partial t}+(\vec{u}\cdot\nabla)\vec{u}\right)=-\nabla P+\nabla\cdot\bar{\bar{\tau}}+\vec{f}$$

unsteadiness

convection

pressure-driven

stress tensor

body forces

Turbulent flow 3D modeling by LES

filtered pressure $p = \bar{p} + \tilde{p}$

$$\frac{\partial \bar{u}_i}{\partial t}(\bar{u}_i \bar{u}_j) = -\frac{1}{\rho_0}\frac{\partial \bar{p}}{\partial x_i} + \nu \frac{\partial}{\partial x_j}\left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_j}\right) - \frac{\partial \tau_{ij}}{\partial x_j}$$

filtered momentum equation

filtered velocity

$$u_i = \bar{u}_i + \tilde{u}_i$$

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0, \quad i = 1, 2, 3$$

filtered continuity equation

resolvable part

subgrid-scale (SGS) part → modeled by dynamic Smagorinsky model

C_s: Smagorinsky constant

$$\tau_{ij} = \bar{u}_i \bar{u}_j - \overline{u_i u_j} \qquad \bar{S}_{ij} = \frac{1}{2}\left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i}\right)$$

$$\tau_{ij} - \frac{1}{3}\tau_{kk}\delta_{ij} = -2\mu_t \bar{S}_{ij}$$

Subgrid-scale eddy viscosity

$$\mu_t = \rho (C_s \Delta)^2 \sqrt{2 \bar{S}_{ij} \bar{S}_{ij}}$$

Lighthill's equation (1952):

$$\frac{\partial^2 \rho}{\partial t^2} - c^2 \Delta \rho = \frac{\partial^2 T_{ij}}{\partial x_i \partial x_j}$$

Lighthill's tensor

viscous stress tensor

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

Incompressible isentropic flow → $T_{ij} \approx \rho_0 u_i u_j$

De Havilland Comet (1949): 1st **turbojet** civil aircraft → much louder than propeller-aircrafts, WHY**?**

No solid boundaries!

Solution of Lighthill's equation in time domain:

$$p(\vec{x}, t) = c^2 \rho(\vec{x}, t) = \iiint_V \int_\tau T_{ij} \frac{\partial^2 G}{\partial y_i \partial y_j} \mathrm{d}\tau \mathrm{d}V$$

radiated jet-induced acoustic pressure

quadrupole noise source

***G*:** Green function in free field

Approximate solution in free field:

$$p(\vec{x},t) = \frac{1}{4\pi}\frac{\partial^2}{\partial x_i \partial x_j}\iiint_V \frac{1}{d} T_{ij}(\vec{y},t)\mathrm{d}\vec{y}$$

volume of source region

$$d = |\vec{x} - \vec{y}|$$

position of receiver point

position of source point

After some mathematical manipulations, and by taking the **Fourier transform (F.T.) of T_{ij}**, one can obtain an **approximate solution in frequency domain:**

F.T. of T_{ij}

F.T. of pressure p

$$P_\omega(\vec{x}) = -\frac{\omega^2}{4\pi c^2}\iiint_V \frac{d_i d_j}{d^3} e^{\frac{-i\omega d}{c}} \hat{T}_{ij}(\vec{y},\omega)\mathrm{d}V$$

Aeroacoustic analogy of Powell (1964):

$$\left(\frac{1}{c^2}\frac{\partial^2}{\partial t^2} - \nabla^2\right) p = \rho \nabla \cdot (\vec{\omega} \times \vec{u}) + \nabla^2 \left(\frac{1}{2}\rho \vec{u}^2\right)$$

Lamb vector

$$\vec{\mathcal{L}} = \vec{u} \times \vec{\omega}$$

Vorticity

$$\vec{\omega} = \overrightarrow{rot}\ \vec{u}$$

Estimation of dipole noise source:

$$\Phi_{\mathcal{D}} = \frac{1}{S_{\mathcal{D}}} \int_{\mathcal{D}} |\nabla \vec{\mathcal{L}}| \, dS$$

surface of source region

Lamb vector divergence

Outline

I. Introduction

II. Theory

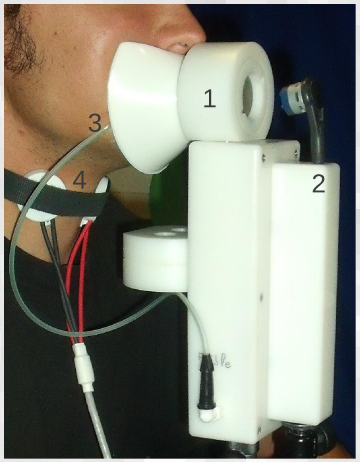
III. Method

- Experiments
- Simulations

IV. Results

V. Conclusion

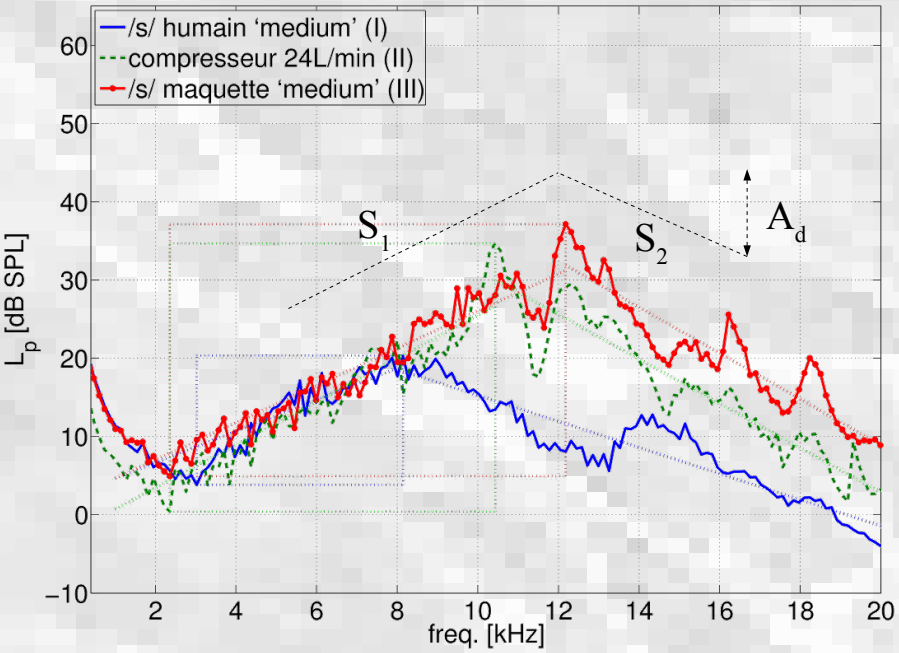
Method: **experiments** *In-vivo* measurements (EVA)



EVA* meas. station
Gipsa-lab Stendhal Univ.

1: oral airflowmeter
2: microphone
3: intra-oral pressure probe
4: electroglottograph (EGG)

**Evaluation Vocale Assistée*



***In-vivo* experiments:**

* **Subjects**: two healthy adult males ('YF' & 'KN')

* **Task**: produced repeated sustained unvoiced **/s/ & /f/ utterances**

* **Three intensity levels**: 'soft'; 'medium'; 'loud'

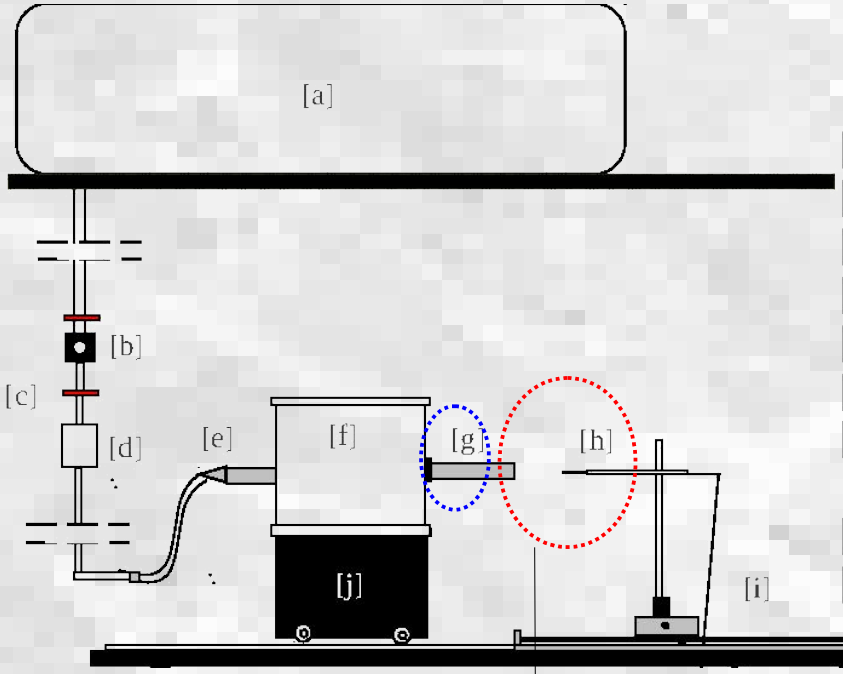
Objective:

→ Obtain some reference ***in-vivo* aerodyn. data & spectral parameters**

$10 \leq Q \leq 300$ L/min

$100 \leq Re \leq 3000$

Hot film meas. setup



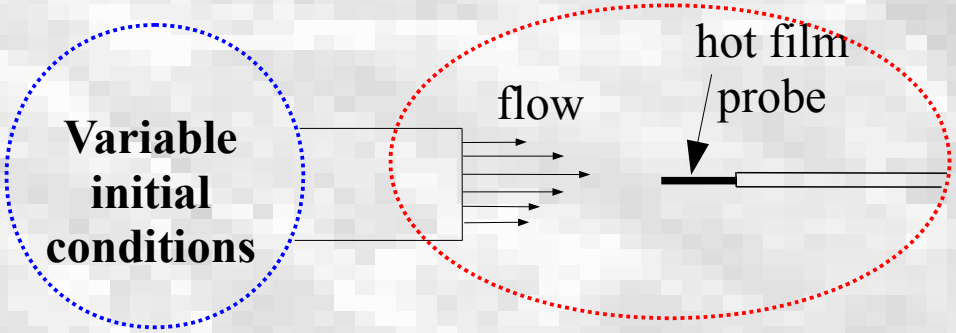
Variable volume flow rate Q

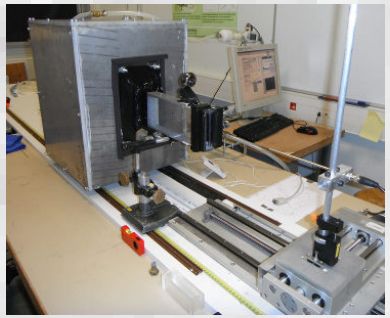
[a] compressor
[b] pressure regulator
[c] valve
[d] flowmeter
[e] divergent
[f] settling chamber
[g] rect. channel (+ replica)
[h] hot film
[i] positioning system

Objective:

→ Meas. of flow velocity field issued from a replica

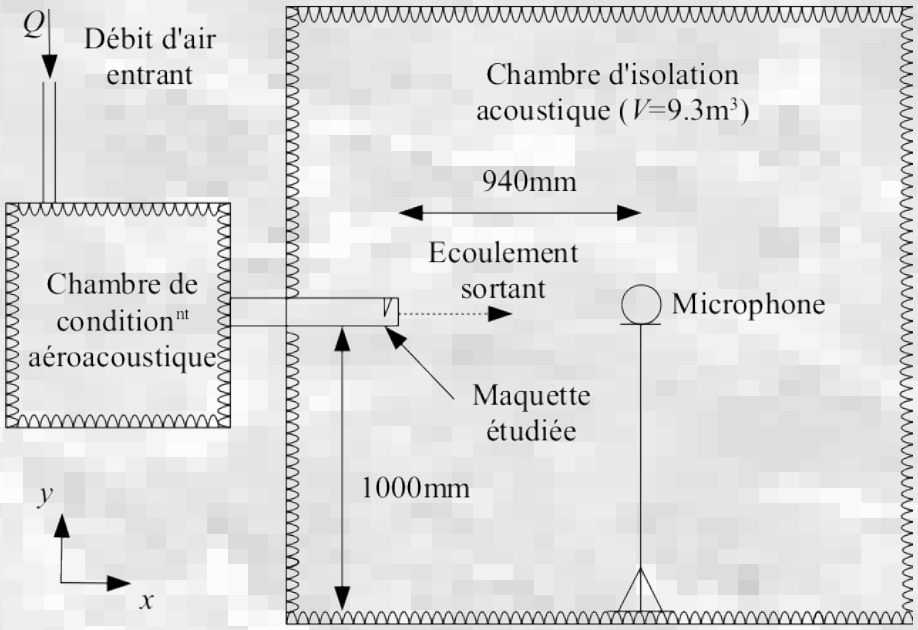
→ Variation of initial conditions & geometry



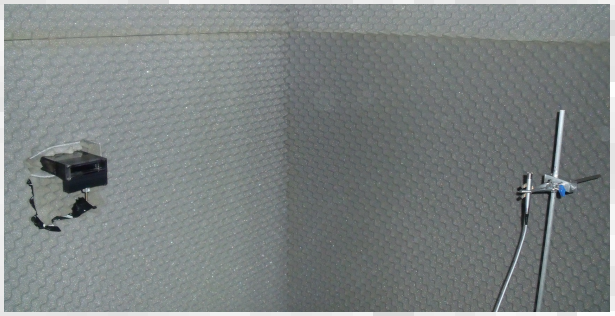


Method: **experiments** | Measurement of flow noise

$10 \leq Q \leq 300$ L/min



Meas. of acoustic pressure



Meas. of acoustic directivity

Objective:

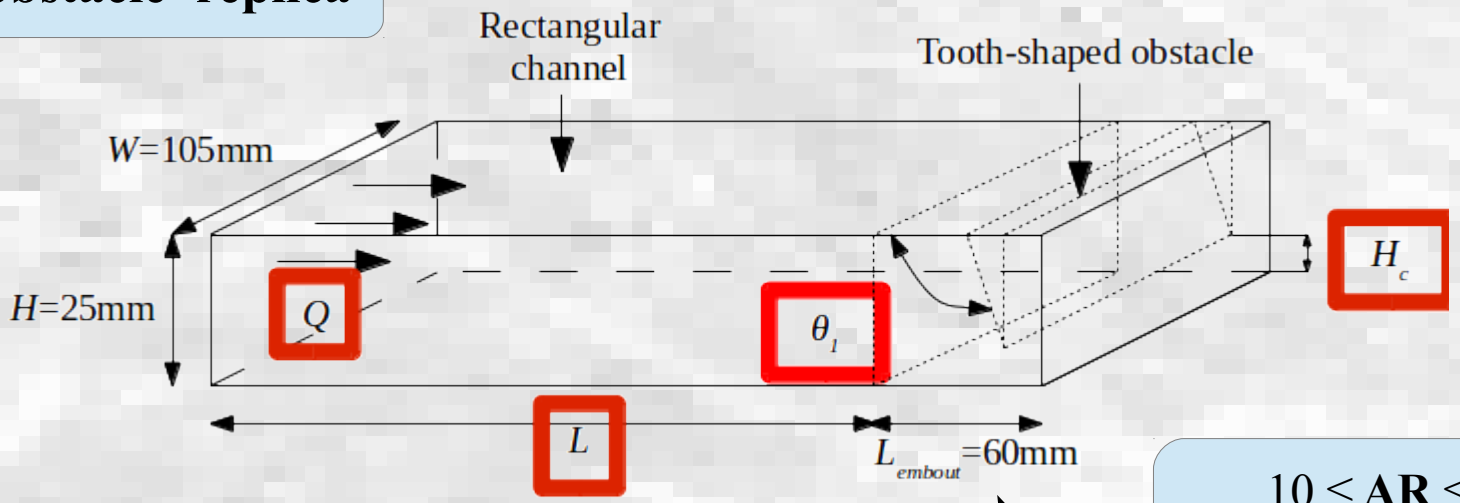
→ Meas. of flow noise issued from a replica

→ Variation of initial conditions & geometry

→Meas. of noise directivity

Van Hirtum, A., & Fujiso, Y. (2012). Insulation room for aero-acoustic experiments at moderate Reynolds and low Mach numbers. App. Acoustics, 73(1), 72-77.

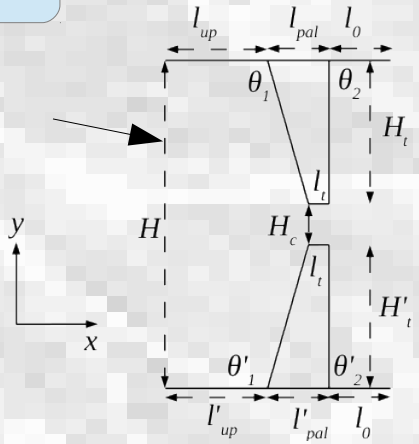
'Single obstacle' replica

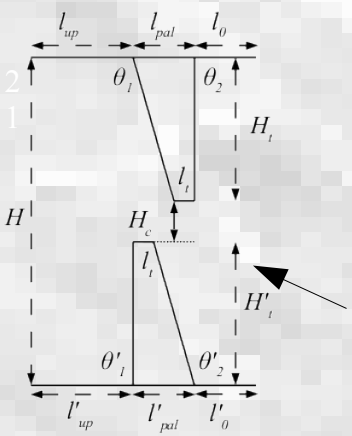


$10 \leq \mathbf{AR} \leq 200$
$\mathbf{H_c/H}$: 2.4; 10; 30; 100%

'Dual obstacle' replica

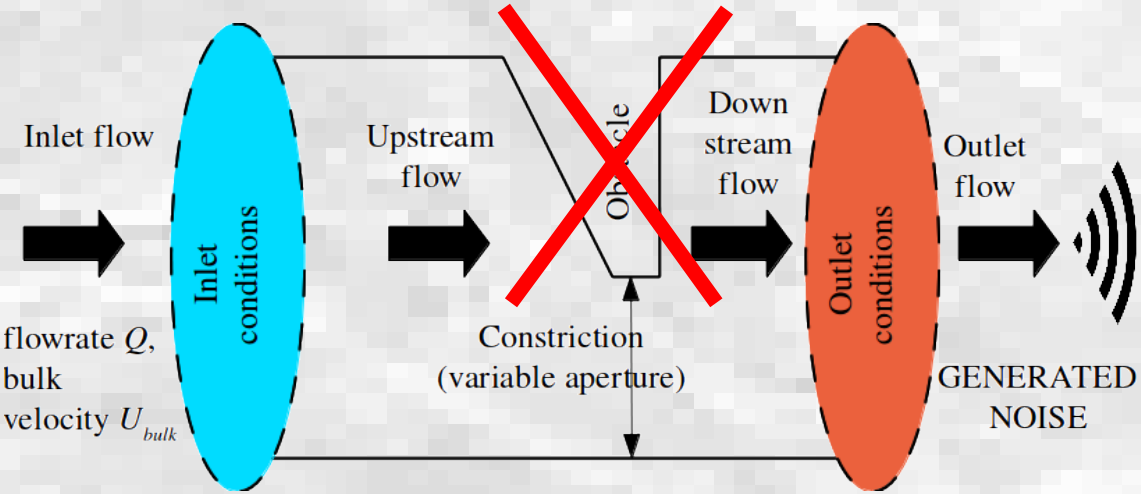
'Symmetric' config.



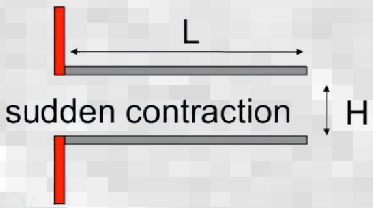


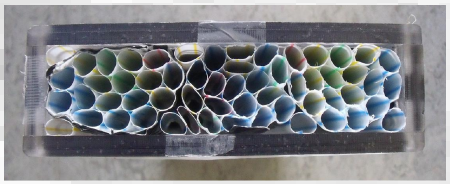
'Asymmetric' config.

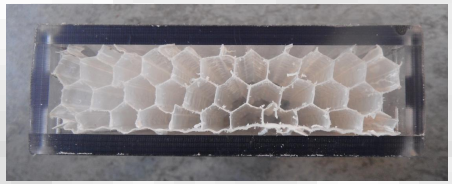
Method: **experiments** | Variation of exp. initial conditions



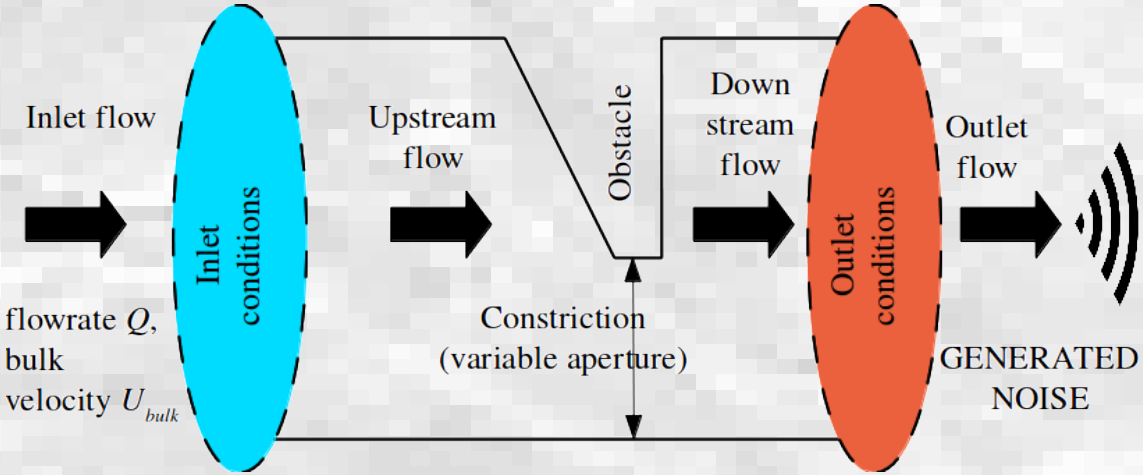
Inlet conditions



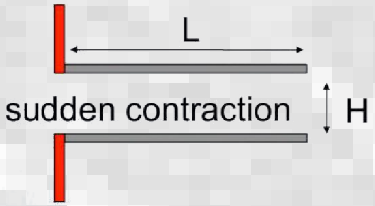


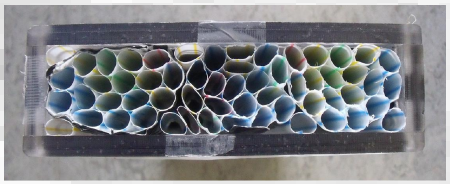


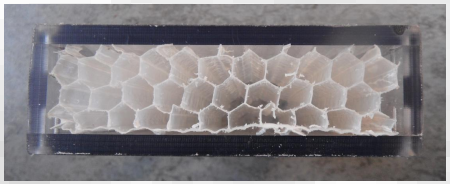
Method: **experiments** | Variation of exp. initial conditions



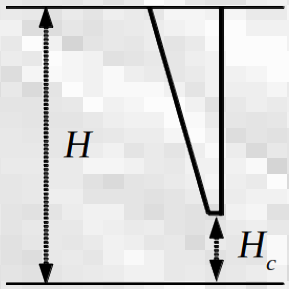
Inlet conditions

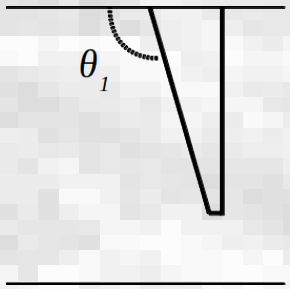




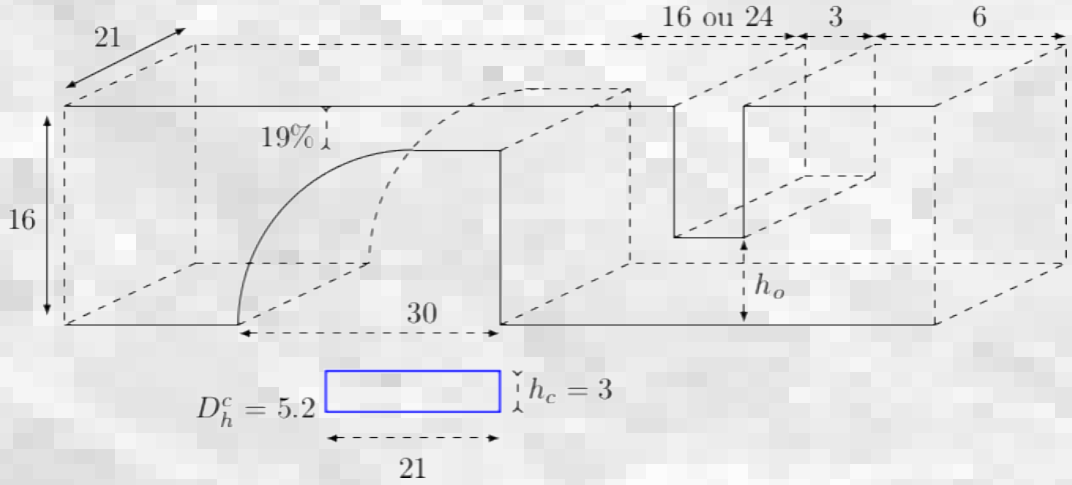


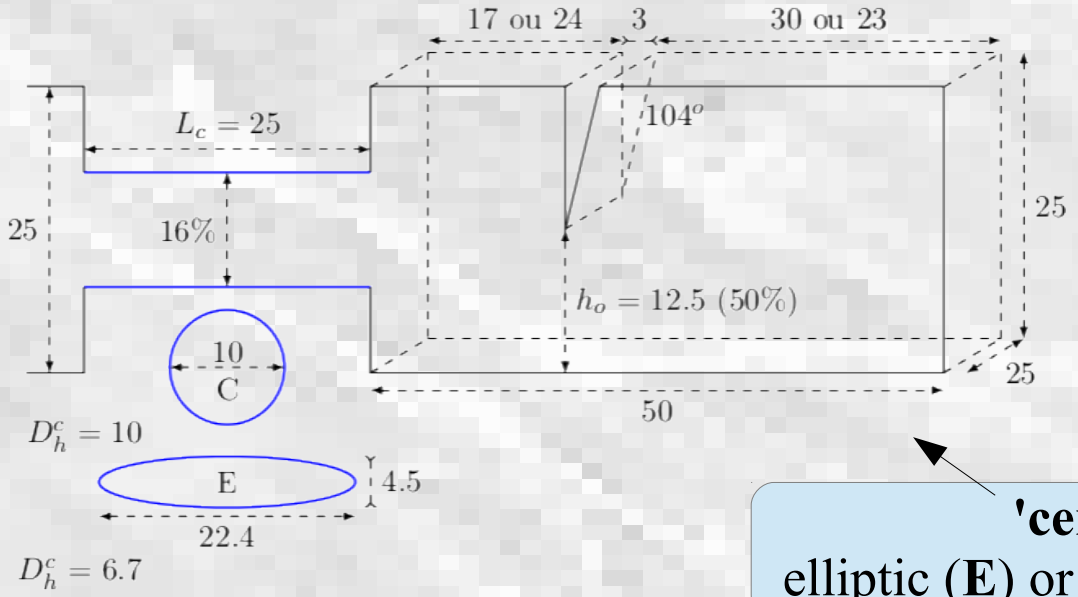
Outlet conditions





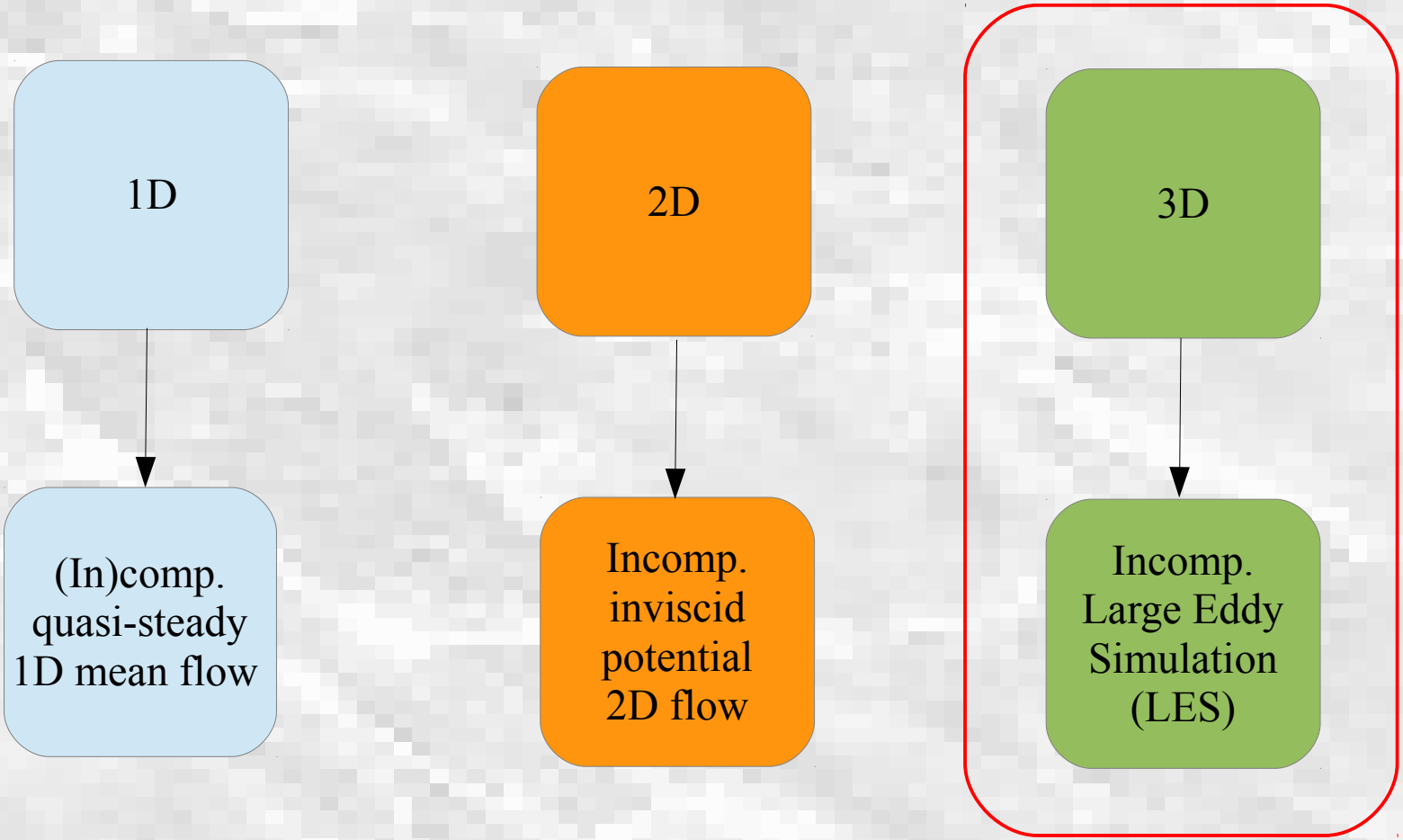
'offset' replica



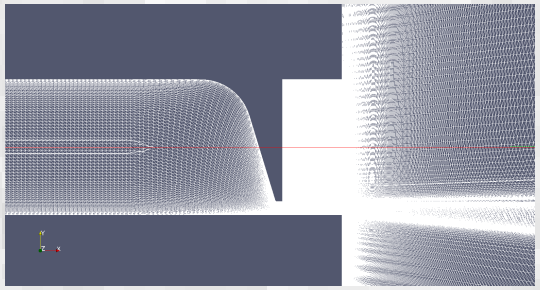


'centred' replica:
elliptic (**E**) or circular (**C**) cross-section

Flow simulations: 3 approaches considered



3D turbulent incomp. flow model: Large Eddy Simulation (LES)



→ **Dynamic Smagorinsky model**

*** Simulated durations:**
$0.018s \leq T_{sim} \leq 0.54s$

*** Reynolds numbers:**
Re = 402; 1079; 2084

*** Constriction degrees:**
H_c/H = 2.4; 10; 30%

LES code:
FrontFlow Blue v6.1

Postprocessing:
ParaView

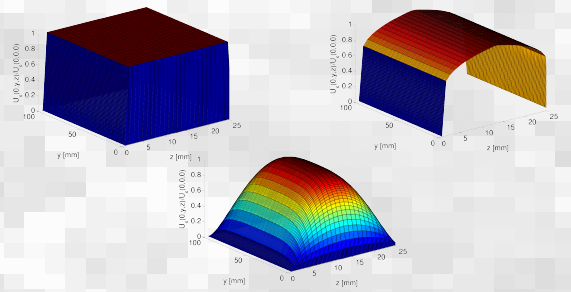
'Single obstacle' mesh:

≈7 millions hexahedral elements

$2.2*10^{-5} < \Delta x < 6.7*10^{-5}$m
$9.5*10^{-6} < \Delta y < 2.7*10^{-5}$m

Supercomputer:
NEC SX9 (Osaka Univ.)

Boundary conditions:
*** Variable inlet velocity profile** →
* No-slip cond. on duct walls
* No backflow at outlet
* 0Pa-static pressure at free field bound.



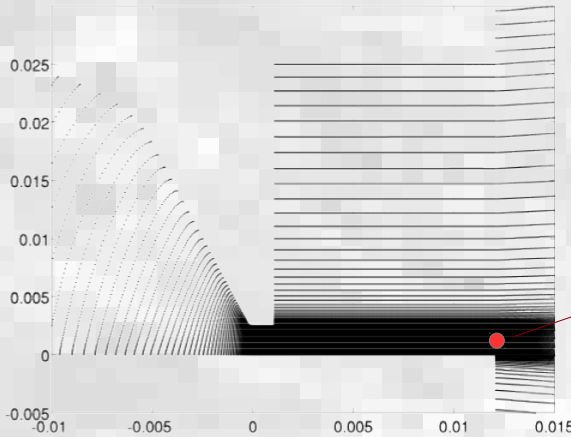
PROBLEM: TURB. JET NOISE PREDICTION

→ How to obtain enough time steps for a **large bandwidth acoustic prediction & for several geometries? (up to 20kHz)**

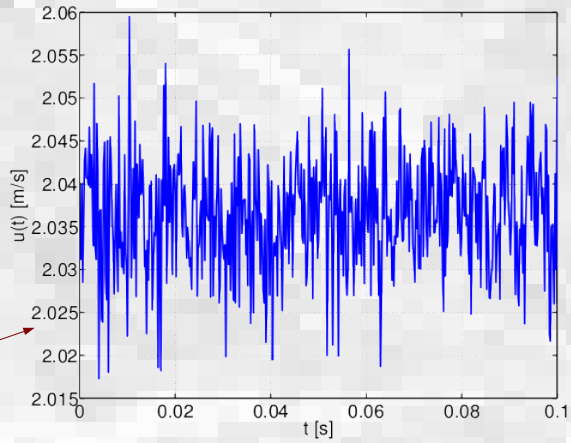
METHOD

→ **Synthetic turbulence**

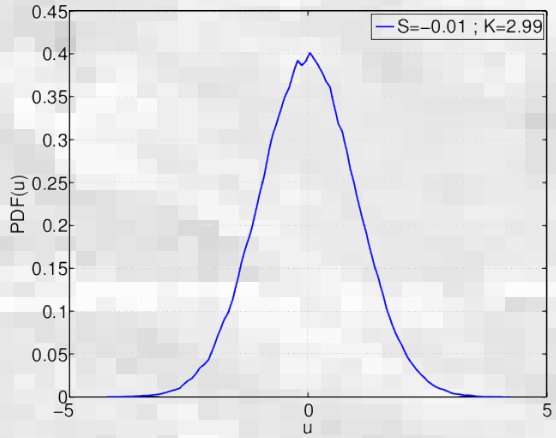
→ **Gaussian regeneration** of all time steps using **LES mean & RMS vel. fields**



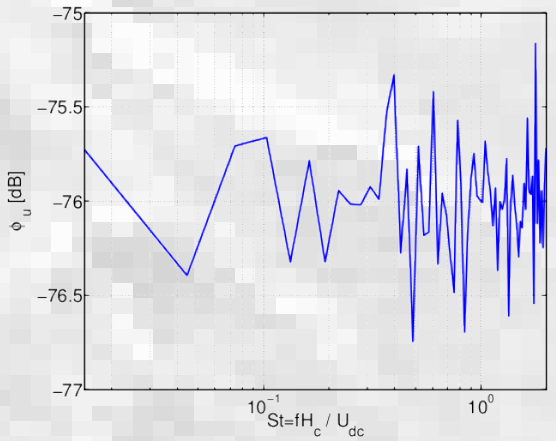
(a) Emplacement du point considéré (en rouge)



(b) Signal temporel de la vitesse longitudinale regénérée au niveau du point

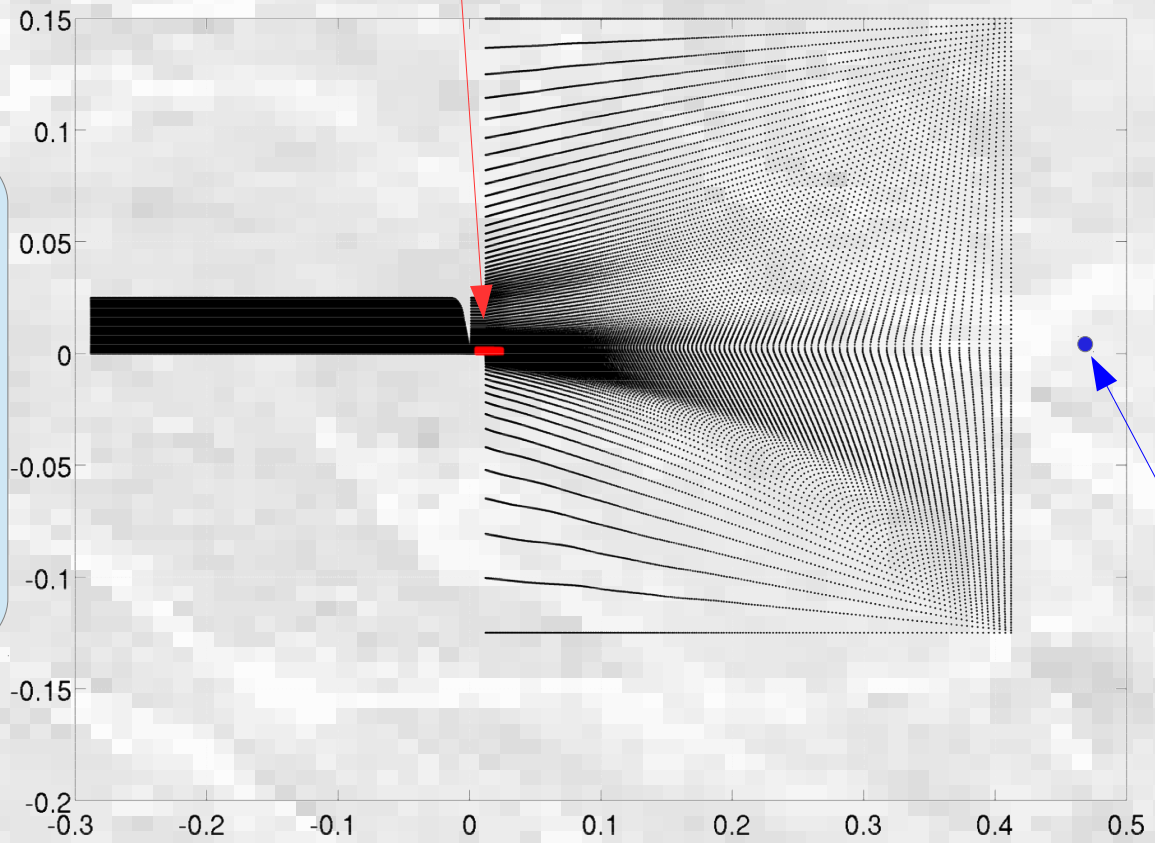


(c) Fonction de densité de probabilité correspondante



(d) Densité spectrale de puissance correspondante

Noise source region used for acoustic predictions using Lighthill's equation approx. solution in freq. domain



1cm-thick 'buffer' layer around source region:

→ Smooth transition to surrounding flow field

Combined use of **LES mean & RMS flow data + synthetic turbulence time steps**

Receiver point (virtual microphone, 0.94m from outlet)

Outline

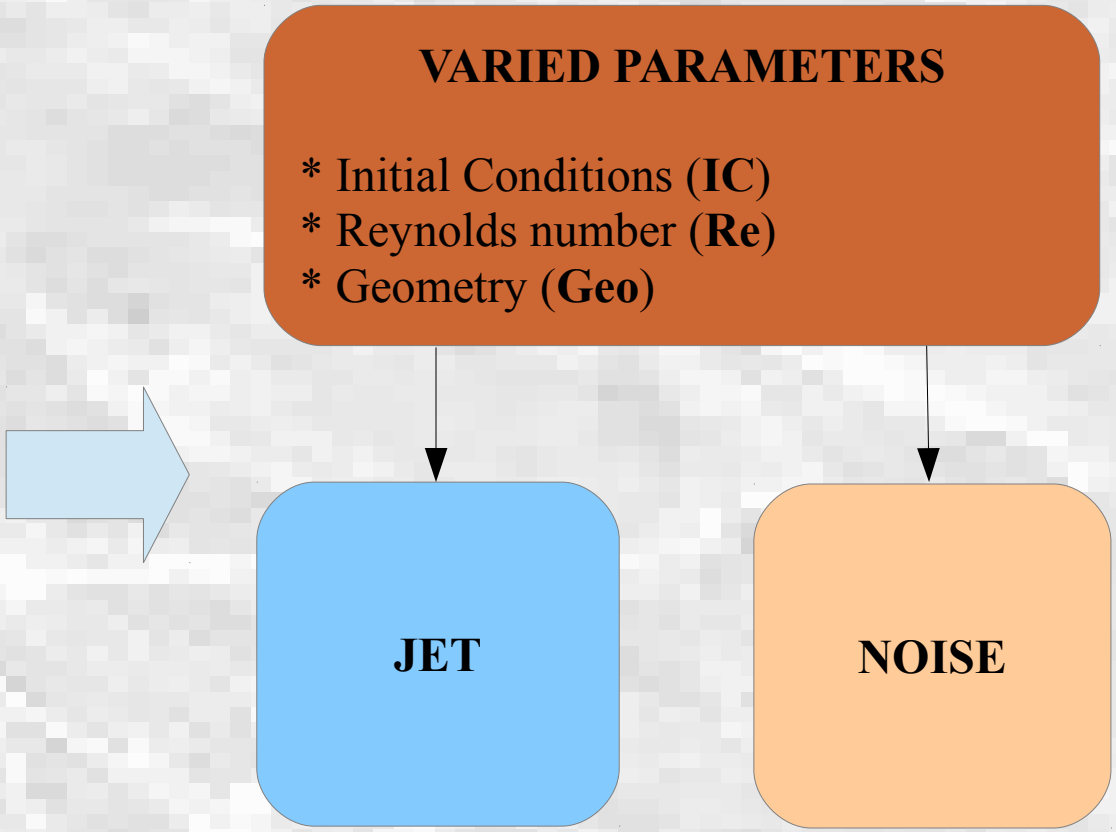
I. Introduction

II. Theory

III. Method

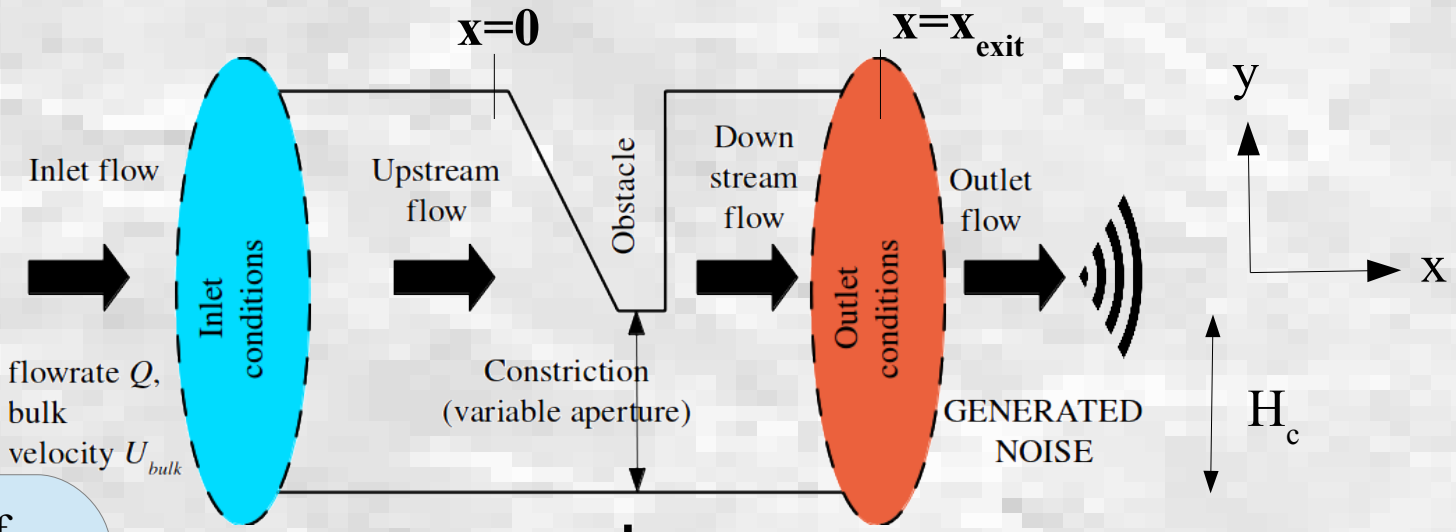
IV. Results
- Experiments
- Simulations

V. Conclusion



Shape of jet:
rectangular or
rather '**hybrid**'?

Single tooth-shaped obstacle replica



Influence of

IC
&
Geo
&
Re

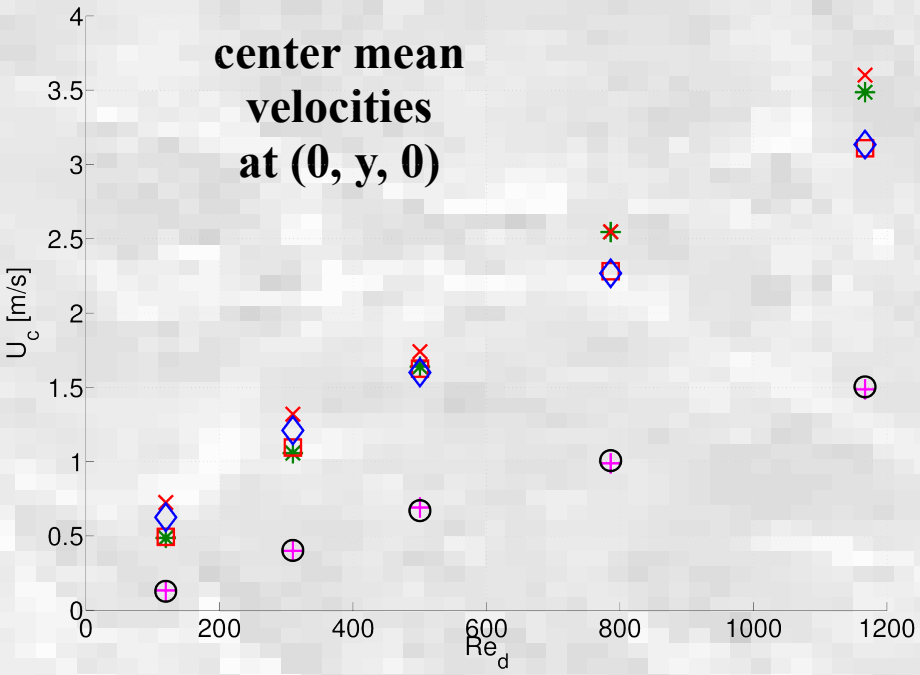
on jet development

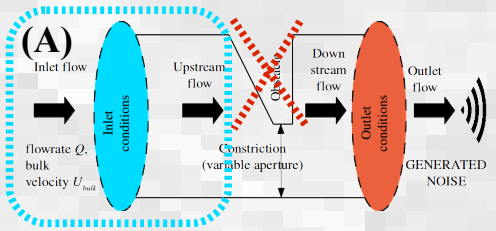
(A) **Upstream** of obstacle:

- transverse profile (0, y, 0)

(B) **Downstream** of obstacle:

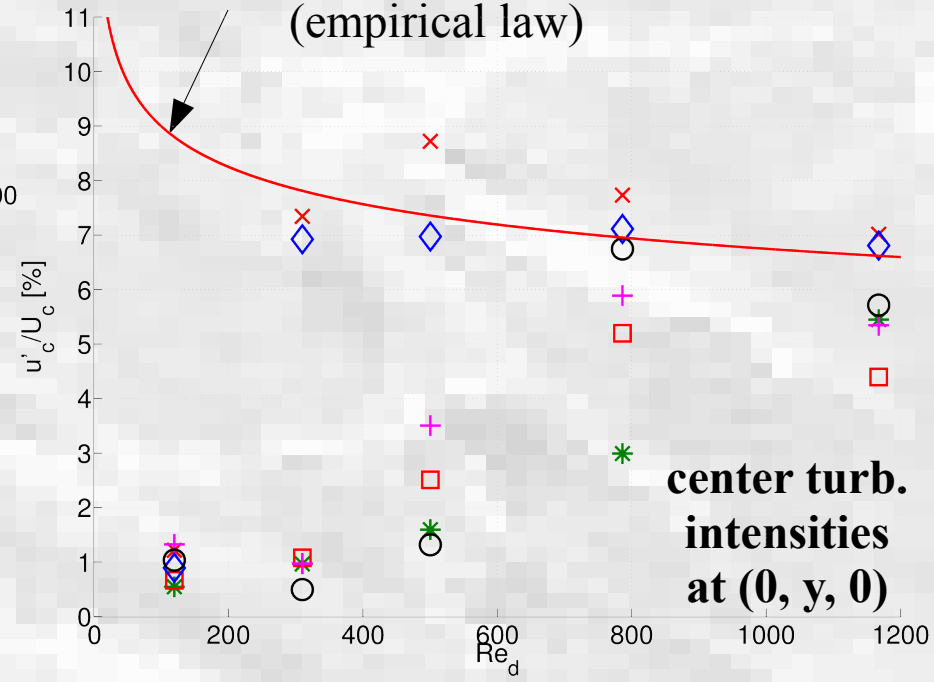
- transverse profile (x_{exit}, y, 0)
- longitudinal profile (x, H_c/2, 0)
- horizontal profile (0, 0, z)





Effect of IC & Re

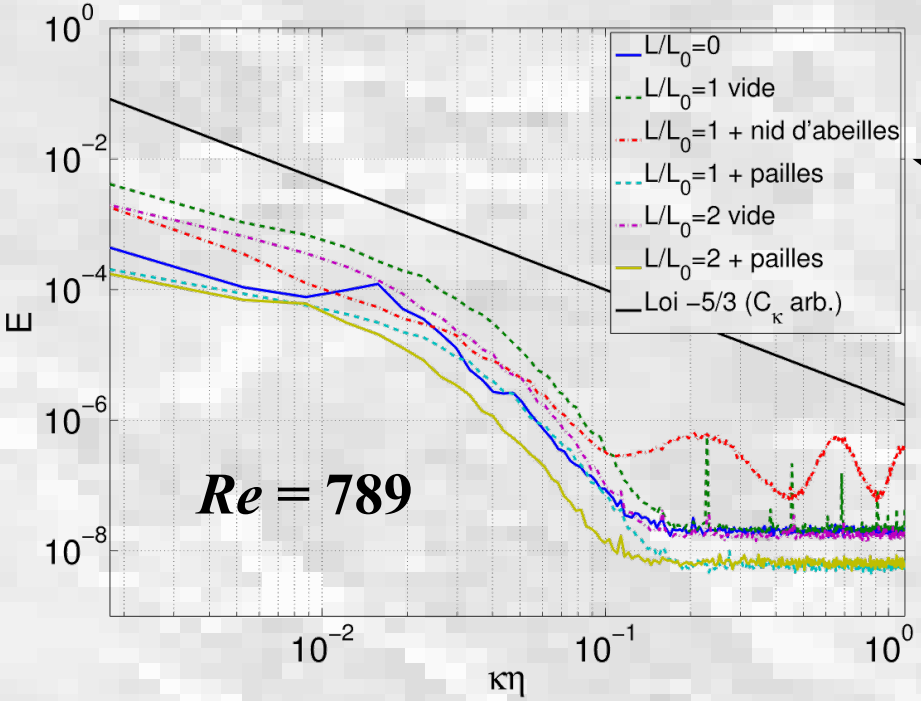
$$Tu_c\ [\%] = 100 \times 0.16 Re_d^{-1/8}$$
(empirical law)



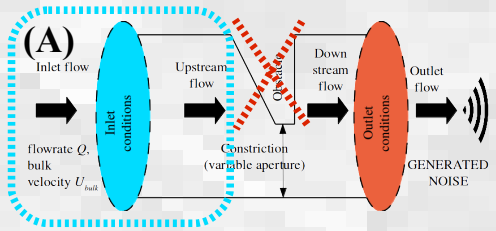
Comparison of initial conditions:

×: no-duct
*: 31cm-duct
◊: 31cm-duct + straws
□: 31cm-duct + honeycomb
+: 62cm-duct
o: 62cm-duct + straws

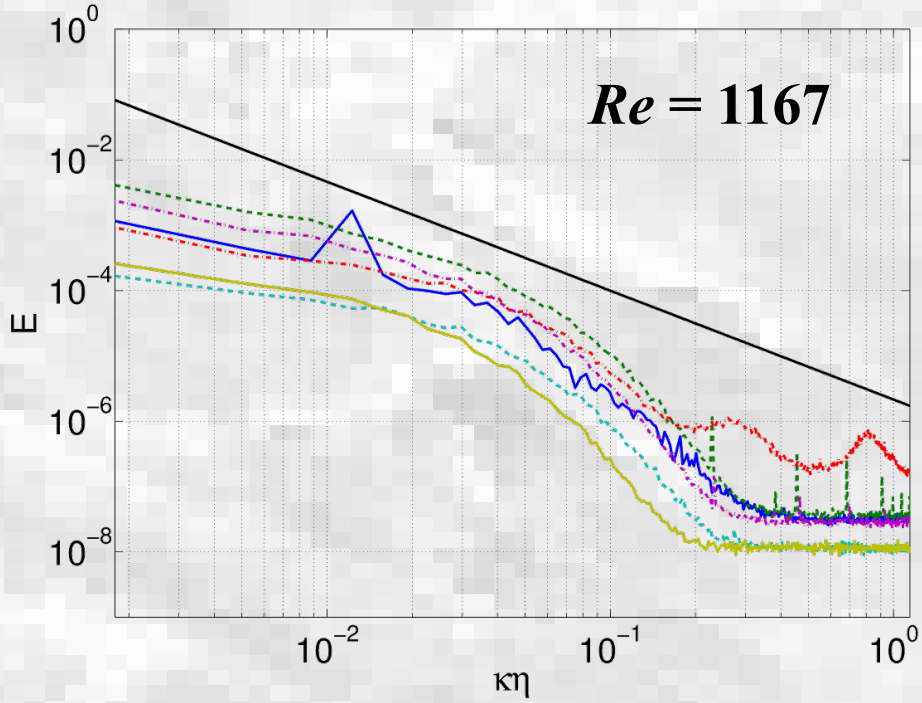
Kolmogorov spectra



Effect of IC & Re



(**duct lengths**: L_0 = 31cm; $2L_0$ = 62cm)

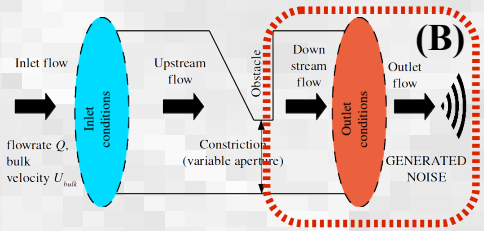


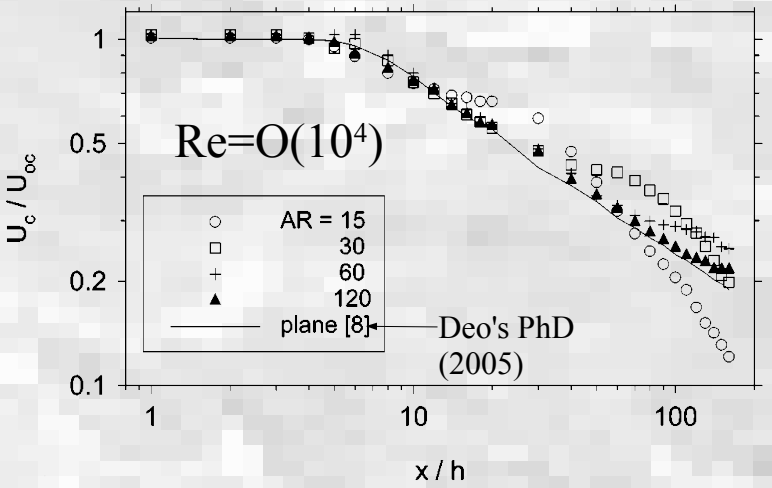
E: power spectral density of center velocity

κ: wave number [m^{-1}]

η=H=25mm

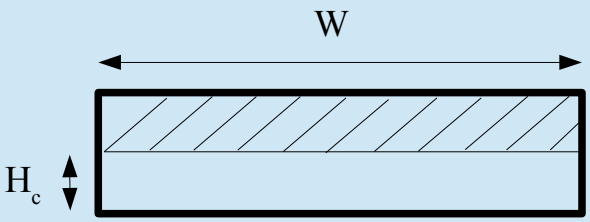
Jet longitudinal decay: comparison with literature



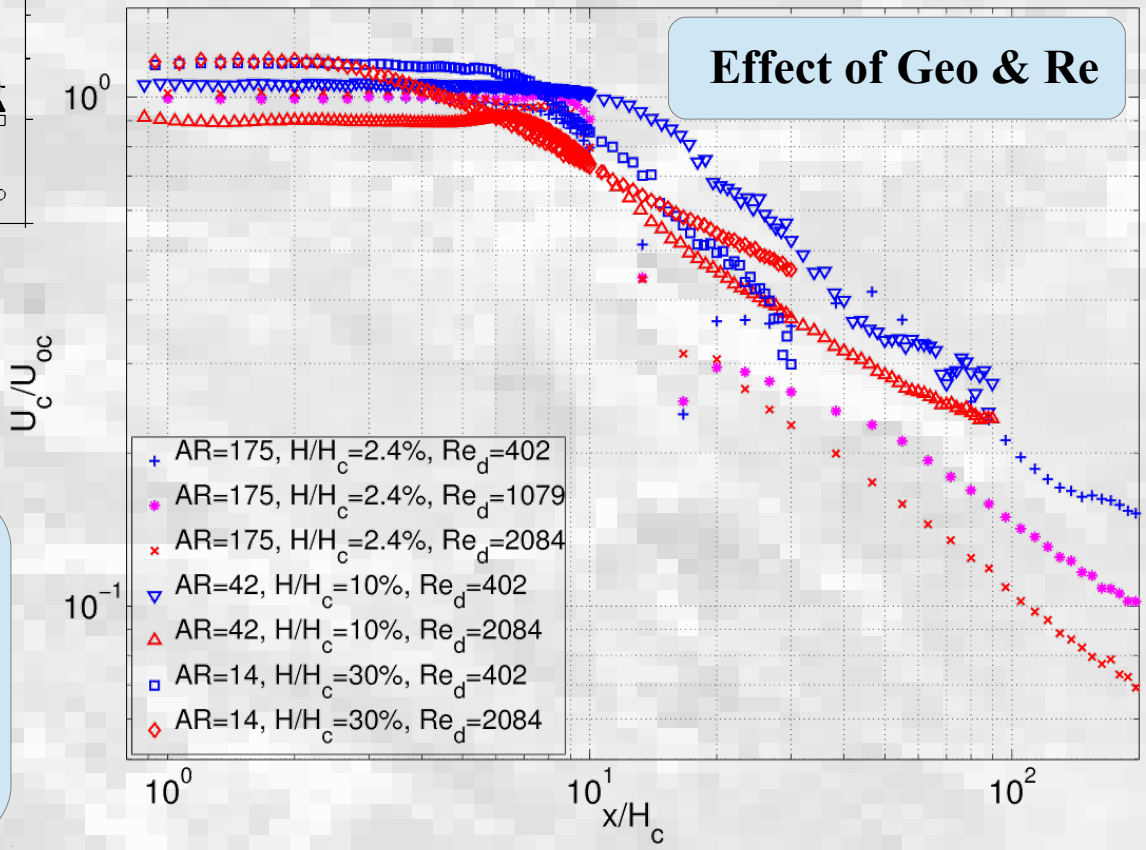


Mi, J., Deo, R. C., & Nathan, G. J. (2005)

AR = aspect ratio = W/H_c

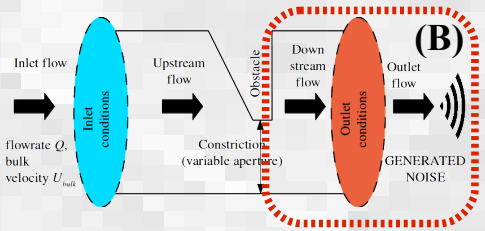


Effect of Geo & Re

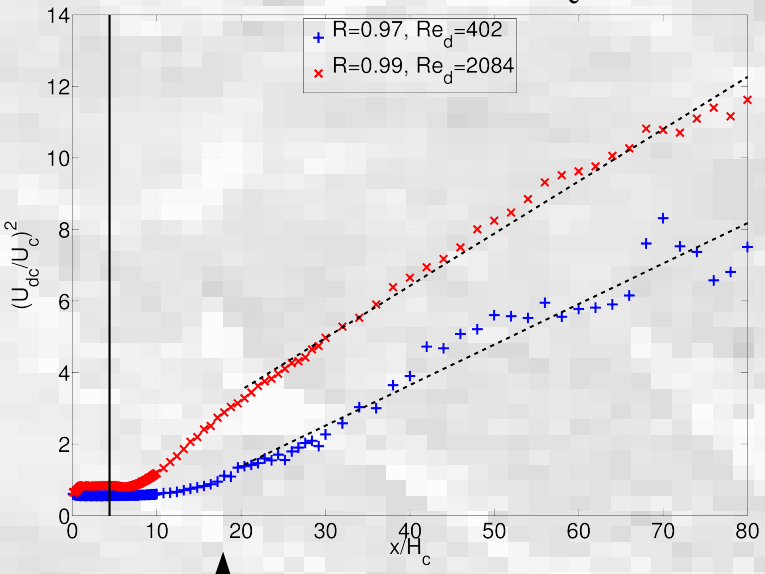


Results: **flow experiments** (B) Downst. of obst. (4): effect of Geo & Re

'Square' decay law:
K_u = decay rate coef.
x_{01} = jet virtual origin

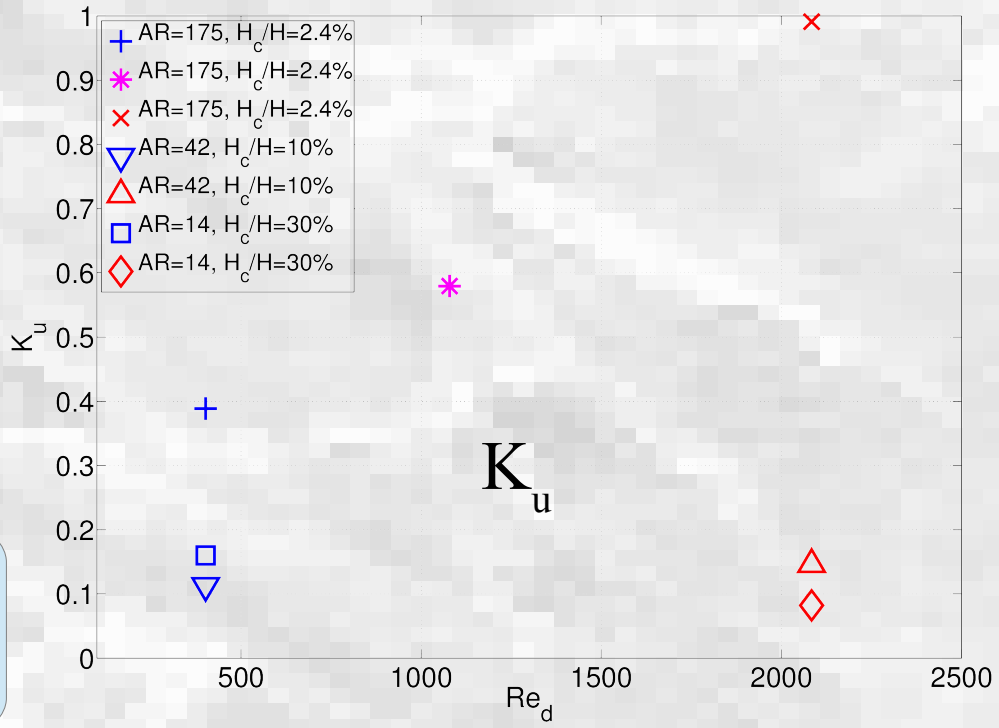


Constriction degree H_c/H=10%

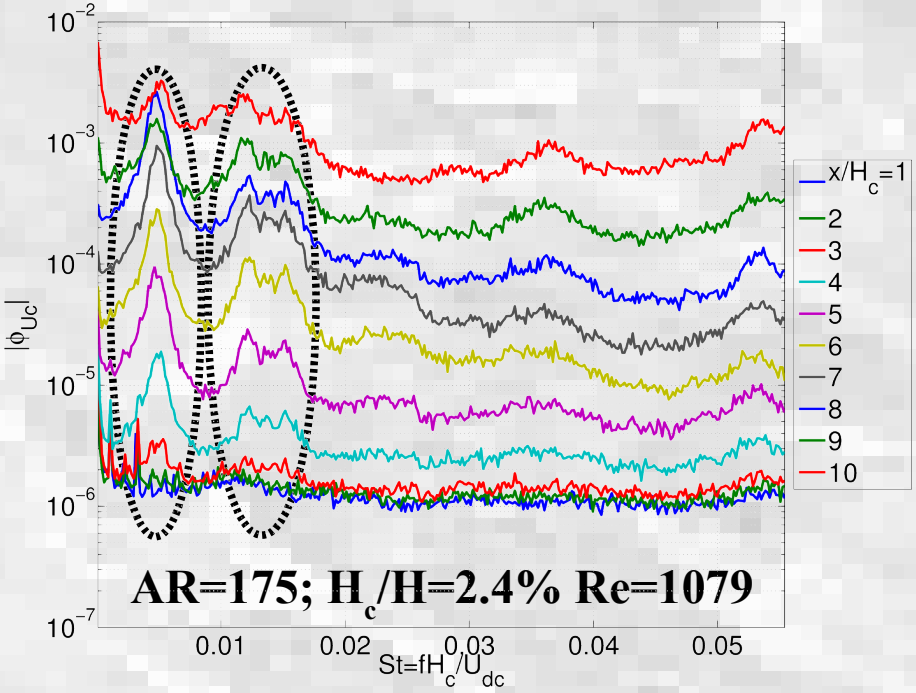


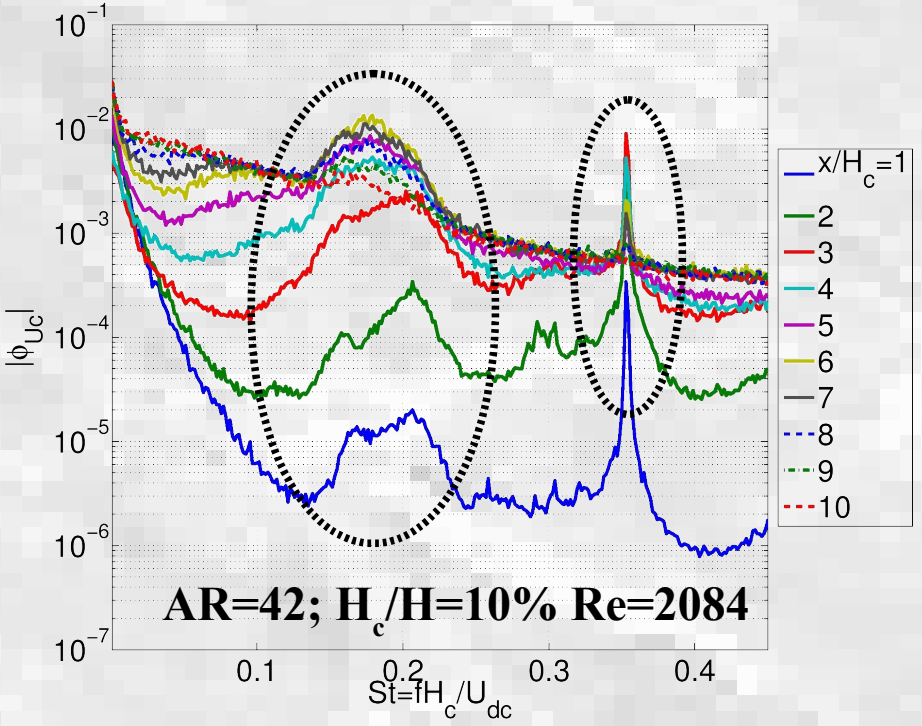
$$\left(\frac{U_{dc}}{U_c}\right)^2 = K_u\left(\frac{x}{H_c} + \frac{x_{01}}{H_c}\right)$$

K_u: effect of Geo & Re



Vortex shedding freq. St* (Strouhal numbers)



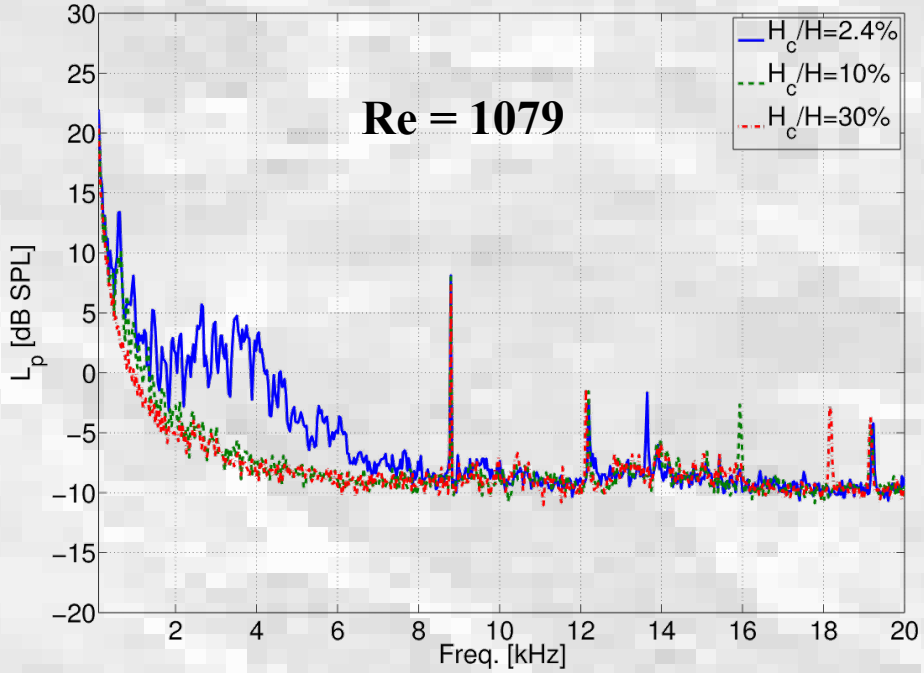


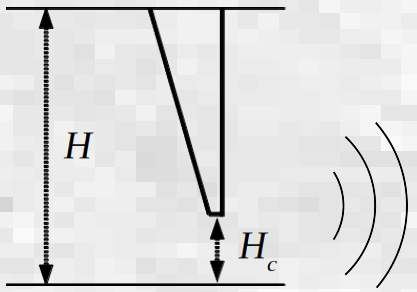
Effect of Geo & Re

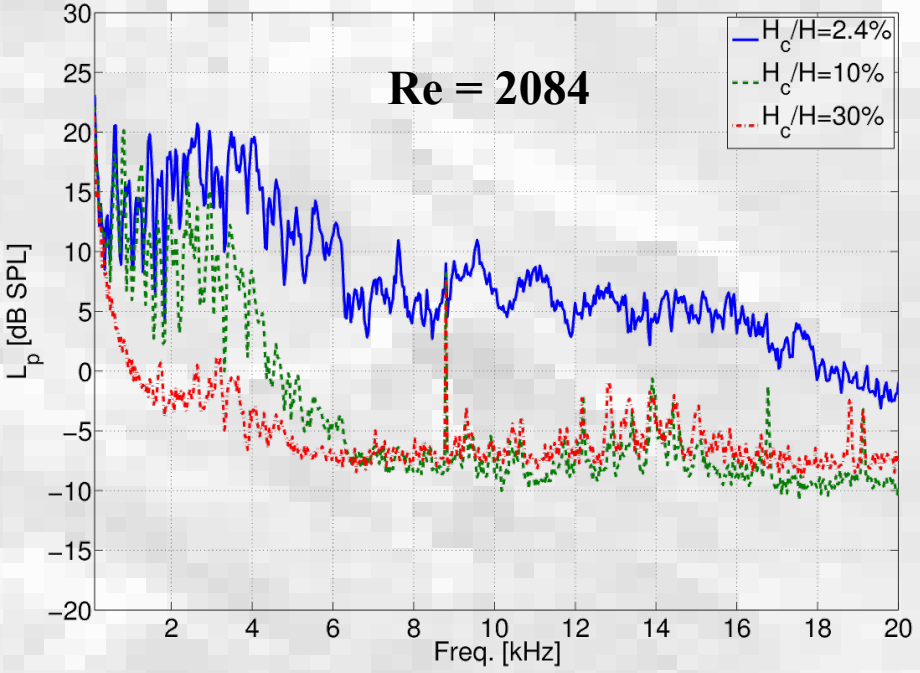
literature →

Étude	Géométrie	*Re*	*AR*	*St**
Beavers et Wilson [BW70]	plane	500–3000	–	0.43
Tsuchiya et al. [THTS89]	rectangulaire	3500	5	0.40
Sato [Sat60]	plane	1500–8000	10 à 67	0.23
Namer et Ötügen [NÖ88]	rectangulaire	1000–7000	56	0.27
Deo et al. [DMN07b]	plane	18000	–	0.24

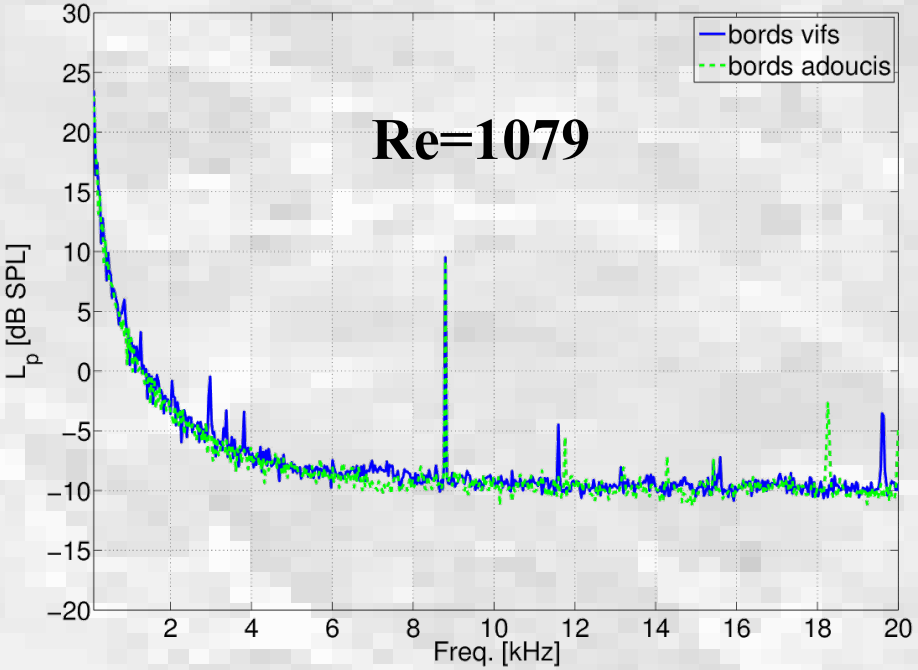
Influence of Geo & Re



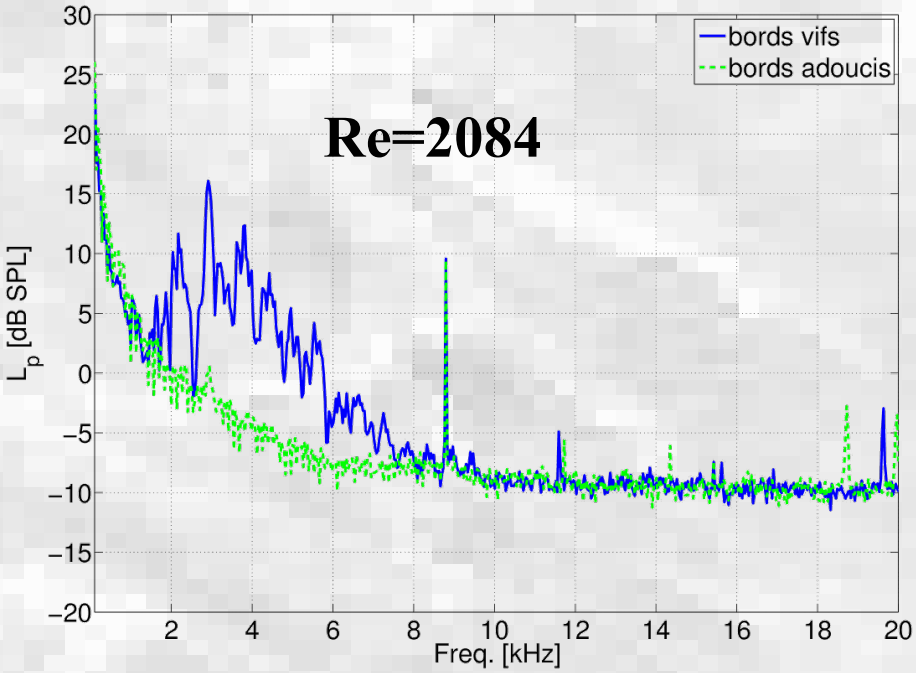




Constriction degree
$H_c/H = 2.4; 10; 30\%$



Outlet section edges: sharp vs soft

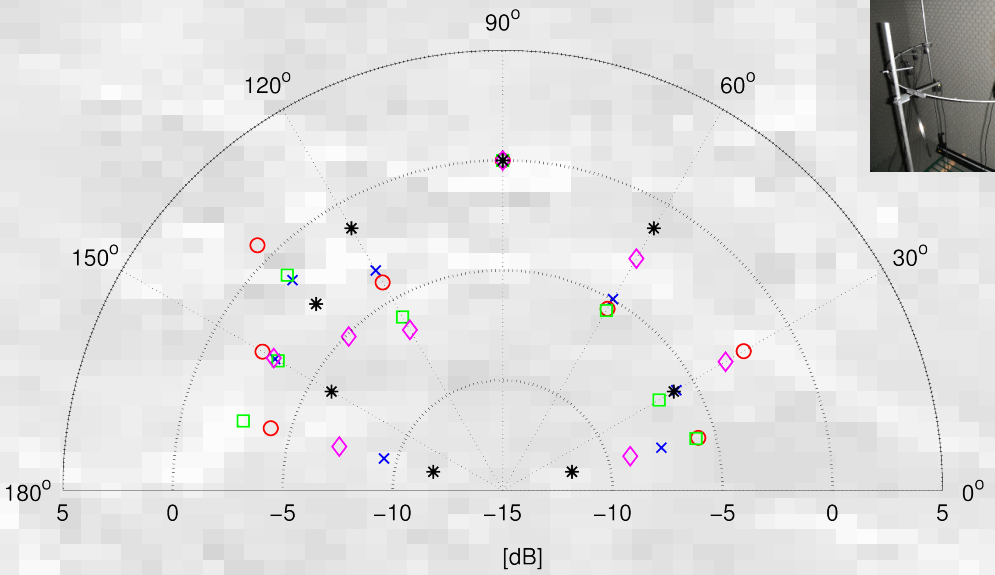


Constriction degree: $H_c/H = 2.4\%$

Results: acoustic experiments

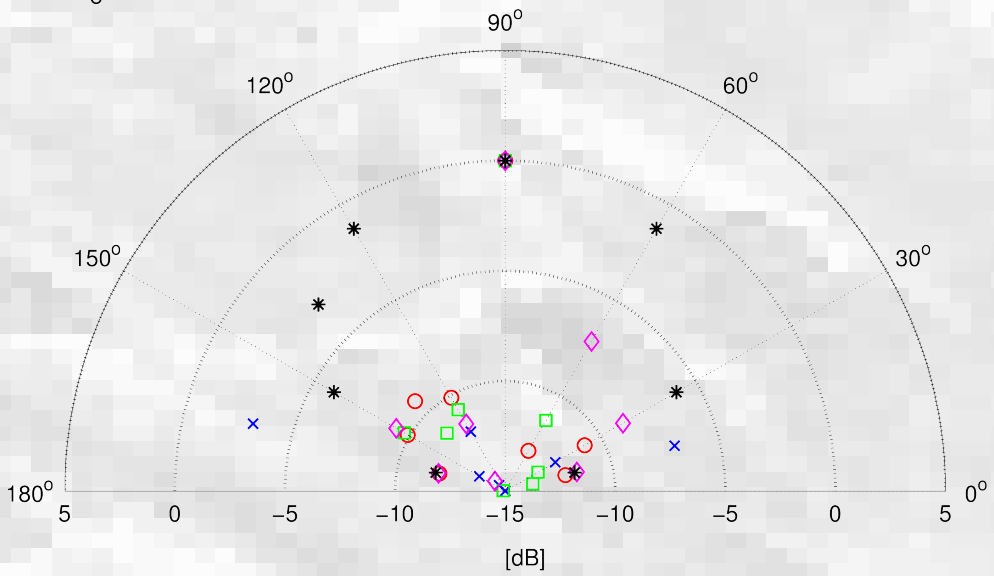
'Single obstacle' replica: effect of Re

Noise directivity
$H_c/H = 2.4\%$



Re = 402

Re = 2084

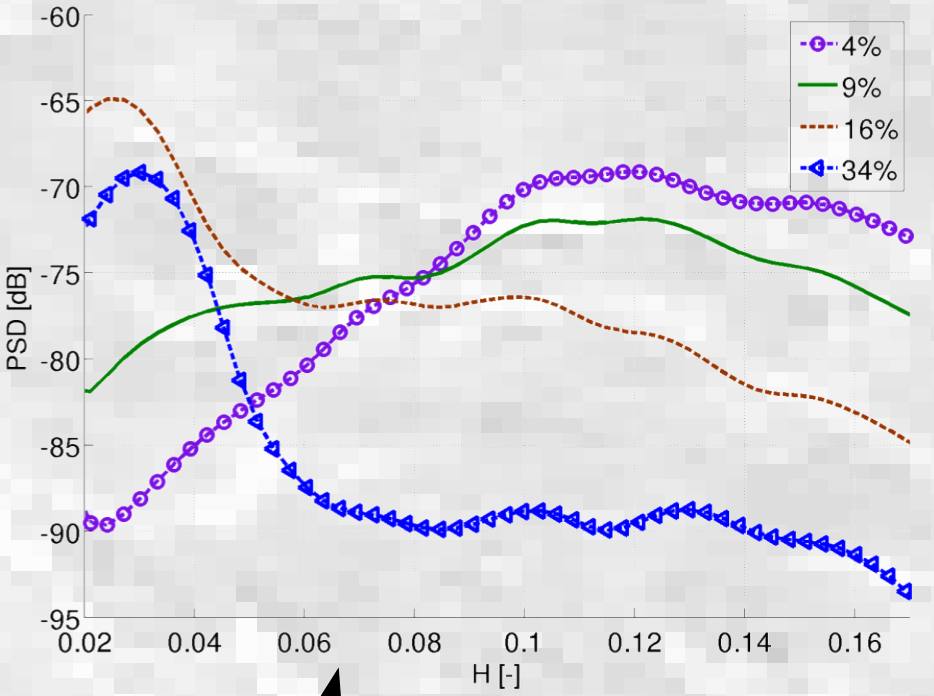


ka = 0.3 (×); ka = 0.35 (o);
ka = 0.40 (□); ka = 0.45 (◊);
(corresp. freq. 1622; 1893; 2163; 2433 Hz)

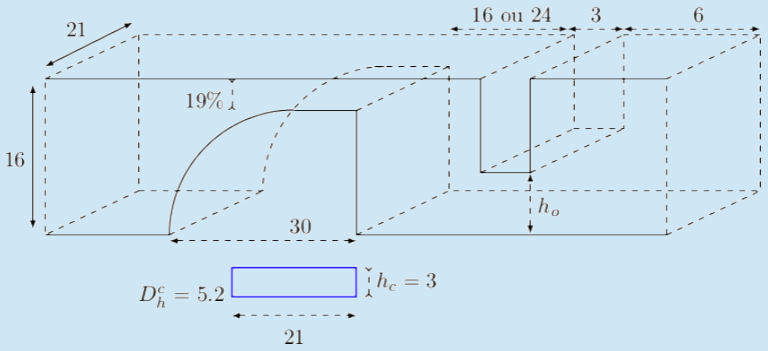
theoretical dipole directivity added for comparison (∗)

Results: acoustic experiments

'Offset' replica: effect of Geo & Re



Constriction-obstacle distance of 24mm

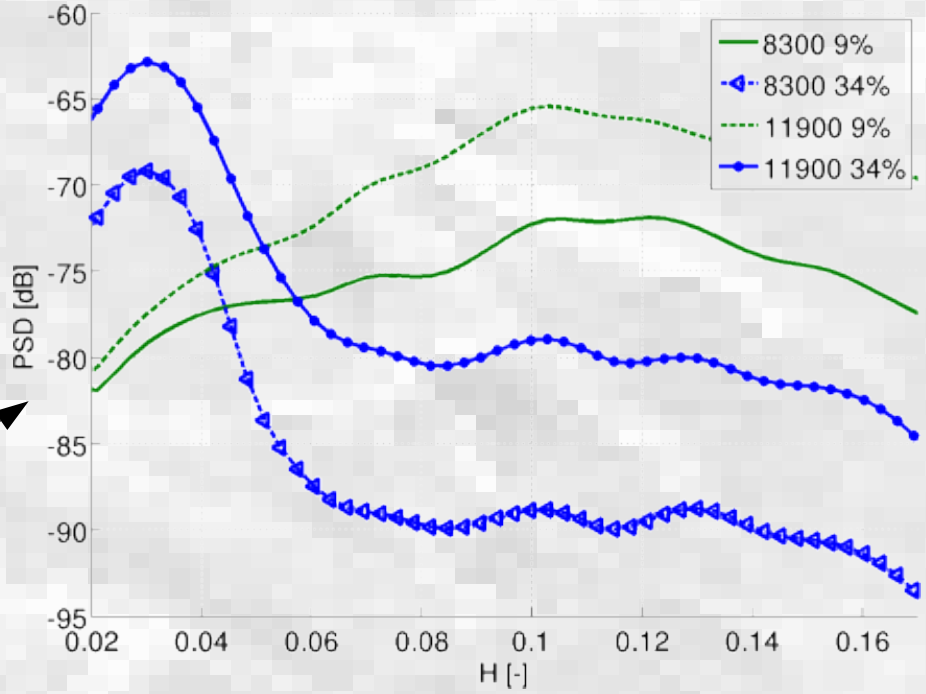


Re = 8300 & constriction degrees 4; 9; 16; 34%

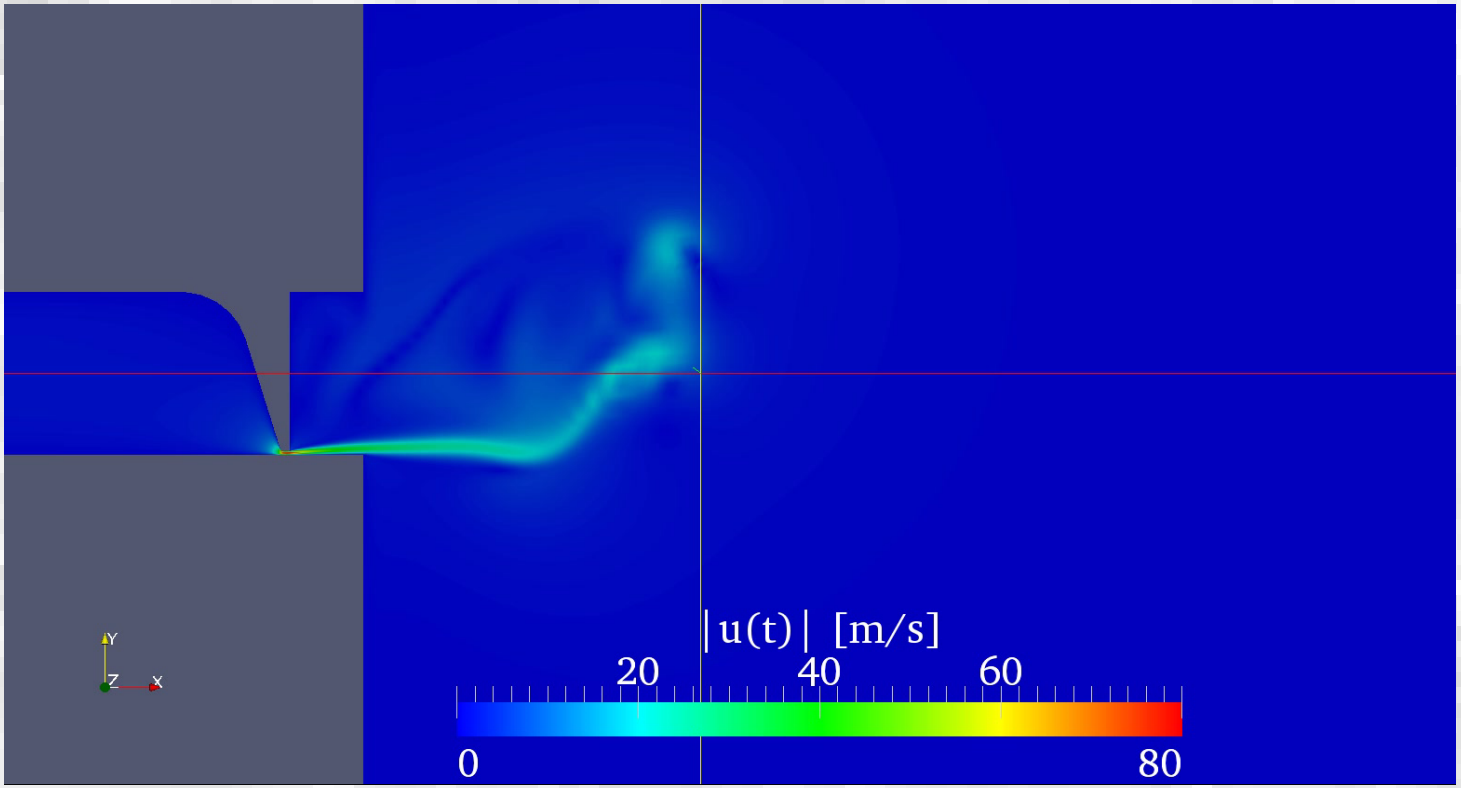
Helmholtz number

$$H = \frac{f D_h^c}{c}$$

Re = 8300; 11900 & constriction degrees 9; 34%



Example: H_c/H = 2.4% & Re = 2084

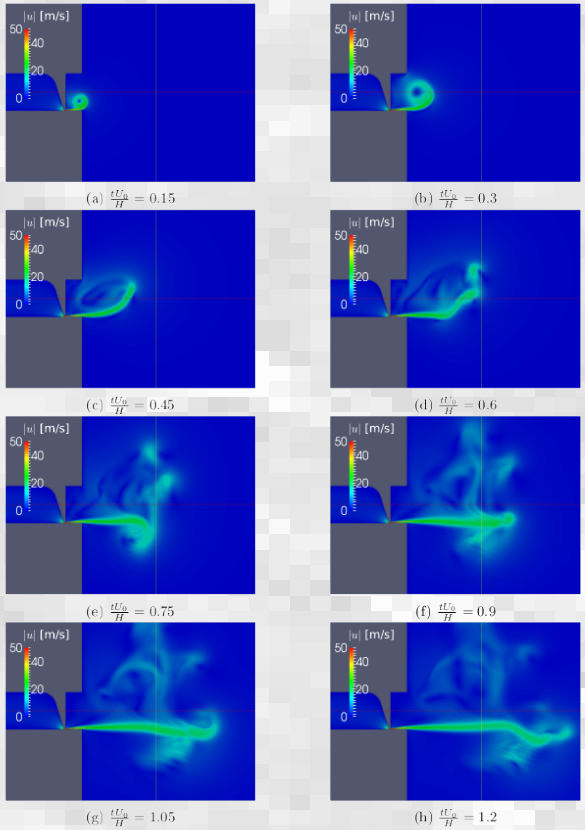


Results: 3D flow simulations

'Single obstacle' mesh: visualizations (2)

Example case:

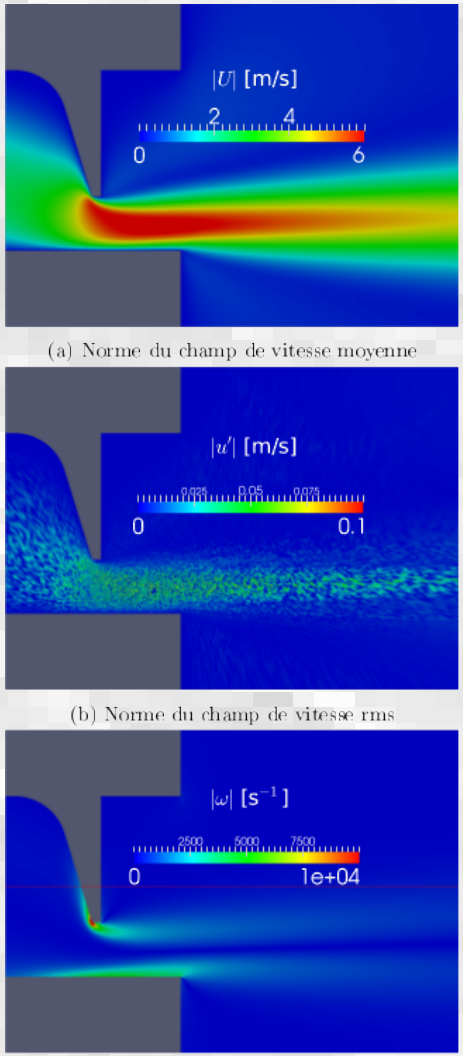
* Re = 2084
* H_c/H = 2.4%
* Uniform inlet vel. Profile
* Mean velocity field



(a) $\frac{tU_0}{H} = 0.15$ (b) $\frac{tU_0}{H} = 0.3$ (c) $\frac{tU_0}{H} = 0.45$ (d) $\frac{tU_0}{H} = 0.6$ (e) $\frac{tU_0}{H} = 0.75$ (f) $\frac{tU_0}{H} = 0.9$ (g) $\frac{tU_0}{H} = 1.05$ (h) $\frac{tU_0}{H} = 1.2$

Other example:

* Re = 2084
* H_c/H = 30%
* Uniform inlet vel. Profile
* TOP: mean vel.
* MID: rms vel.
* BOT: vorticity

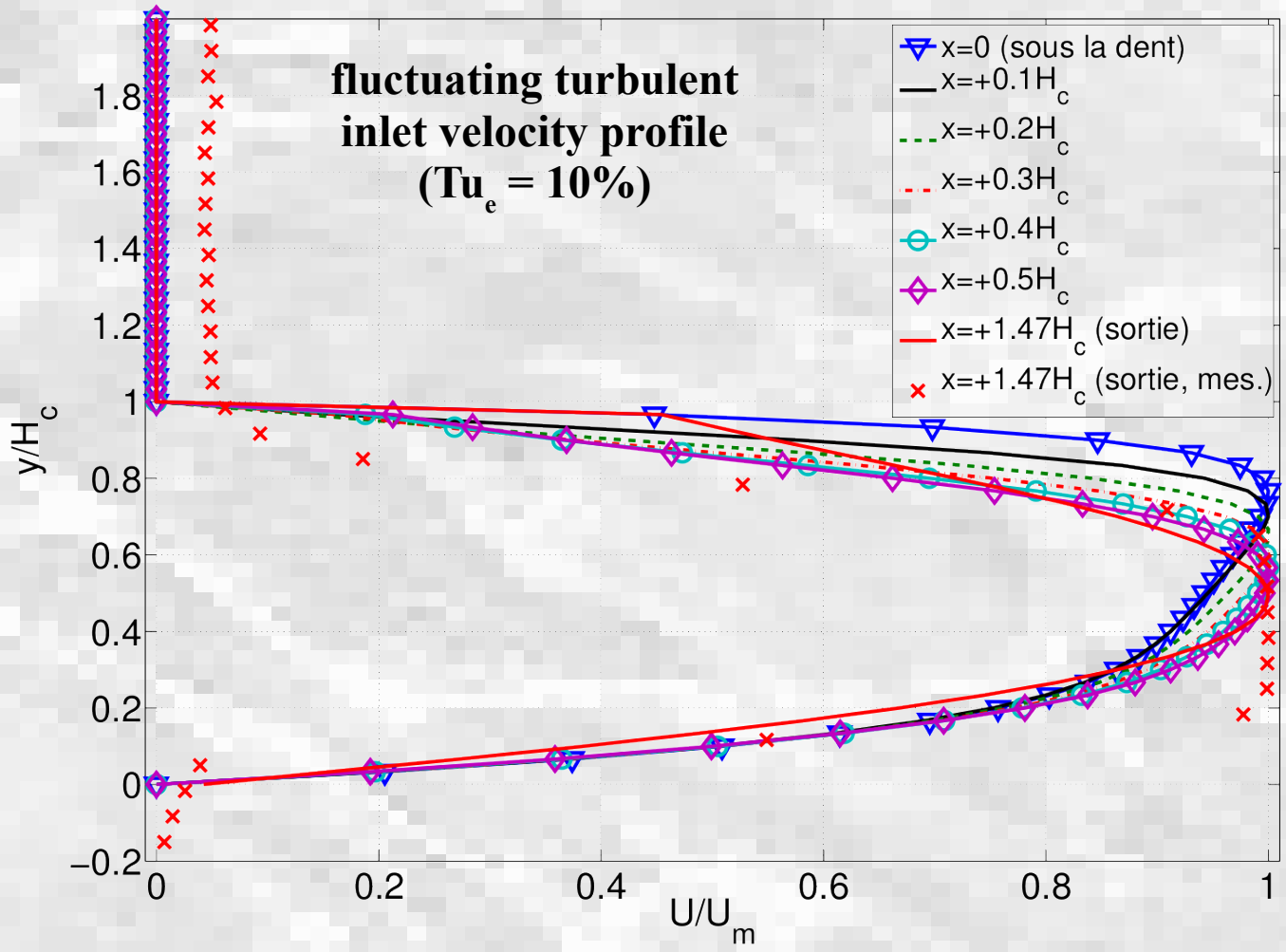


(a) Norme du champ de vitesse moyenne

(b) Norme du champ de vitesse rms

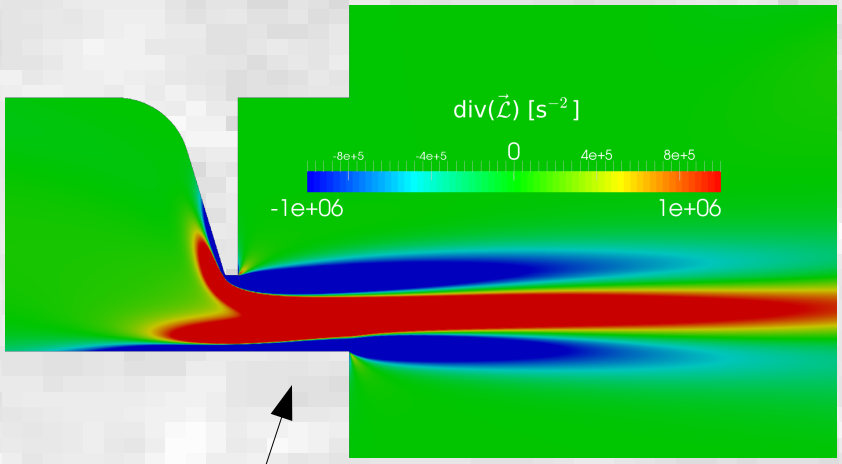
(c) Norme du champ de vorticité

Comparison of transverse mean velocity profiles simulated at several longitudinal positions downstream from the obstacle (H_c/H = 30%; Re = 2084)



Results: **3D flow simulations**

'Single obstacle' mesh: dipole noise source



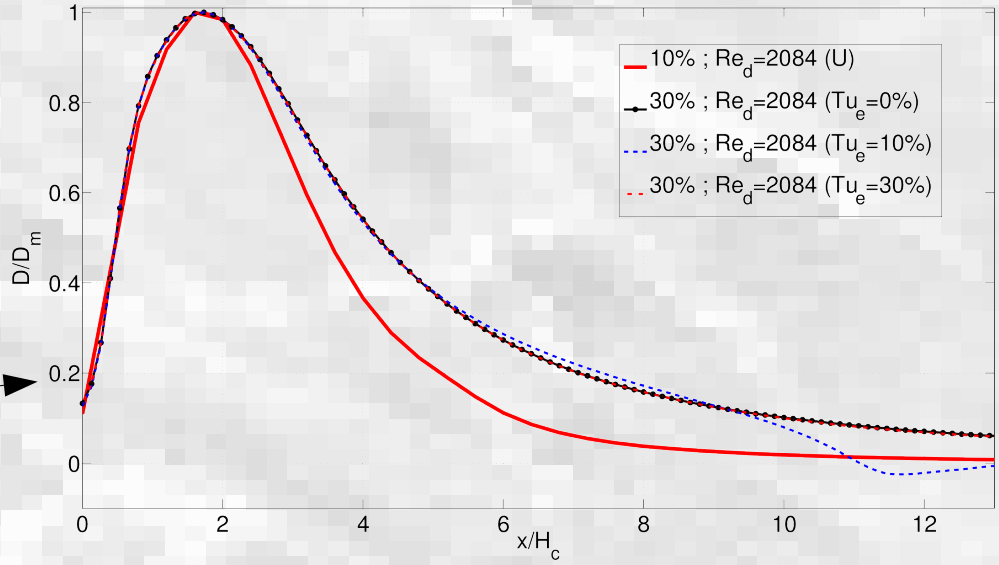
Longitudinal visualization of Lamb vector divergence field (H_c/H = 30%; Re = 2084)

Lamb vector → $\vec{\mathcal{L}} = \vec{u} \times \vec{\omega}$

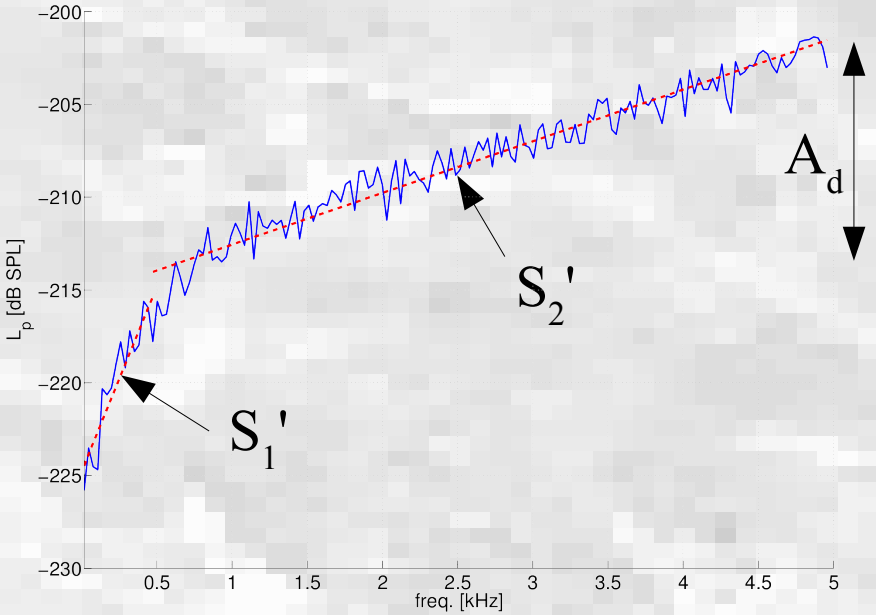
velocity

vorticity

Comparison of normalized Lamb vector divergences for different inlet conditions & Reynolds numbers



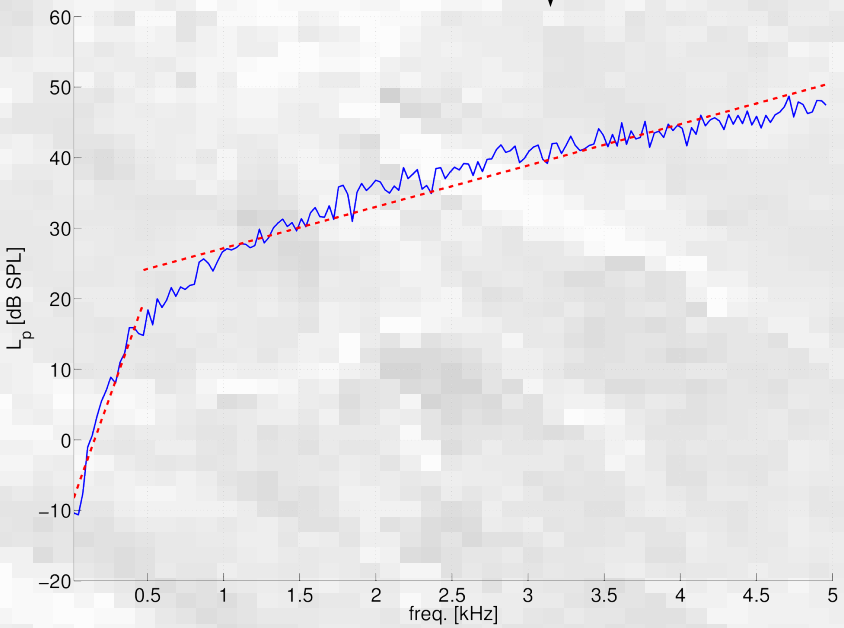
H_c/H = 10%; Re = 2084



without

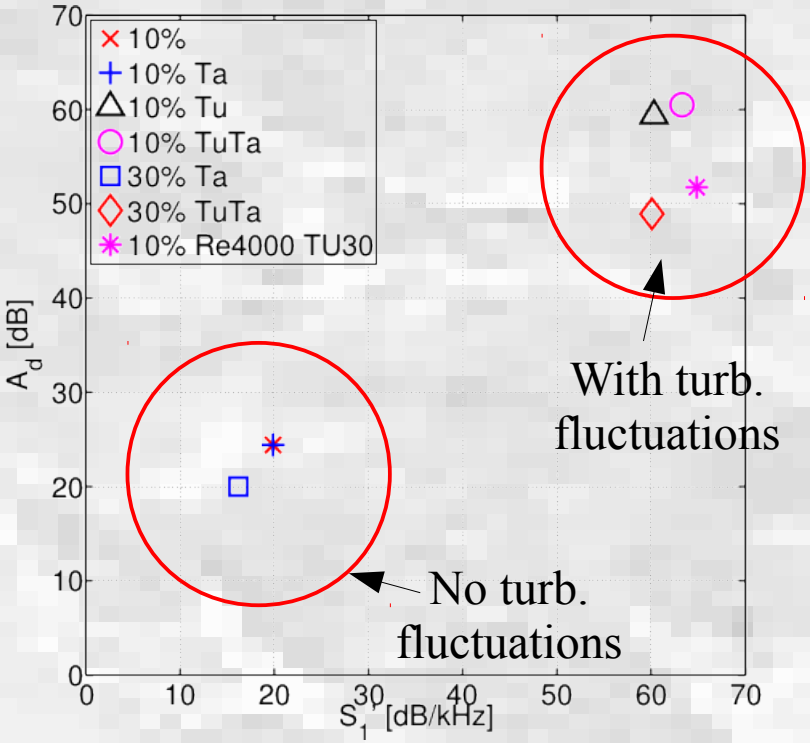
Random Gaussian turbulent fluctuations

with



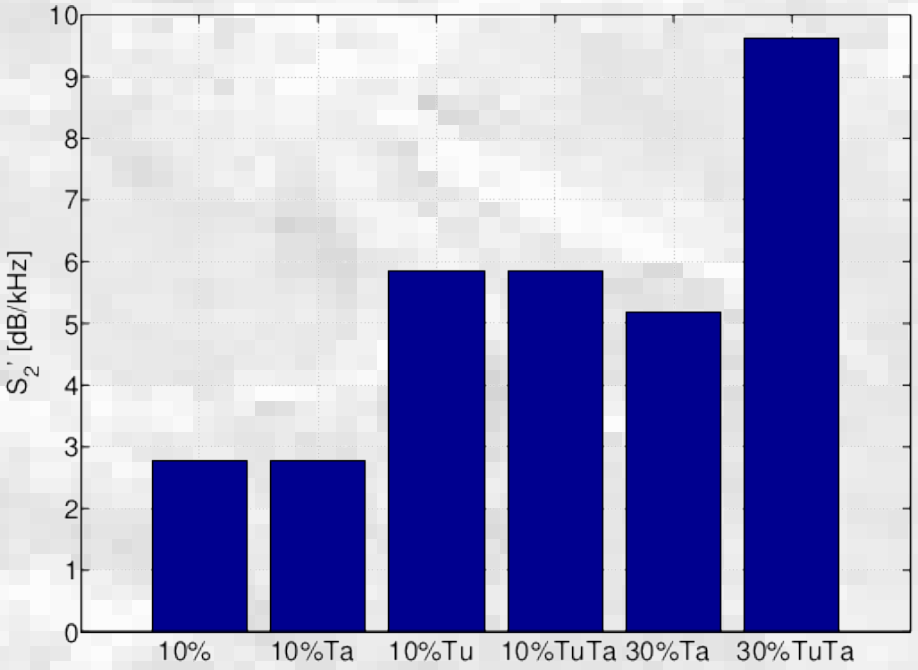
Spectral parameters:

* dynamic amplitude A_d
* spectral slopes S_1' & S_2'



Spectral parameters:

* dynamic amplitude A_d
* spectral slopes S_1' & S_2'



P%: constriction degree
Tu: with Gaussian turbulent fluctuations
Ta: with 'buffer layer'

Outline

I. Introduction

II. Theory

III. Method

IV. Results

V. Conclusion

Previous studies:
* Reynolds number *Re* = 4000 (exp.+sim.)
* Constriction degree (exp.+sim.)
* Uniform inlet velocity profile (sim.)

This thesis

Unvoiced fricative production

Flow initial conditions?

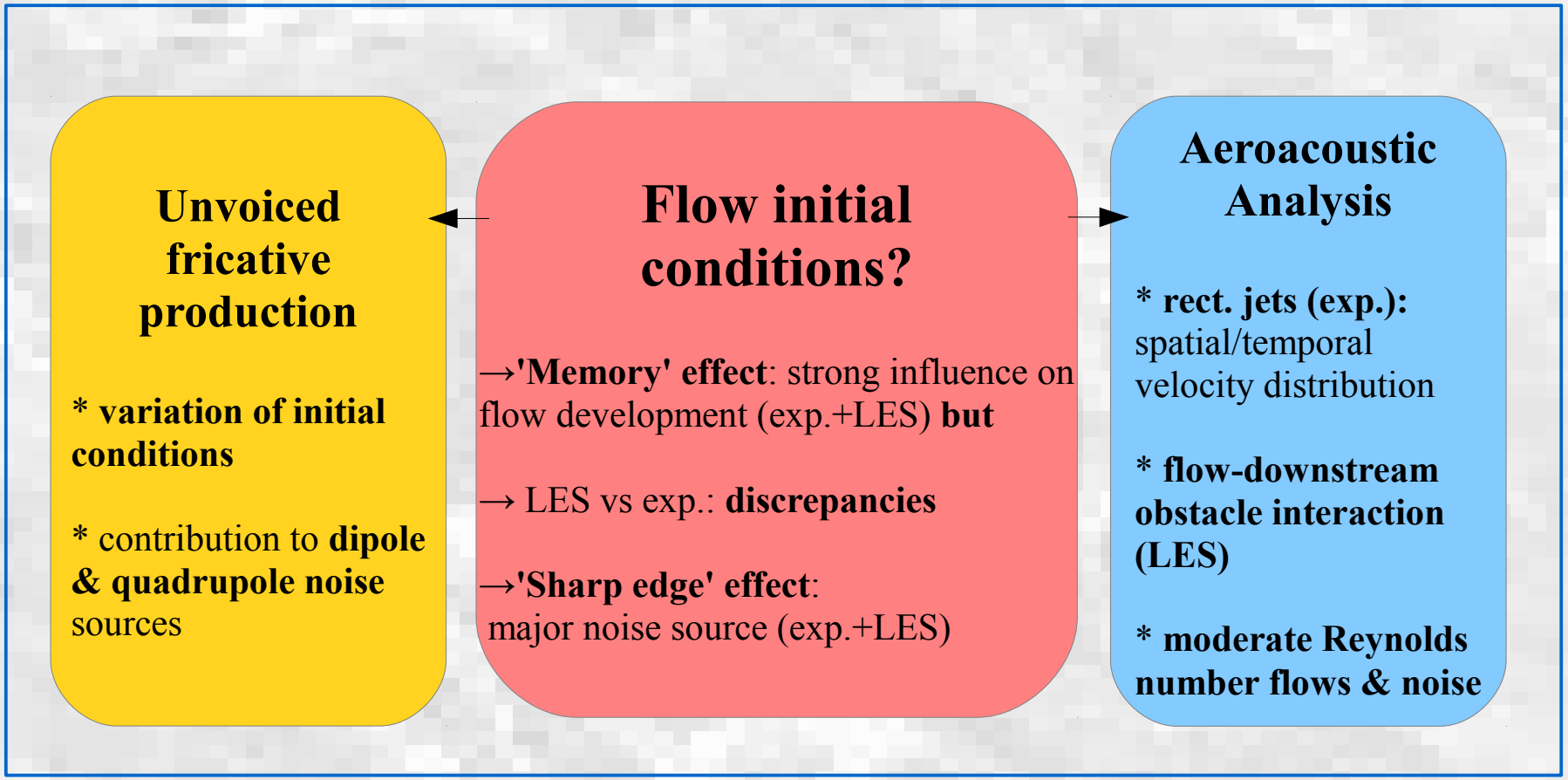
Reynolds numbers *Re*?

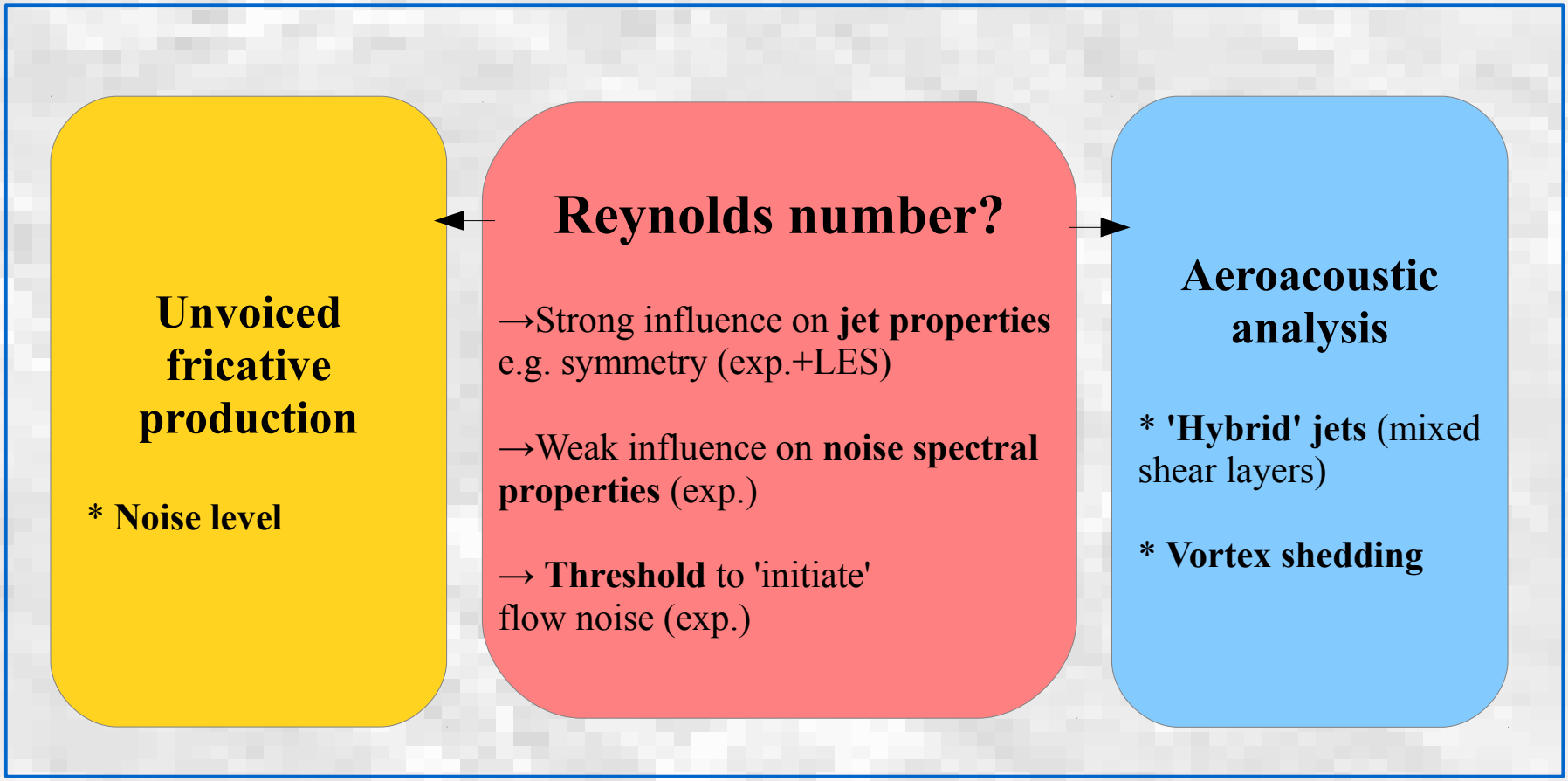
Obstacle(s) geometry?

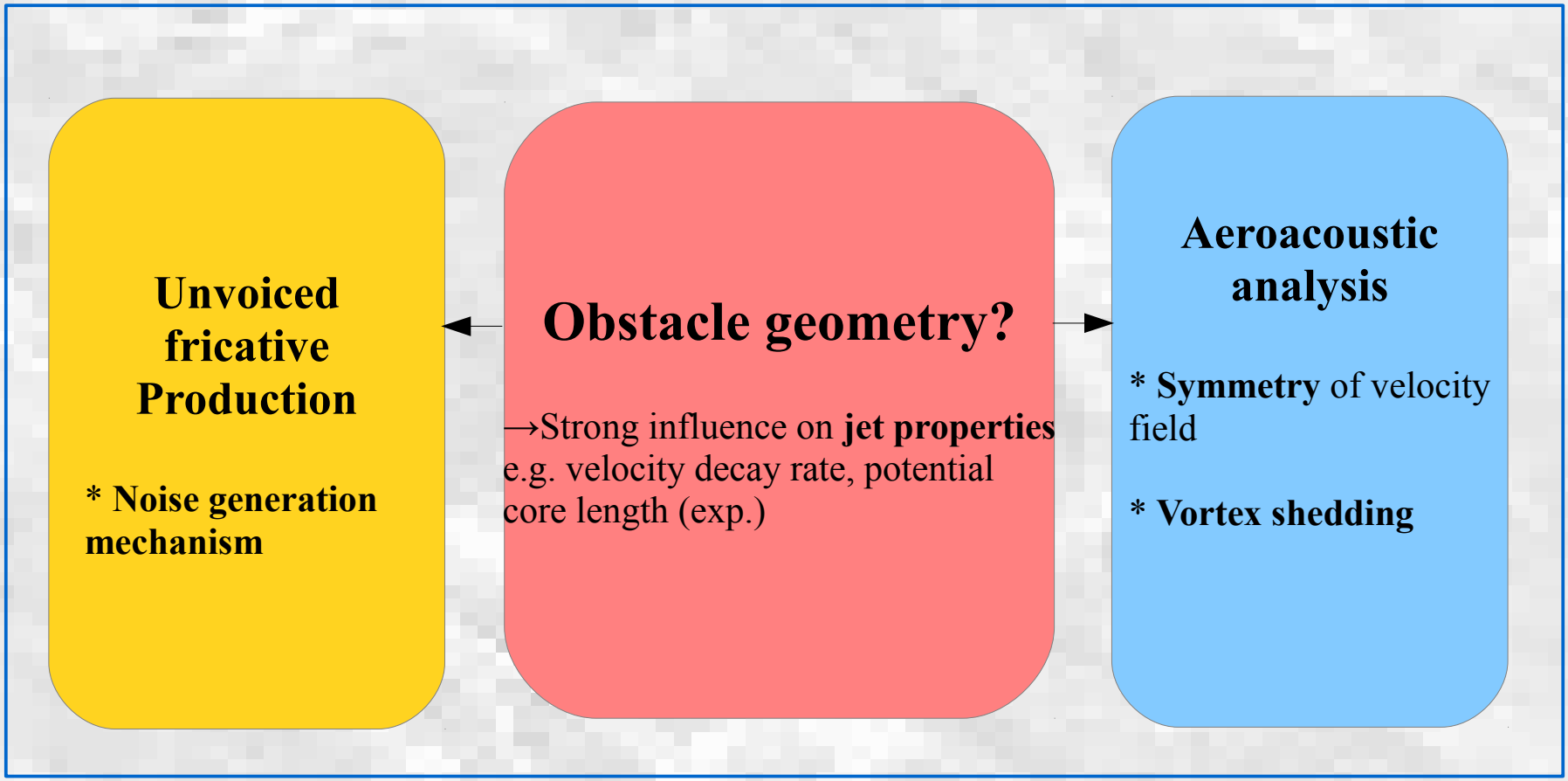
Aeroacoustic analysis

* Experiments
* Simulations

Influence of flow initial conditions




Unvoiced fricative production
* Noise level
Reynolds number?
→Strong influence on **jet properties** e.g. symmetry (exp.+LES)
→Weak influence on **noise spectral properties** (exp.)
→ **Threshold** to 'initiate' flow noise (exp.)
Aeroacoustic analysis
* **'Hybrid' jets** (mixed shear layers)
* **Vortex shedding**


Unvoiced fricative Production
* Noise generation mechanism
Obstacle geometry?
→Strong influence on jet properties e.g. velocity decay rate, potential core length (exp.)
Aeroacoustic analysis
* Symmetry of velocity field
* Vortex shedding

* **Study of jet stability...**

* Further development of **turbulence simulation method,** e.g. taking into account large coherent structures...

* Further development of **aeroacoustic prediction methods** (e.g. Ffowcs Williams & Hawkings analogy taking into account solid boundaries)...

* **Transverse modes**...

* **Other (potential) applications:**
  - Oral/dental health care...

Publications

JOURNAL PUBLICATIONS

Steady laminar axisymmetrical nozzle flow at moderate Reynolds numbers: modelling and experiment
Grandchamp, Xavier and **Fujiso, Yo** and Wu, Bo and Van hirtum, Annemie. Journal of Fluids Engineering - T ASME 134 2012 011203

Insulation room for aero-acoustic experiments at moderate Reynolds and low Mach numbers.
Van Hirtum, Annemie and **Fujiso, Yo**. Applied Acoustics 73 1 2012 72-77

CONFERENCES

Experimental and numerical characterization of aerodynamic noise applied to moderate Reynolds number airflow
Fujiso,Yo and Van Hirtum, Annemie and Kazunori, Nozaki and Wada, Shigeo. ICA 2013 proceedings - Volume 19 of POMA (Proceedings of Meetings on Acoustics) - 21st International Congress on Acoustics (ICA 2013) - 165th Meeting of the Acoustical Society of America

Study of unvoiced fricative speech production: Influence of initial conditions on flow development.
Fujiso,Yo and Van Hirtum, Annemie and Nozaki, Kazunori and Wada, Shigeo. ICA 2013 proceedings - Volume 19 of POMA (Proceedings of Meetings on Acoustics) - 21st International Congress on Acoustics (ICA 2013) - 165th Meeting of the Acoustical Society of America

Aeroacoustic characterisation of single and dual tooth-shaped obstacle replicas in relation to the study of unvoiced fricative speech production.
Fujiso, Yo and Van Hirtum, Annemie. Acoustics 2012 Nantes - Acoustics 2012

Ecoulement laminaire axisymétrique stationnaire dans un convergent : modélisation et validation expérimentale
Fujiso, Yo and Wu, Bo and Grandchamp, Xavier and Van Hirtum, Annemie. Actes du CFM 2011 - 20ème Congrès Français de Mécanique (CFM 2011)

Jet rond en aval d‘une contraction brusque.
Grandchamp, Xavier and **Fujiso, Yo** and Van Hirtum, Annemie. Actes du CFM 2011 - 20ème Congrès Français de Mécanique (CFM 2011)

Caractérisation d‘un convergent axisymétrique destiné à la validation expérimentale de production de parole
Fujiso, Yo and Wu, Bo and Grandchamp, Xavier and Van Hirtum, Annemie. Actes des 9ème RJCP 2011 - 9ème Rencontres des Jeunes Chercheurs en Parole 2011 (RJCP 2011)

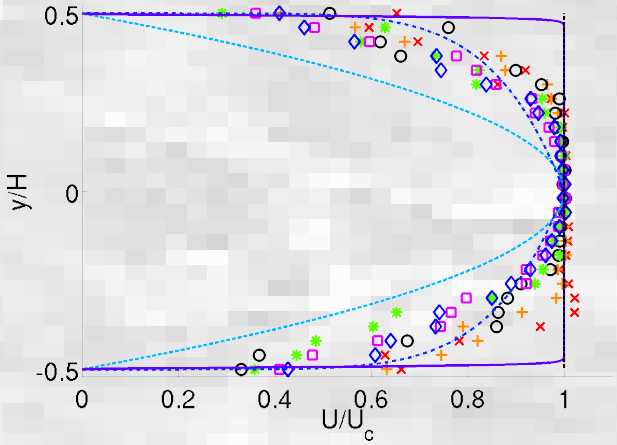
Thank you for your attention!

Acknowledgements:

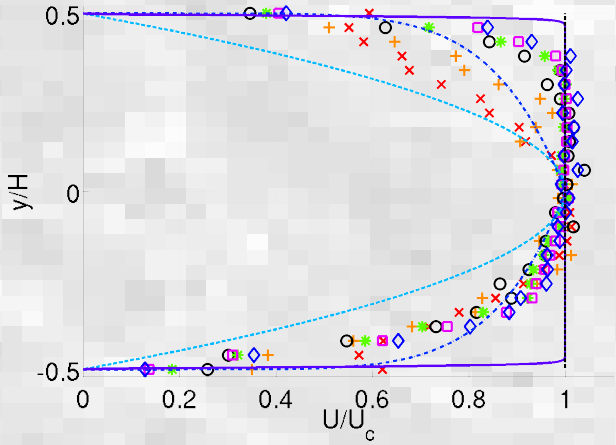
ANR Petaflow ANR-09-BLAN-0376-01
Rhône-Alpes region (CMIRA 2011)
K. Nozaki & S. Wada
Osaka Univ. / Cybermedia Center

Ducts with obstacle(s): *in-vitro* exp.

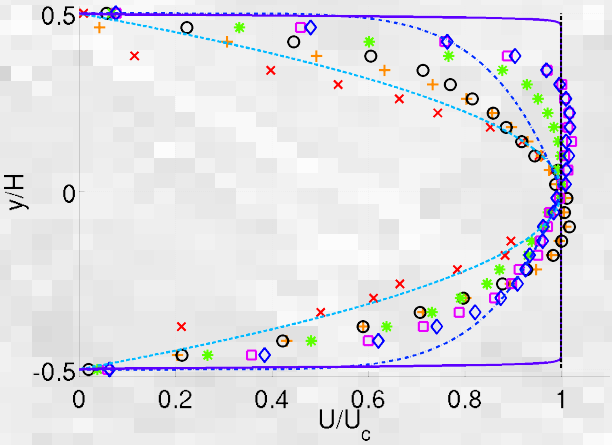
Inlet flow data: mean transverse profiles



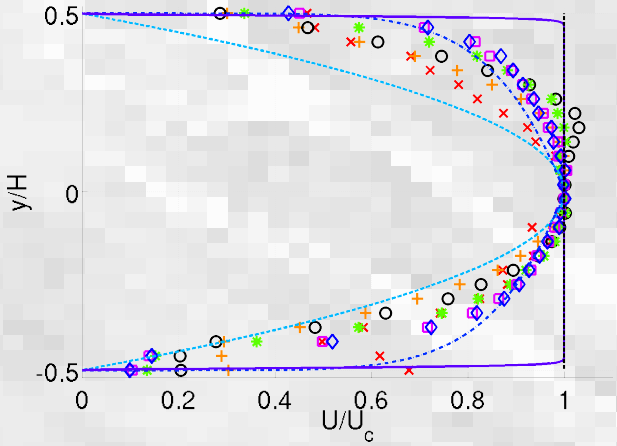
L=0cm



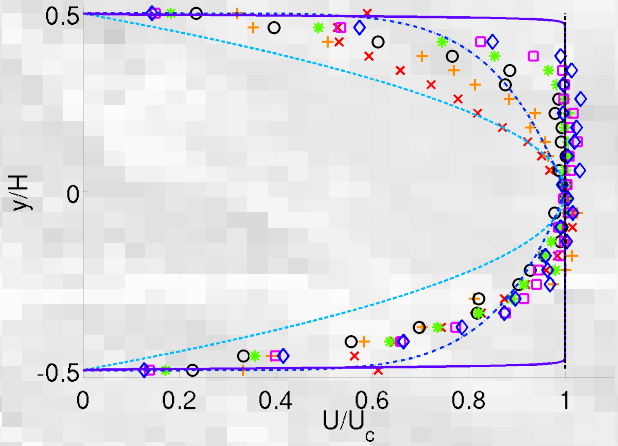
L=31cm



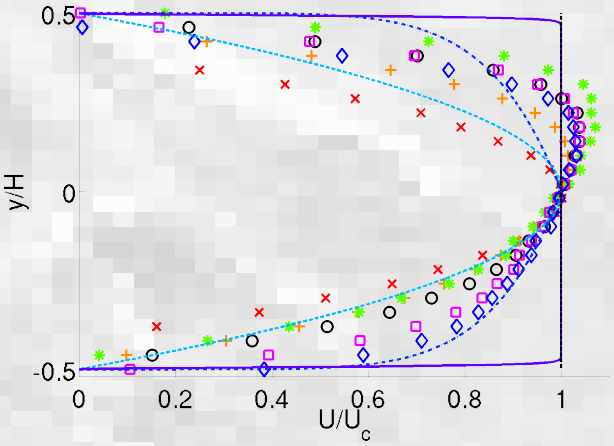
L=31cm + nid d'abeille



L=31cm + pailles



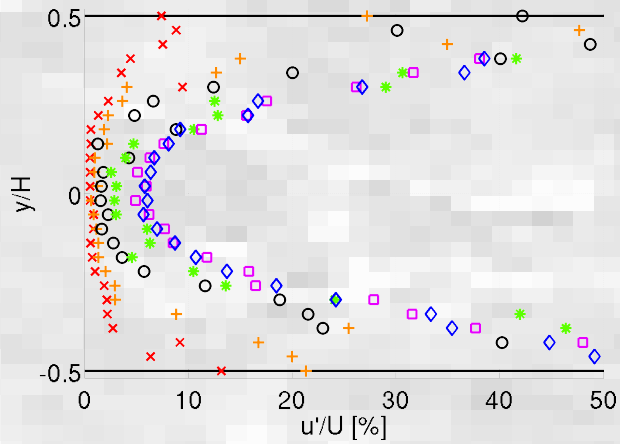
L=62cm



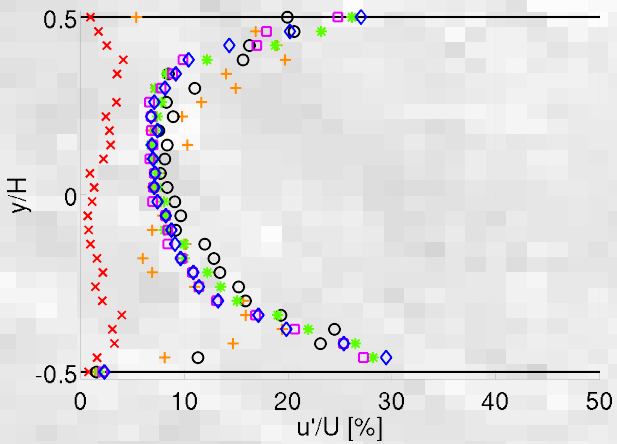
L=62cm + pailles

Ducts with obstacle(s): *in-vitro* exp.

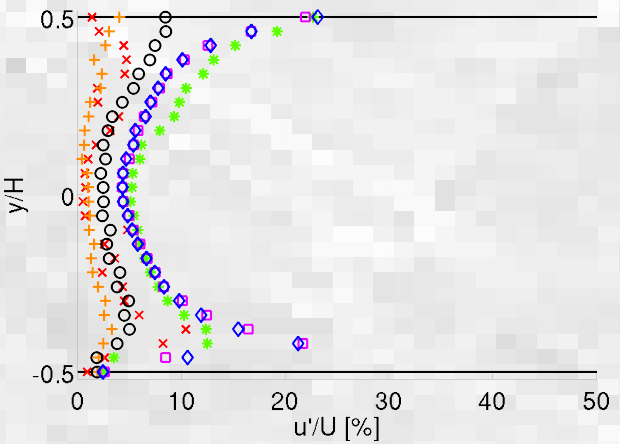
Inlet flow data: turbulence intensity profiles



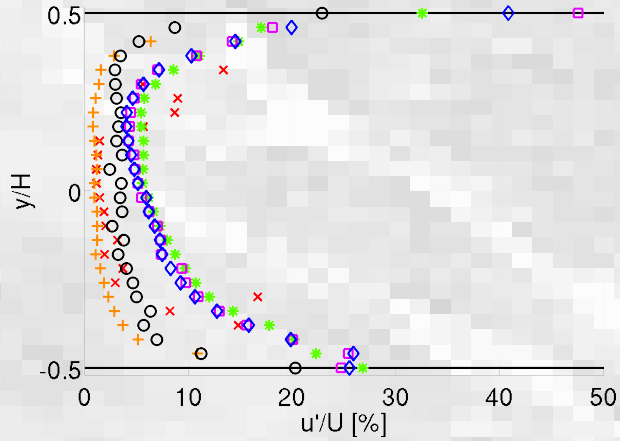
L=0cm



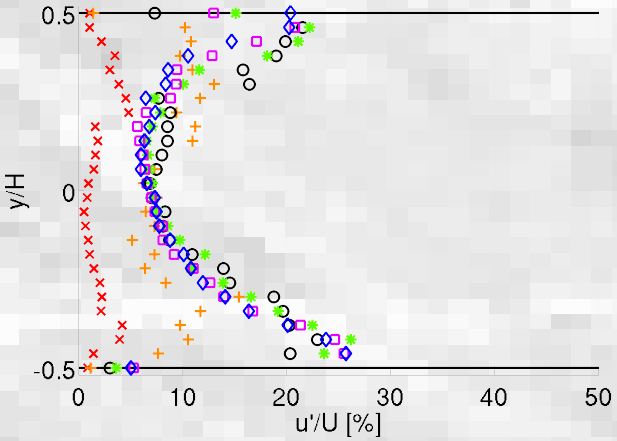
L=31cm



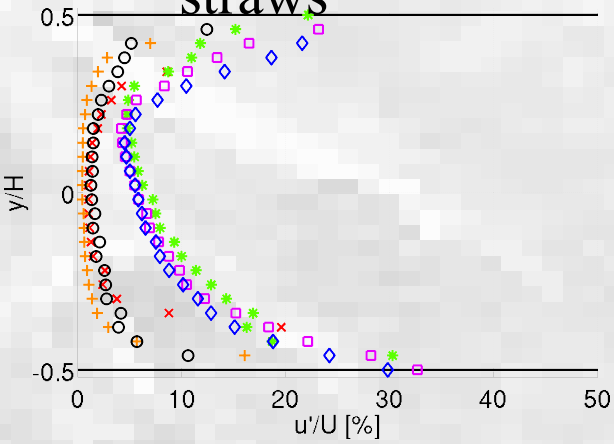
L=31cm + straws



L=31cm + honeycomb



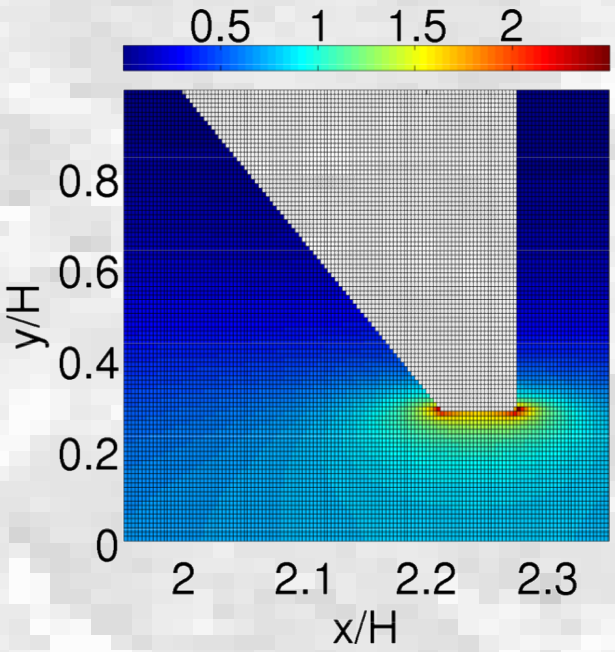
L=62cm

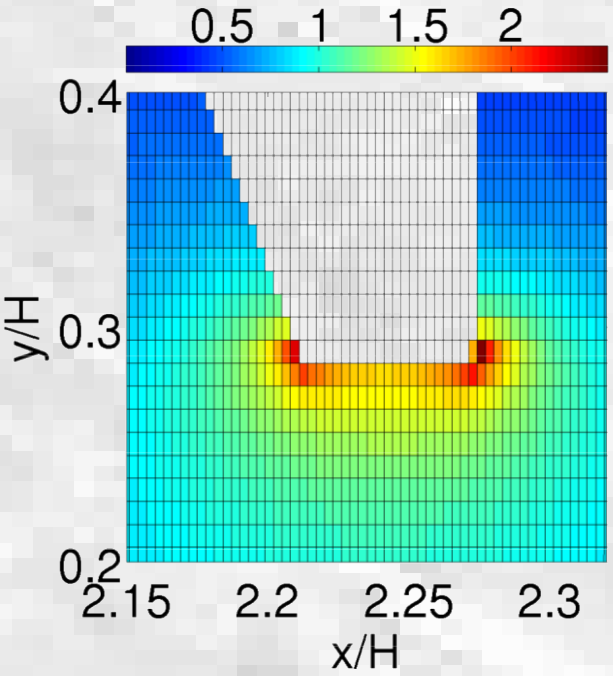


L=62cm + straws

Ducts with obstacle(s): num. simul.

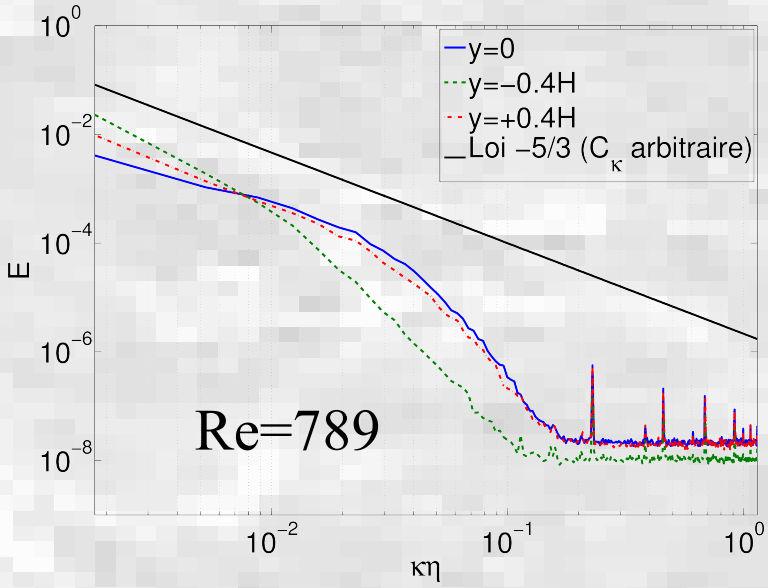
2D simulations

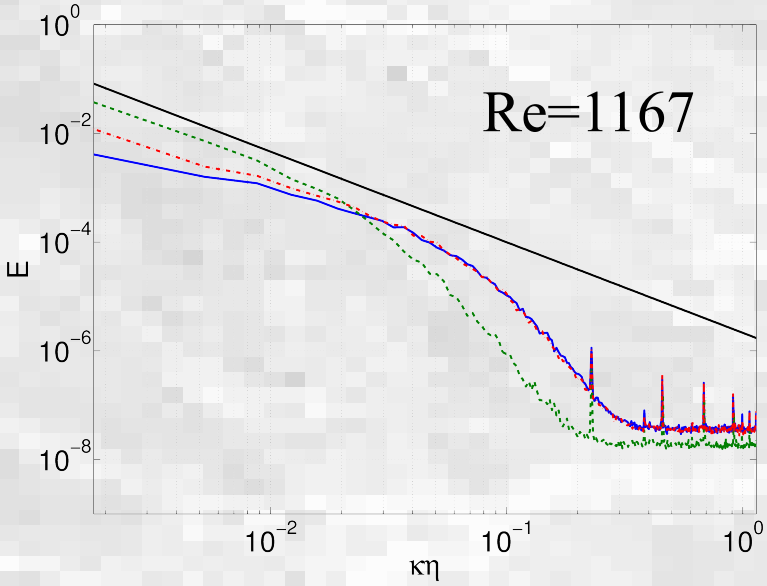


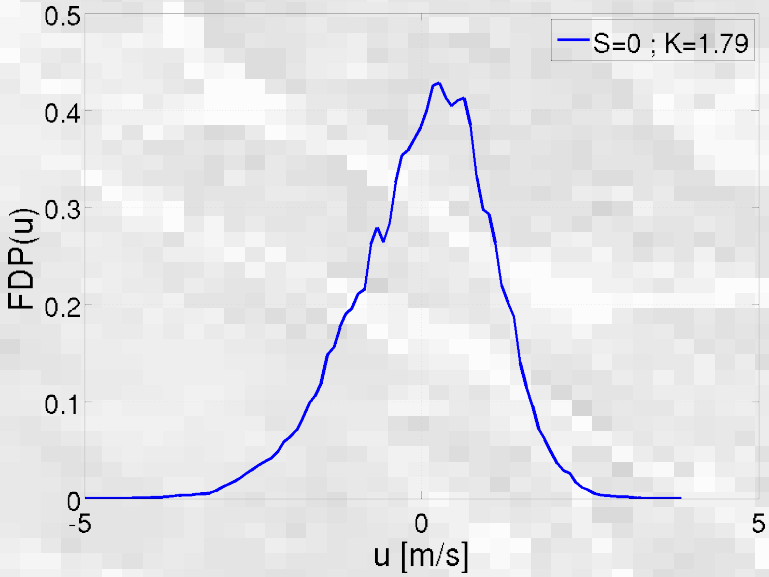


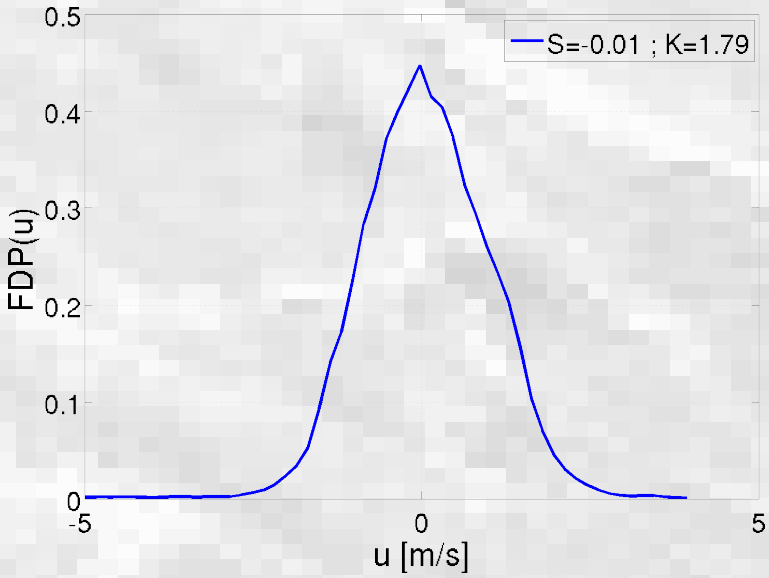
Ducts with obstacle(s): *in-vitro* exp.

Inlet flow data: Kolmogorov spectra



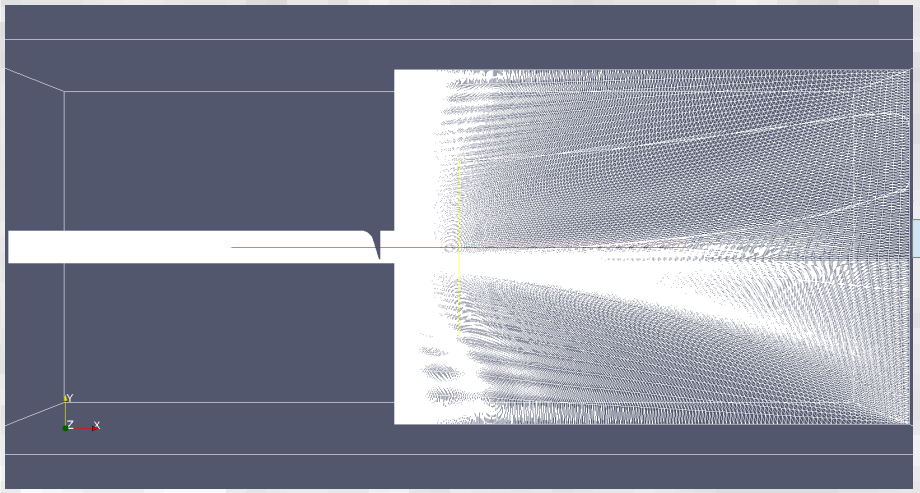


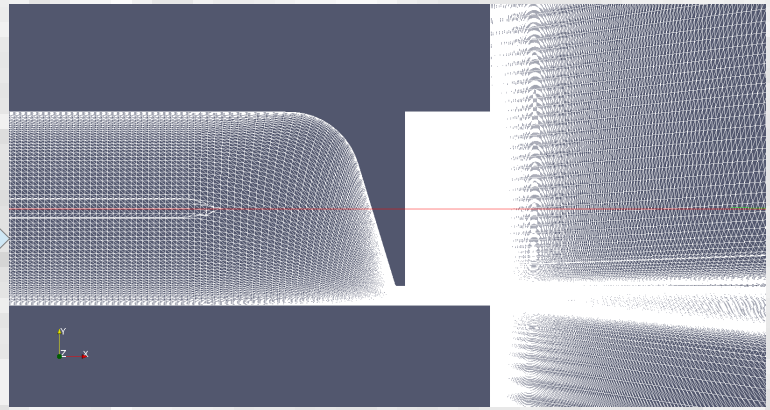




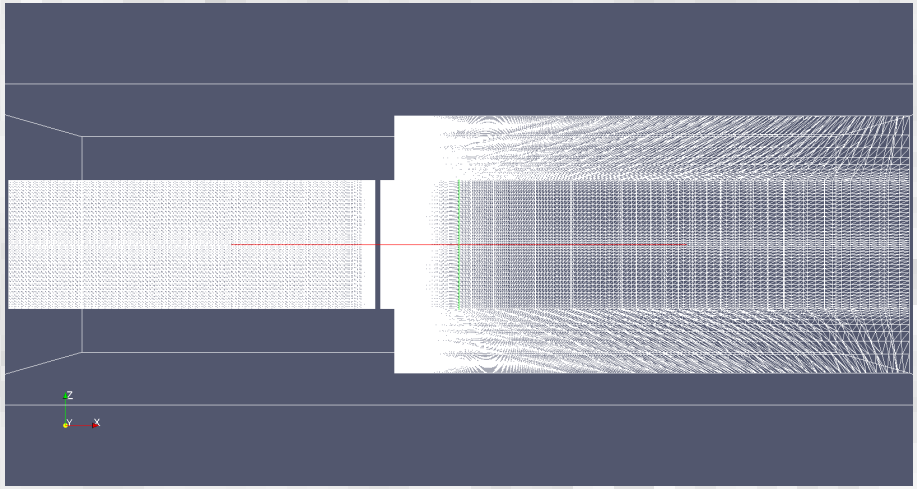
Ducts with obstacle(s): num. simul.

3D simul. (LES): geometry

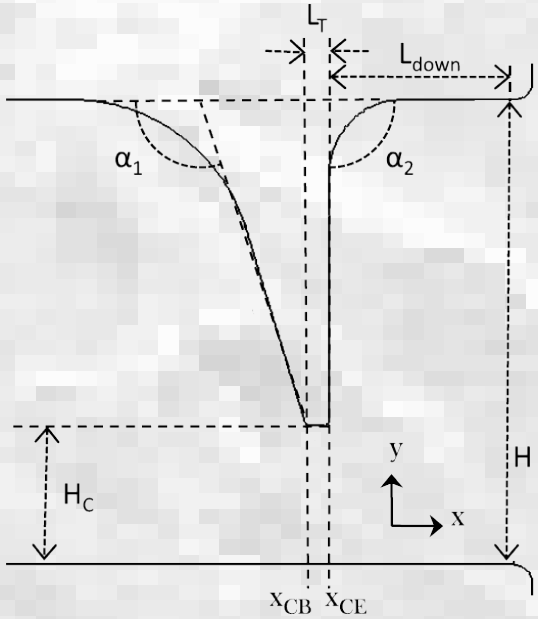




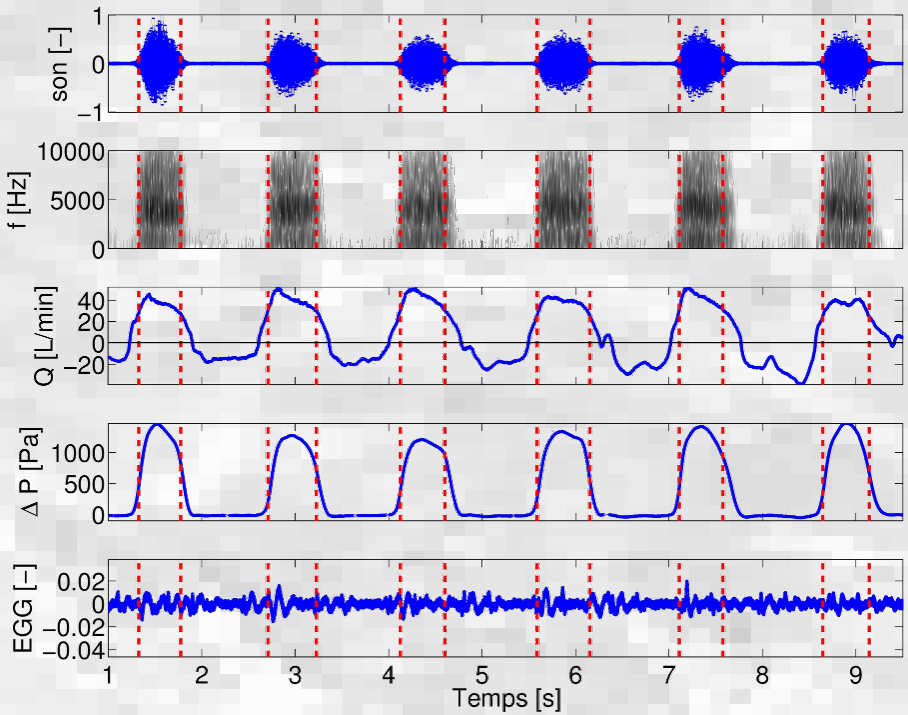
(*xy*) plane



(*xz*) plane



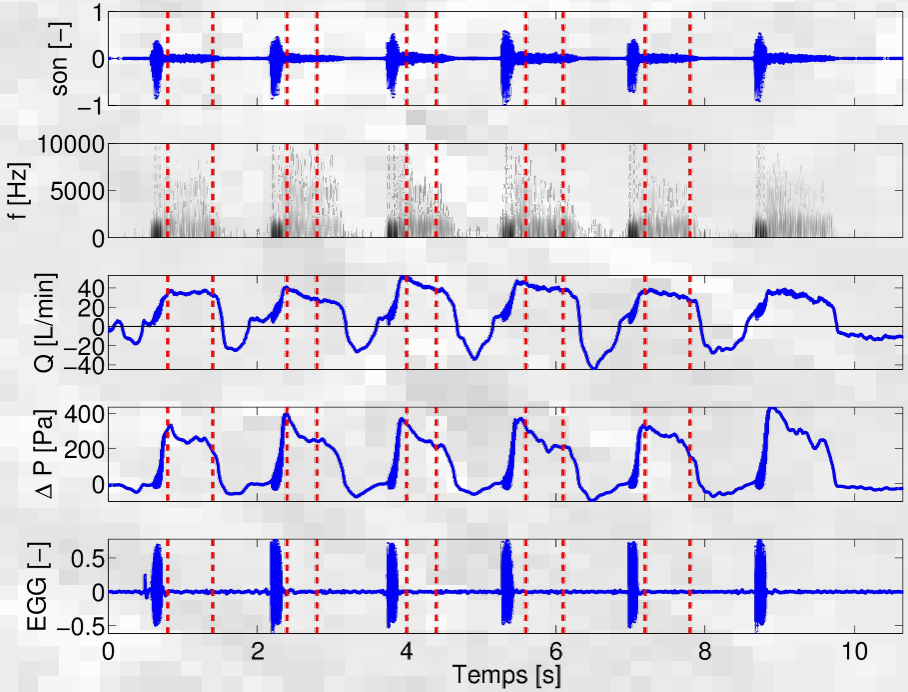
In-vivo data & reconstr. oral cavity



/s/ subject 'KN'
'medium' level

In-vivo EVA data: examples

/f/ subject 'YF'
'medium' level



→ Production of sibilant /s/ severely affected by teeth!



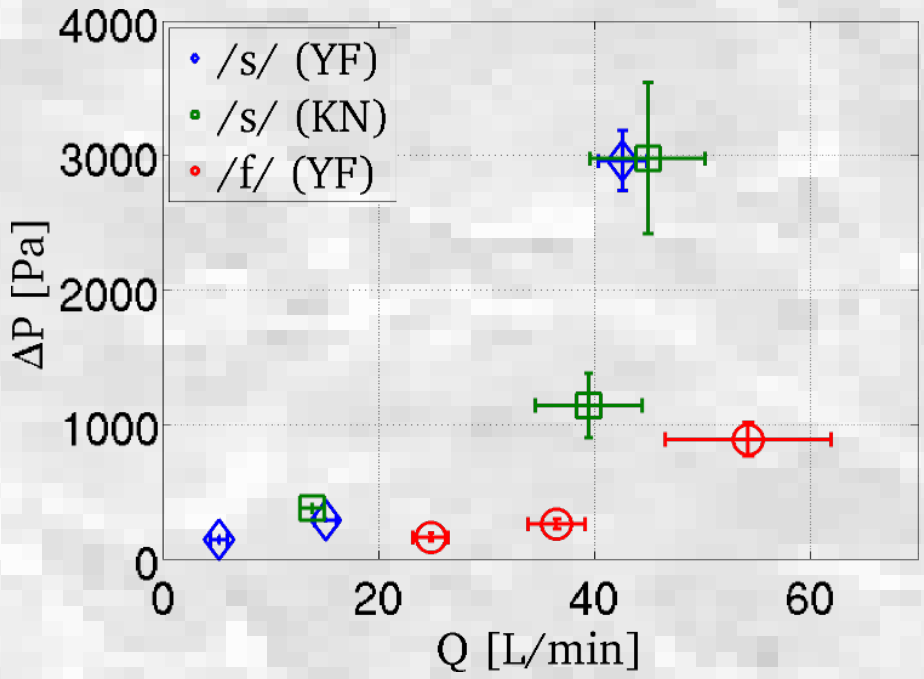
→ How to quantitatively assess this?

→ *In-vitro* reconstruction of *in-vivo* geometry?

→ Relevance of a dual approach? (*in-vivo* & *in-vitro* exp. data)

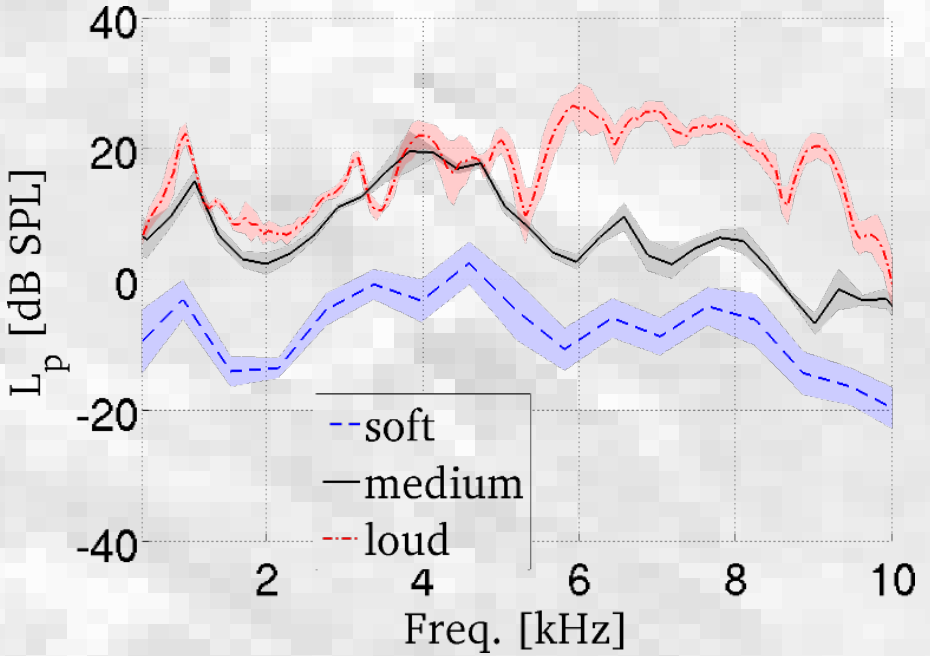
→ A potential biomarker for dental/oral medical care?

In-vivo data & reconstr. oral cavity



In-vivo EVA data

$$L_p(f) = 10 \times \log_{10}\left(\frac{|P(f)}{p_{ref}^2}\right)$$



$$\Delta P = \frac{\rho Q^2}{2c_s^2}\left(\frac{1}{A_c^2} - \frac{1}{A_0^2}\right)$$

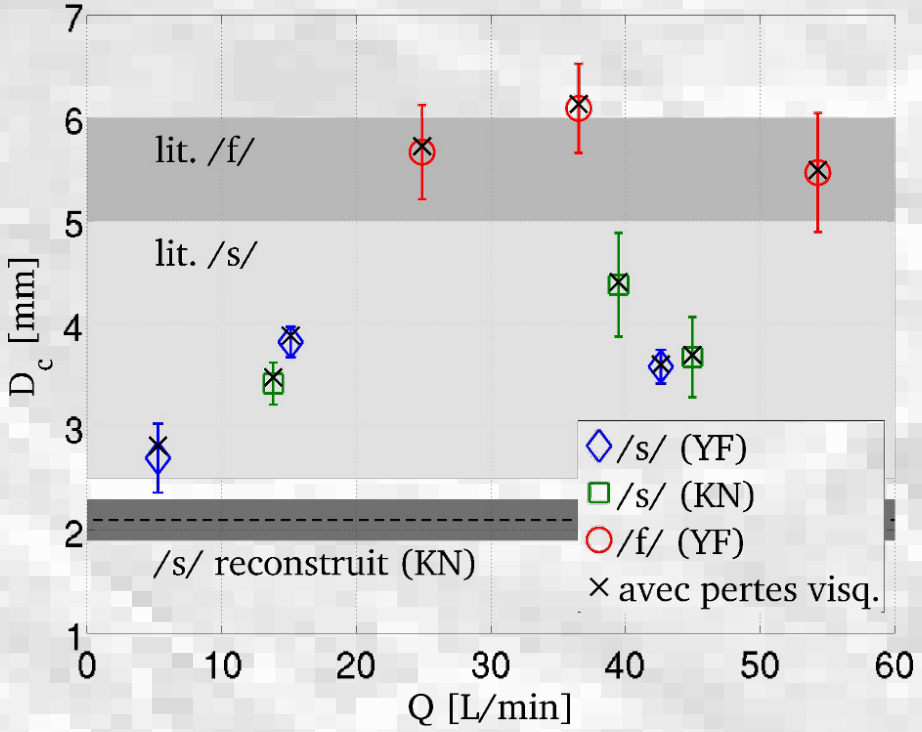
Without viscous losses

$$A_c = \frac{Q}{\sqrt{\frac{2\Delta P}{\rho}}}$$

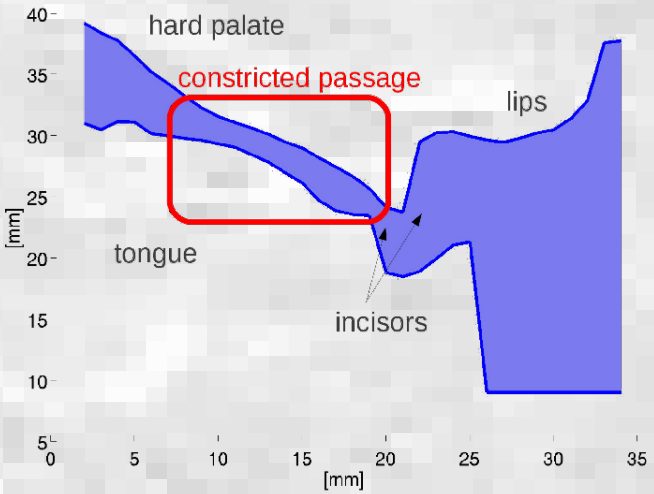
With viscous losses

$$A_c = \sqrt{\frac{Q^2 + 16\pi\nu QL}{\frac{2\Delta P}{\rho}}}$$

$$D_C = 2\sqrt{A_c/\pi}$$

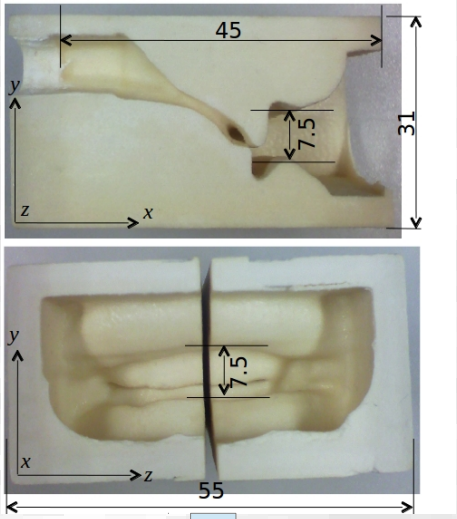


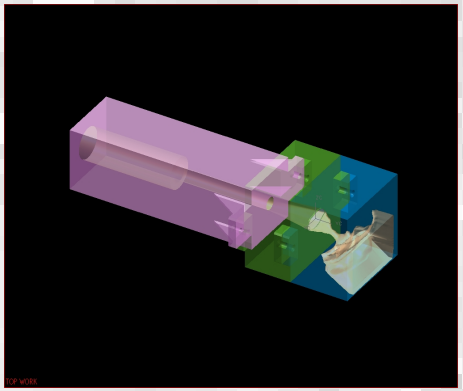
CT* scan during a 30s sustained sibilant /s/



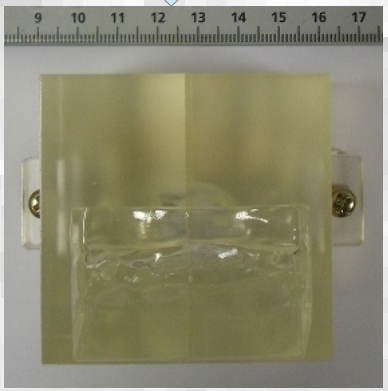
*CT Computerized Tomography

Plaster cast





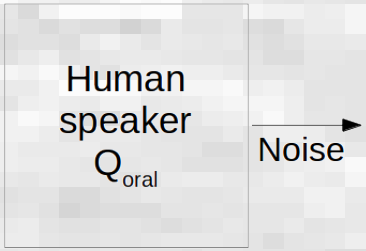
Mechanical replica (upstr. duct + reconstr. oral cavity)



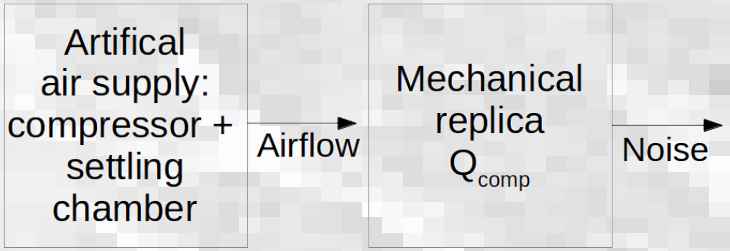
Reconstructed oral cavity

Acoustic experiment: comparison of human & reconstructed sibilant /s/ noises

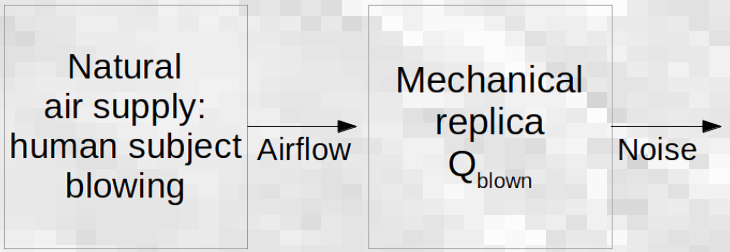
- **Case (I): Q_{oral} *a priori* measured ('soft', 'medium', 'loud')**

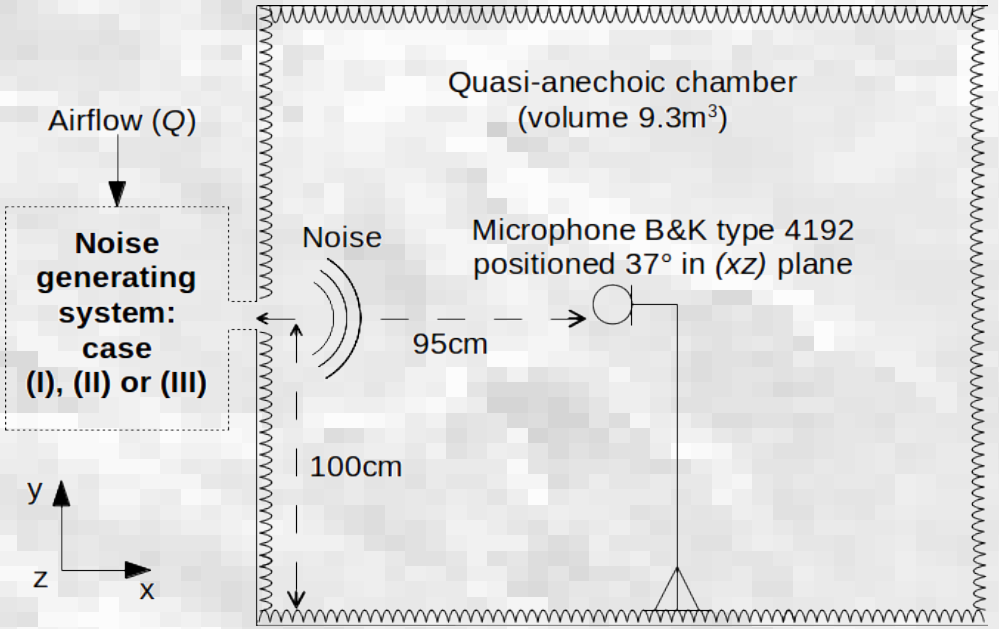


- **Case (II): Q_{comp} measured by volume flow meter**



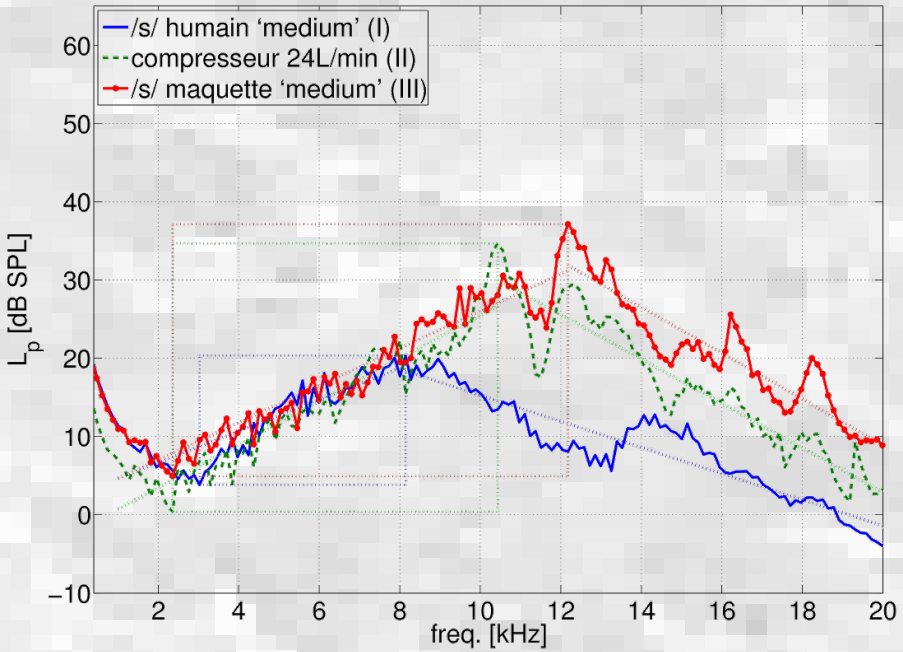
- **Case (III): Q_{blown} *a priori* measured ('soft', 'medium', 'loud')**



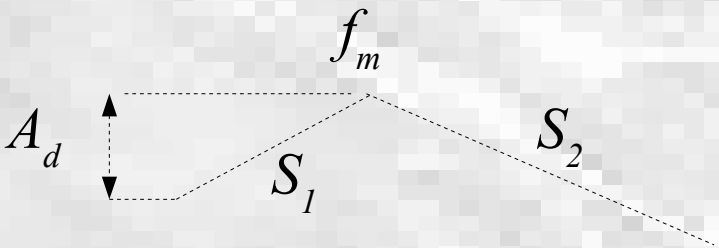


In-vivo data & reconstr. oral cavity

Comparison of noise spectra (0-20kHz)



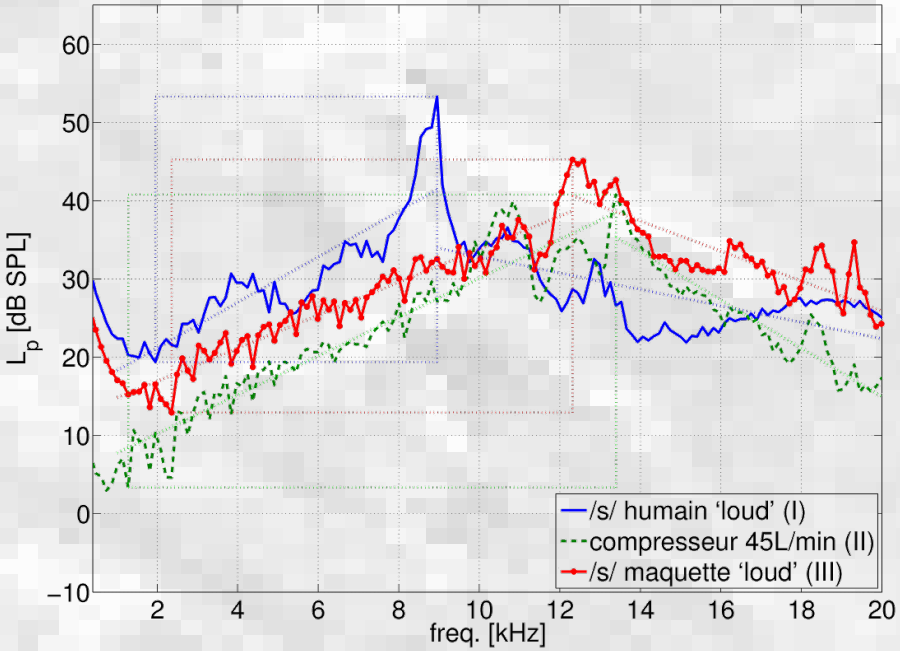
medium



Spectral parameters:

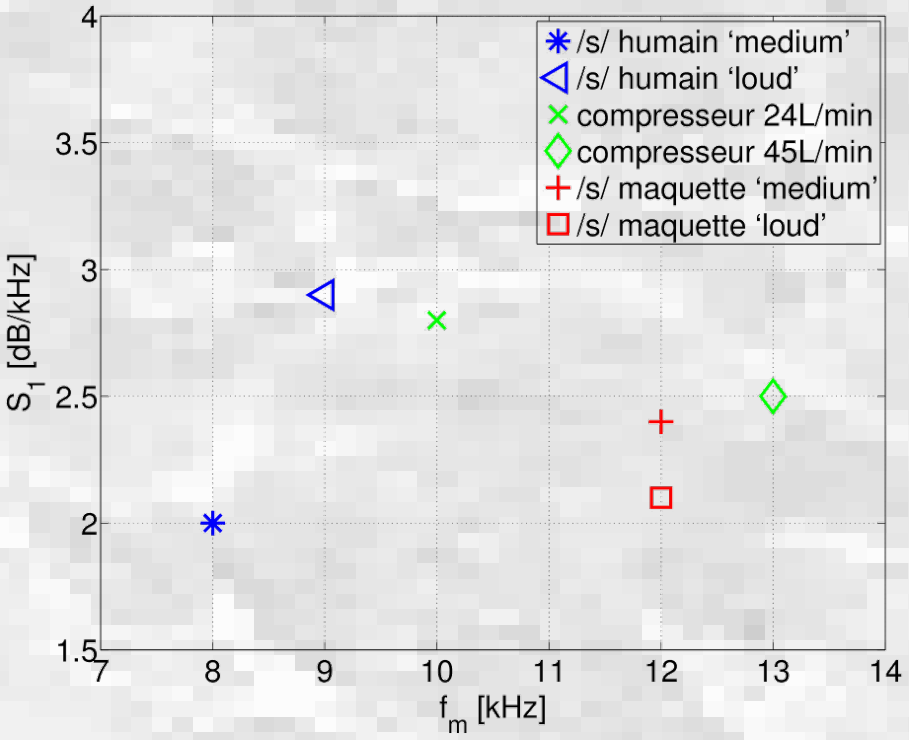
* spectral peak f_m
* spectral slopes S_1 & S_2
* dynamic amplitude A_d

loud



In-vivo data & reconstr. oral cavity

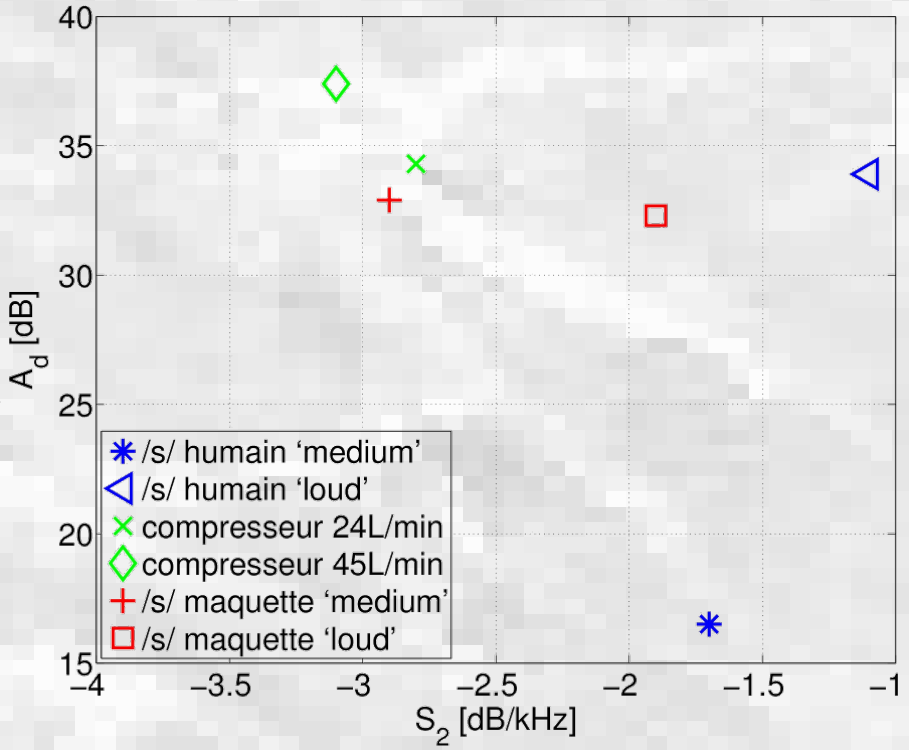
Estimated spectral parameters

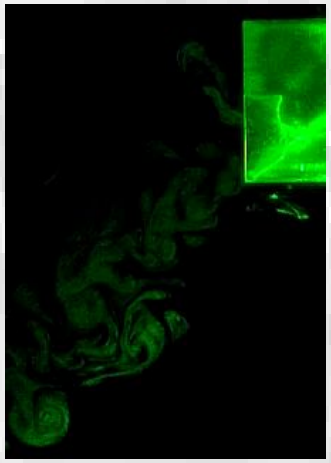


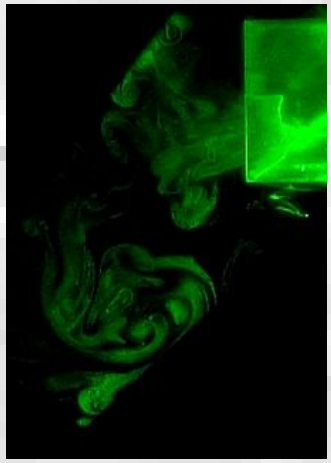
spectral peak

S_1 & S_2: spectral slopes

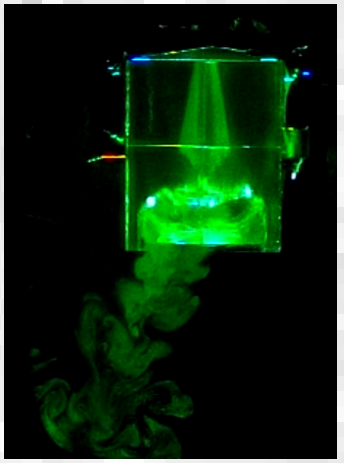
dynamic amplitude







Transverse views [rajouter débits]

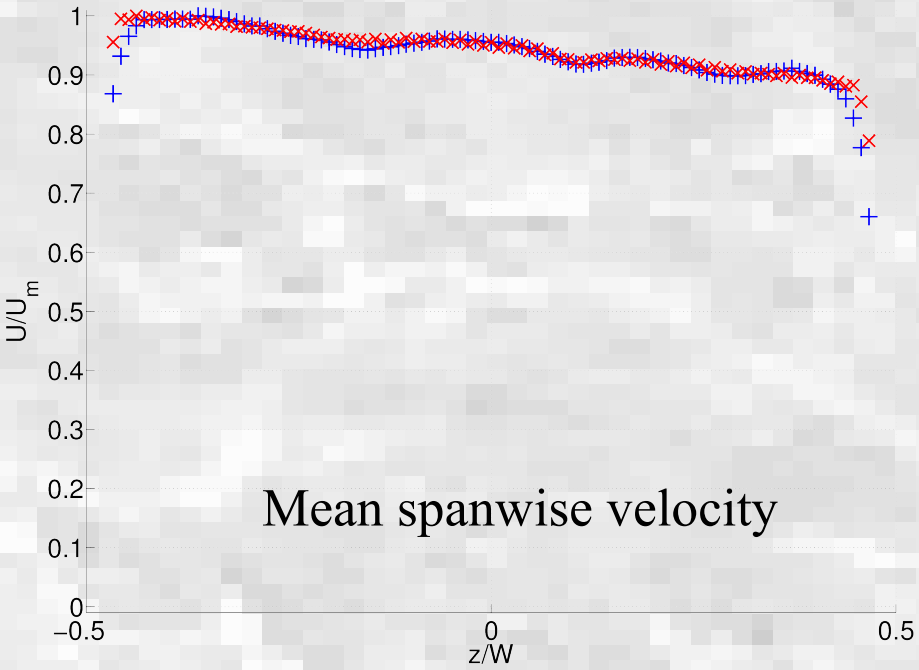


Longitudinal view [36L/min]

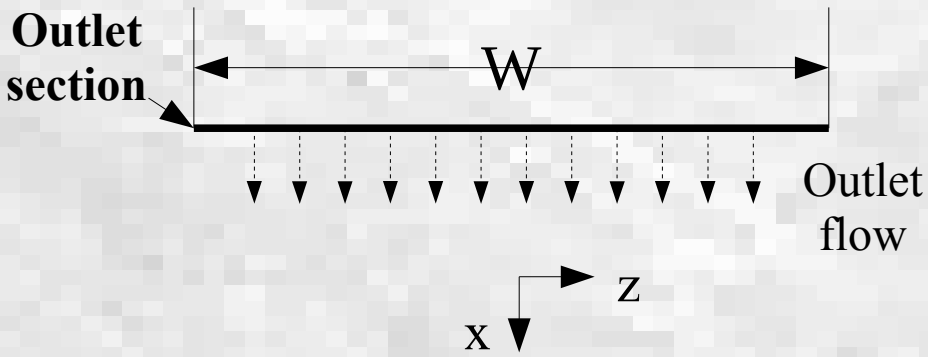
→ Complicated flow (bifurcating...)!

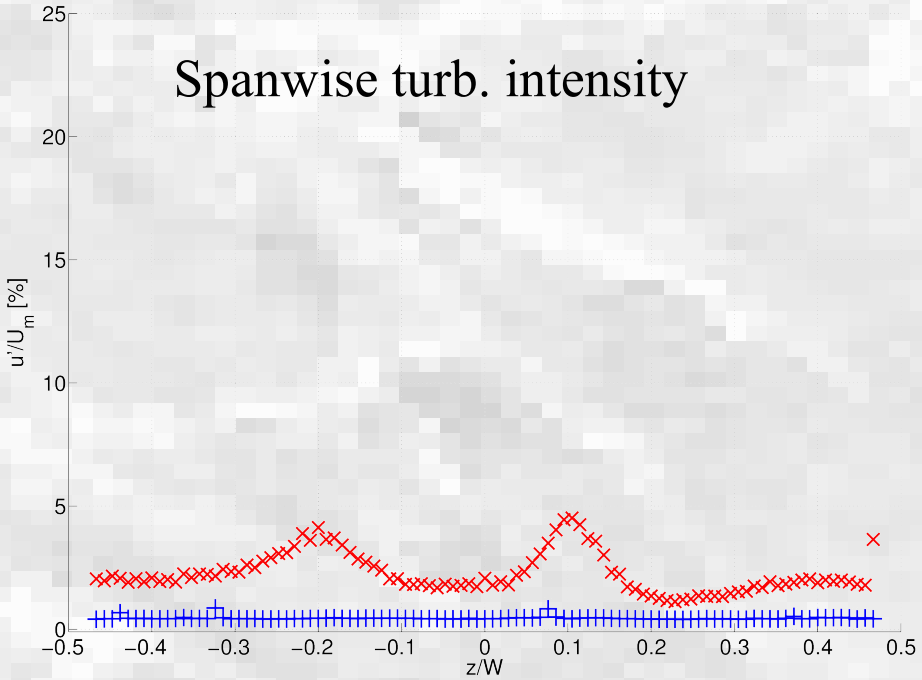
Focus on simplified duct + obstacle(s) geometries...

Outlet flow: spanwise profiles



Mean spanwise velocity



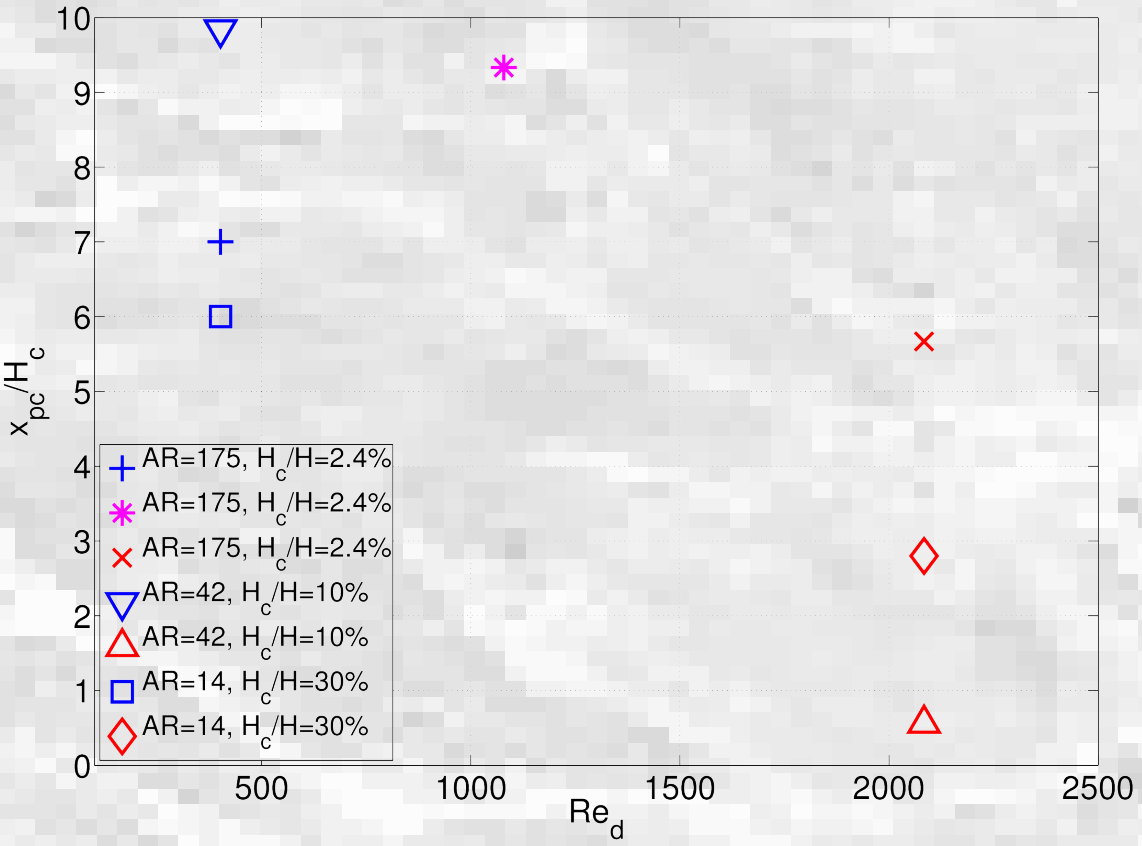


Spanwise turb. intensity

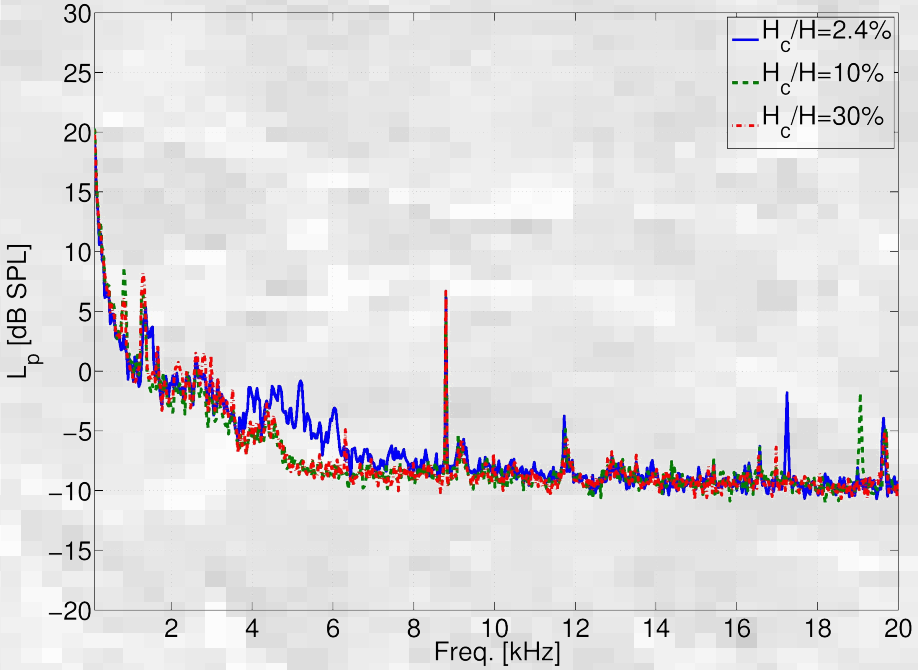
→ 2D flow hypothesis admitted!

Ducts with obstacle(s): *in-vitro* exp.

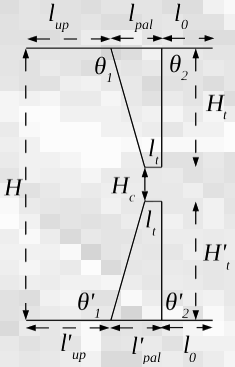
Potential core lengths



Dual obstacle replica: results

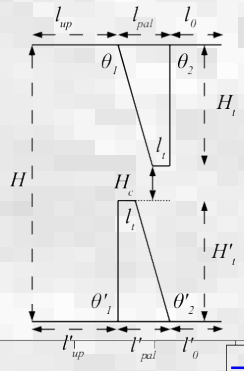


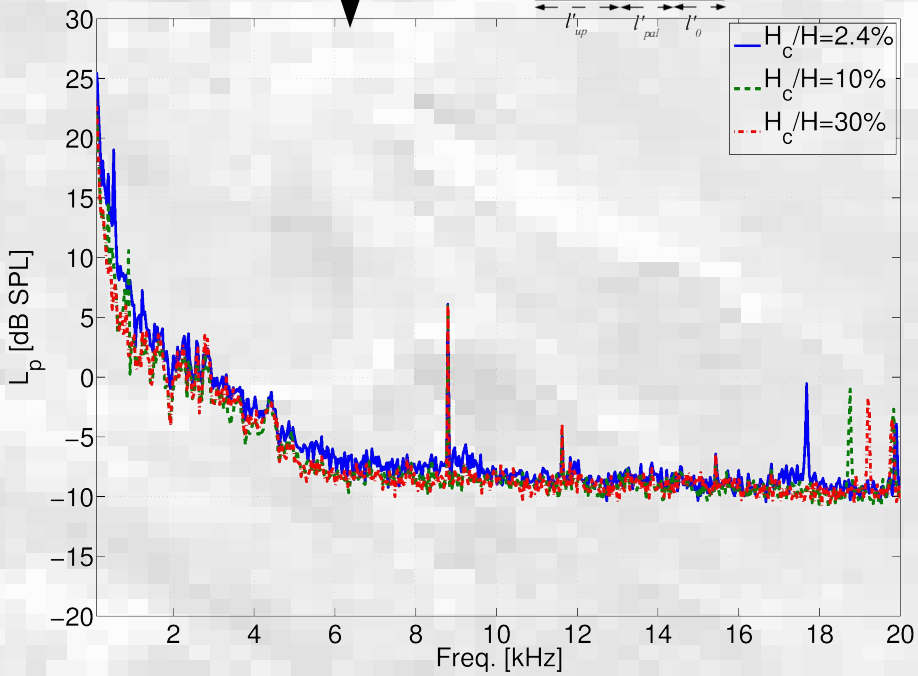
Symmetric configuration



Influence of obstacle configuration & aperture degree H_c/H; Re = 2084

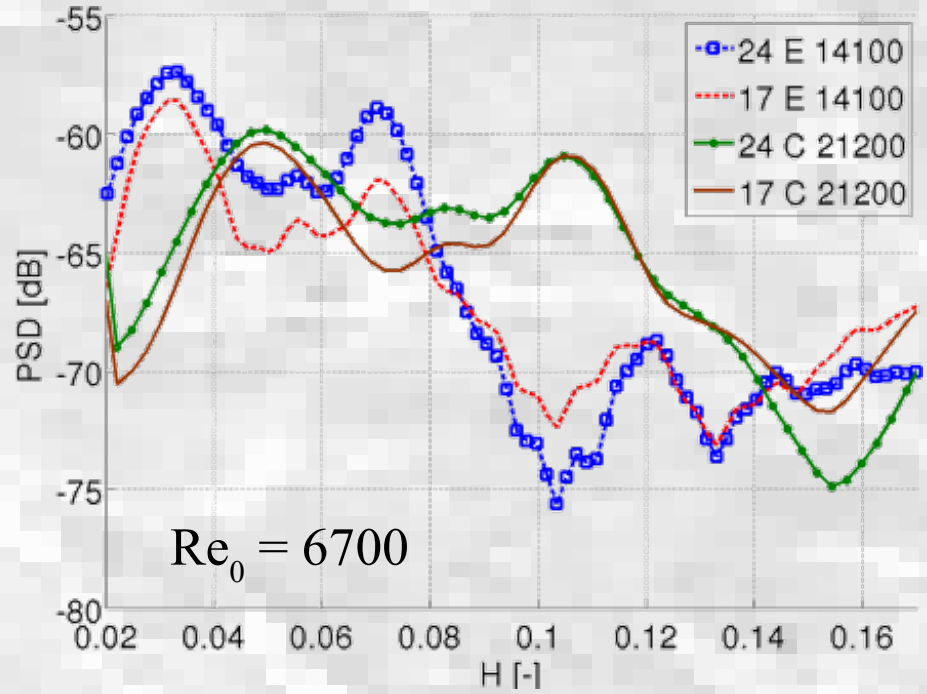
Asymmetric configuration

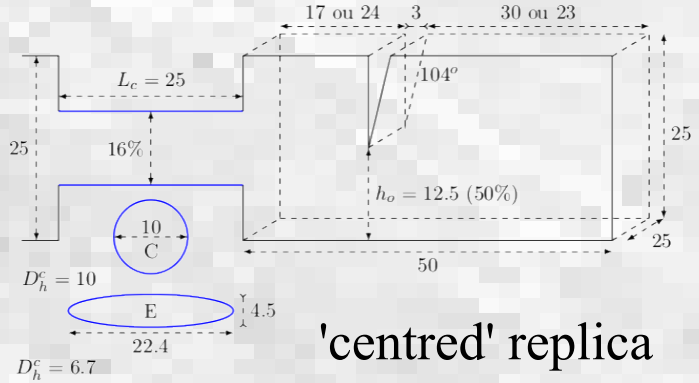




Ducts with obstacle(s): *in-vitro* exp.

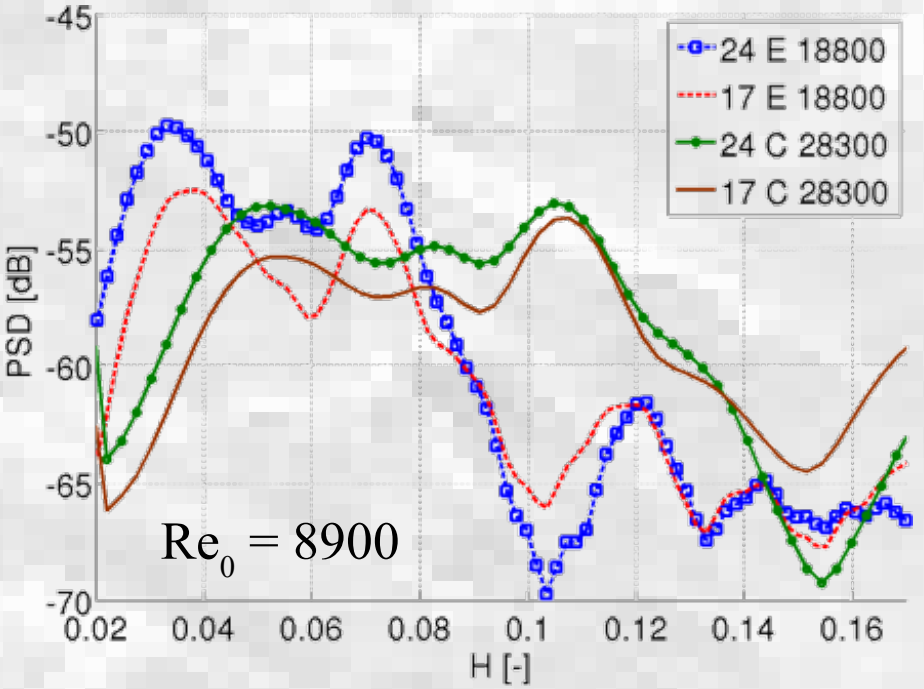
'Centred' replica: acoustic spectra





'centred' replica

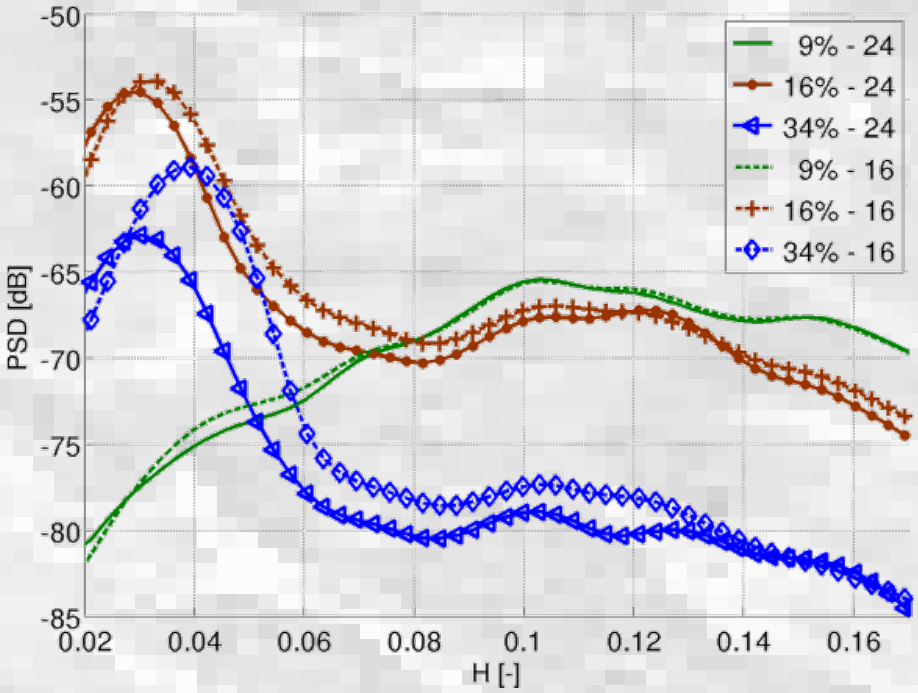
→ Measured spectra as function of **constriction-obstacle distance** (17 or 24mm); **cross-section shape** (E or C); **cross-section Reynolds number Re$_c$** (14100; 21200; 18800; 28300)

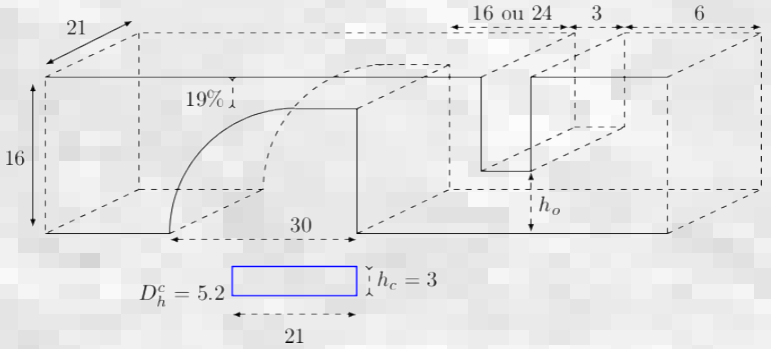


Helmholtz number: $H = \frac{f D_h^c}{c}$

Ducts with obstacle(s): *in-vitro* exp.

'Offset' replica: variation of parameters





'offset' replica

* Re_c = 11900
* aperture degrees 9; 16; 34%
* constriction-obstacle distance 16 or 24mm

Wind turbine:
Re=O(10^7), M<0.2

Boeing 787: Re=O(10^8),
M<0.9

TGV: Re=O(10^7),
M<0.4

- Various applications...
- Various Reynolds & Mach numbers...

$$Re = \frac{UH}{\nu}$$

$$M = \frac{U}{c}$$

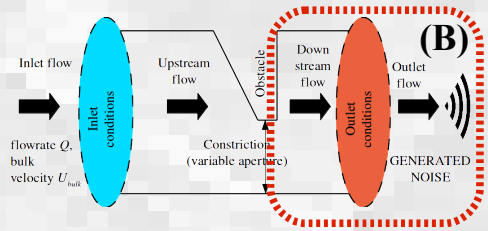
Volvo V60:
Re=O(10^6), M<0.2

Hurricane: Re=O(10^9),
M<0.3

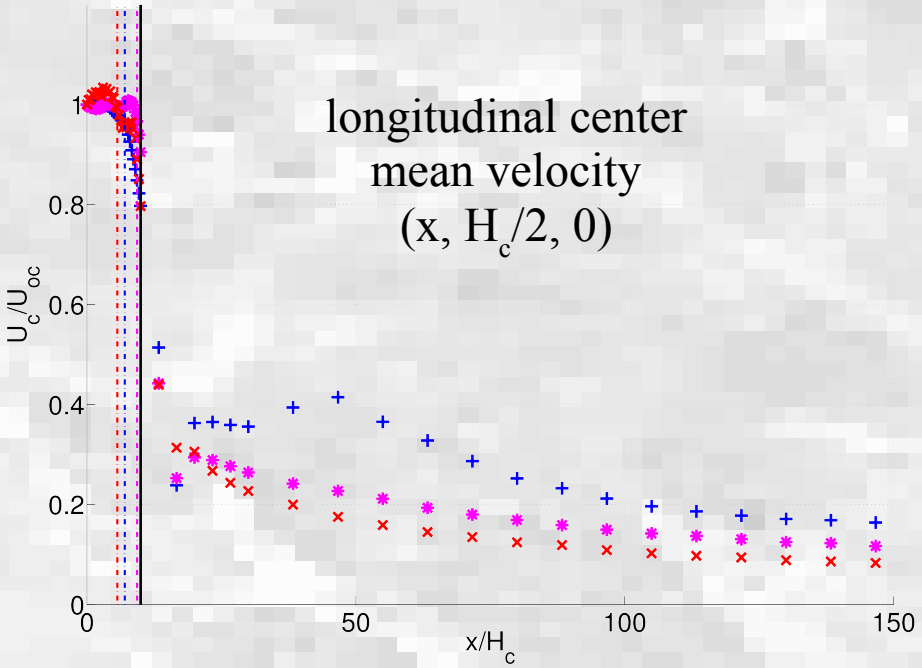
* U: characteristic velocity [m/s]
* H: characteristic length [m]
* c: speed of sound in air [≈343m/s at 293K]
* v: air kinematic viscosity [≈15*$10^{-6}$$m^2$/s at 293K]

→ What about moderate Reynolds & low Mach numbers flows? i.e. Re=O(10^4) & M<0.3

Jet longitudinal decay: $H_c/H = 2.4\%$



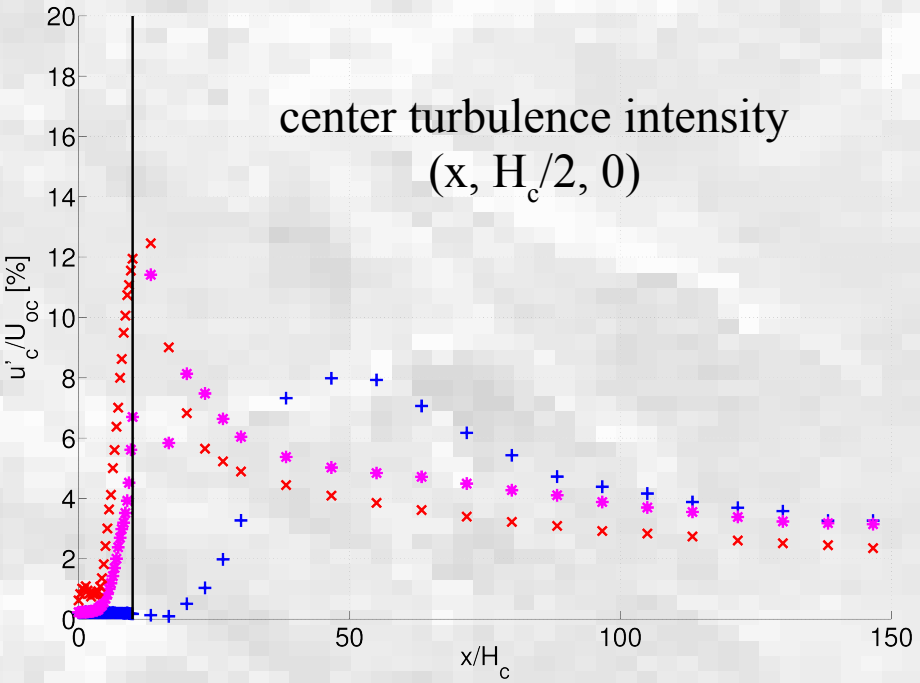
longitudinal center mean velocity $(x, H_c/2, 0)$

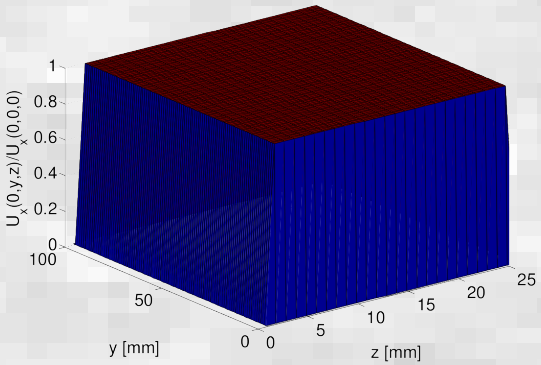


Reynolds numbers:
+: 402
×: 1079
*: 2084

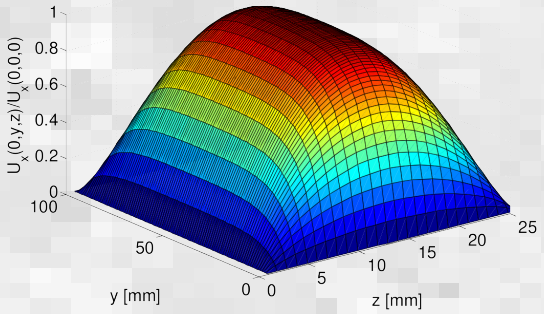
Effect of Re

center turbulence intensity $(x, H_c/2, 0)$

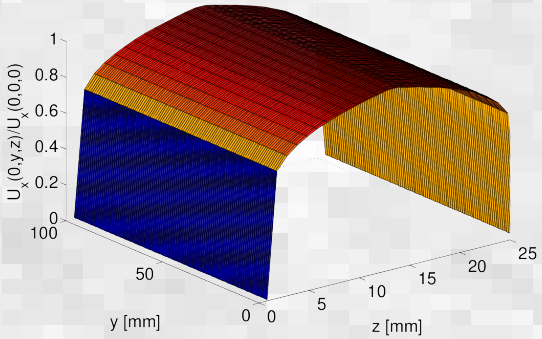




Uniform inlet vel. profile

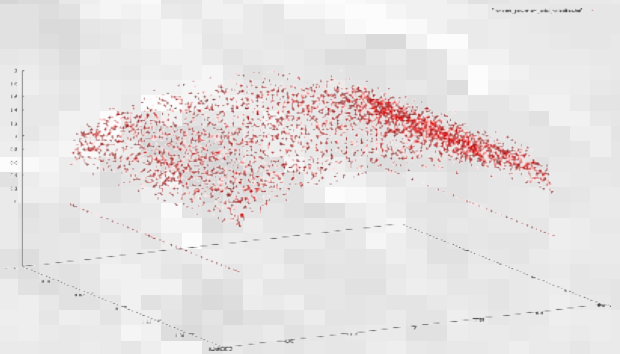


3D-parabolic inlet vel. profile

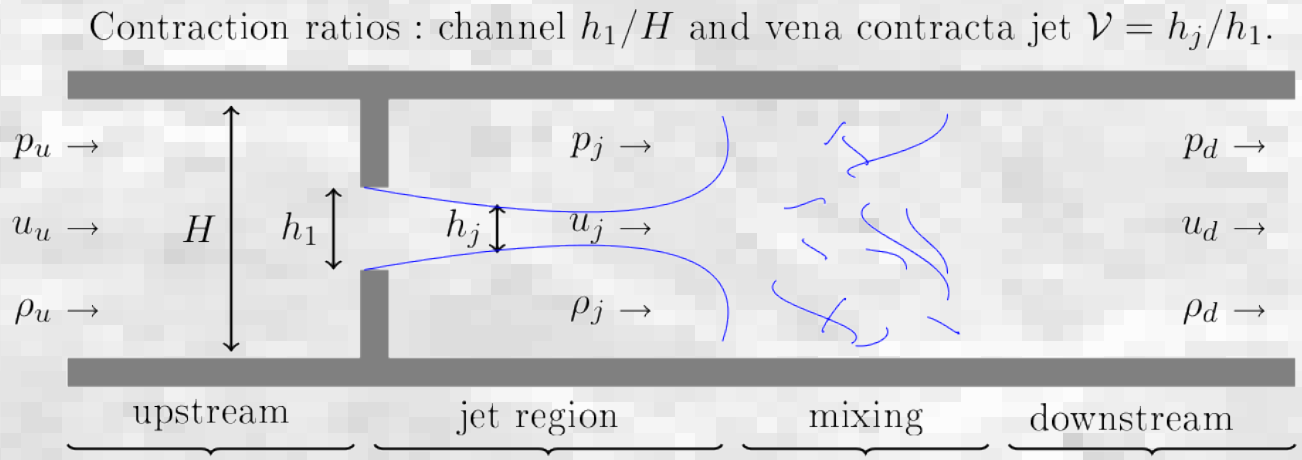


Static turbulent inlet vel. profile

Dynamic turbulent inlet vel. profile:
* **gaussian fluctuations**
* **injected inlet turbulence intensity levels: Tu_e = 0; 10; 30%**



(In)comp. quasi-steady 1D mean flow through a semi-infinite pipe



Scattering matrix

$$\begin{pmatrix} p_d^+ \\ p_u^- \end{pmatrix} = \begin{pmatrix} T^+ & R^- \\ R^+ & T^- \end{pmatrix} \begin{pmatrix} p_u^+ \\ p_d^- \end{pmatrix},$$

$$\begin{pmatrix} p_d^+ \\ p_u^- \end{pmatrix} = \frac{1}{2 + M_u\beta} \begin{pmatrix} 2 & M_u\beta \\ M_u\beta & 2 \end{pmatrix} \begin{pmatrix} p_u^+ \\ p_d^- \end{pmatrix}, \quad (1)$$

M_u: Mach number of pipe steady flow

$$\beta = \left(\frac{H}{h_j} - 1 \right)^2$$

Potential (irrotational) incomp. 2D flow model

$\vec{u} = (u, v)$

Continuity & irrotational flow:

$$u = \frac{\partial \psi}{\partial y}, \quad v = -\frac{\partial \psi}{\partial x},$$

$$u = \frac{\partial \phi}{\partial x}, \quad v = \frac{\partial \phi}{\partial y},$$

Cauchy-Riemann conditions:

$$\frac{\partial \phi}{\partial x} = \frac{\partial \psi}{\partial y}, \quad \frac{\partial \phi}{\partial y} = -\frac{\partial \psi}{\partial x}$$

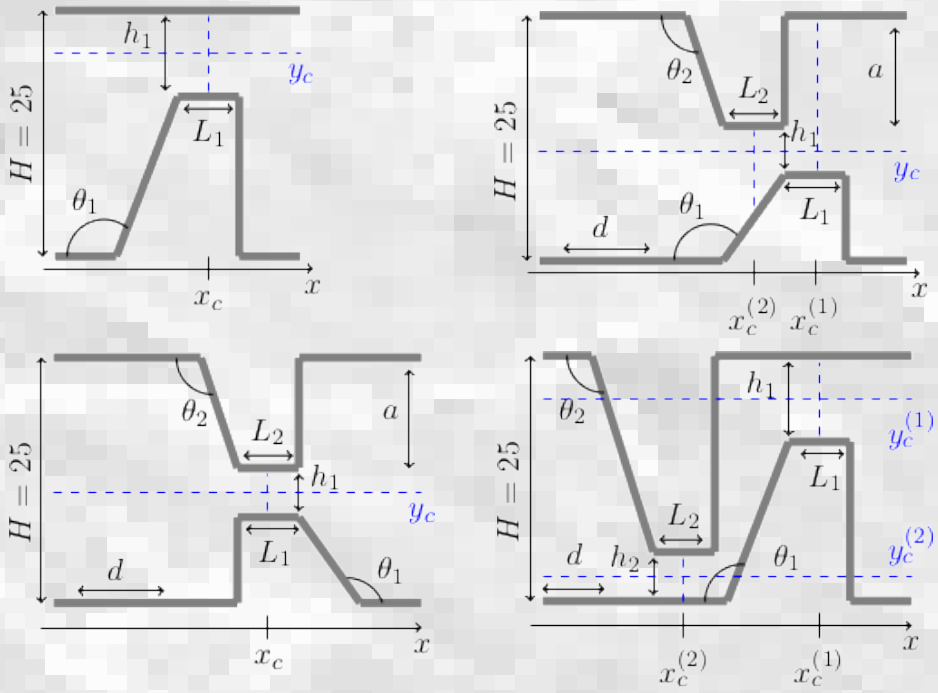
Laplace's equation:

$$\nabla^2 \psi = \frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial y^2} = 0$$

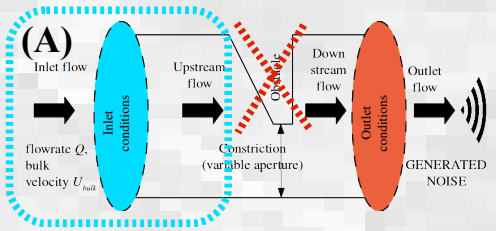
Ψ: stream function

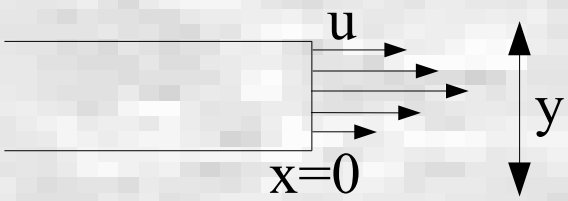
Φ: velocity potential

Geometries:

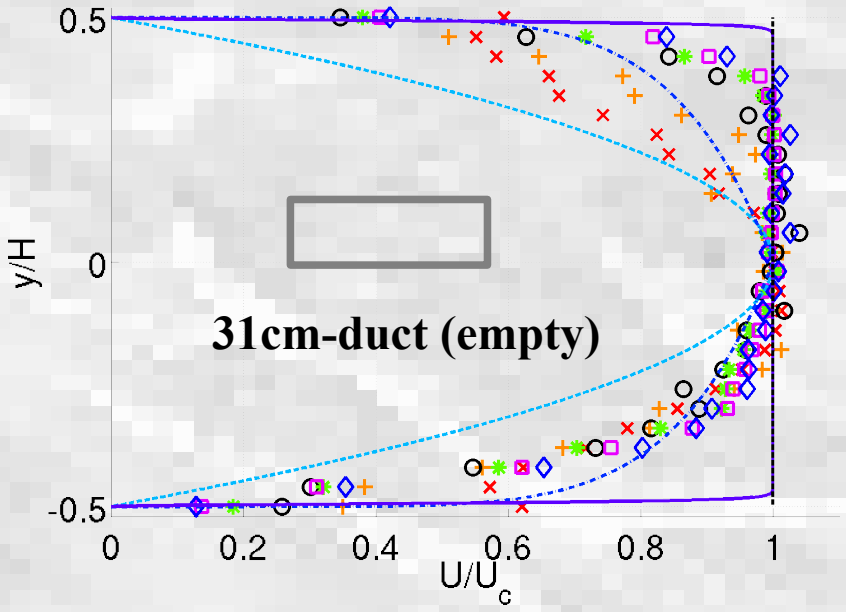


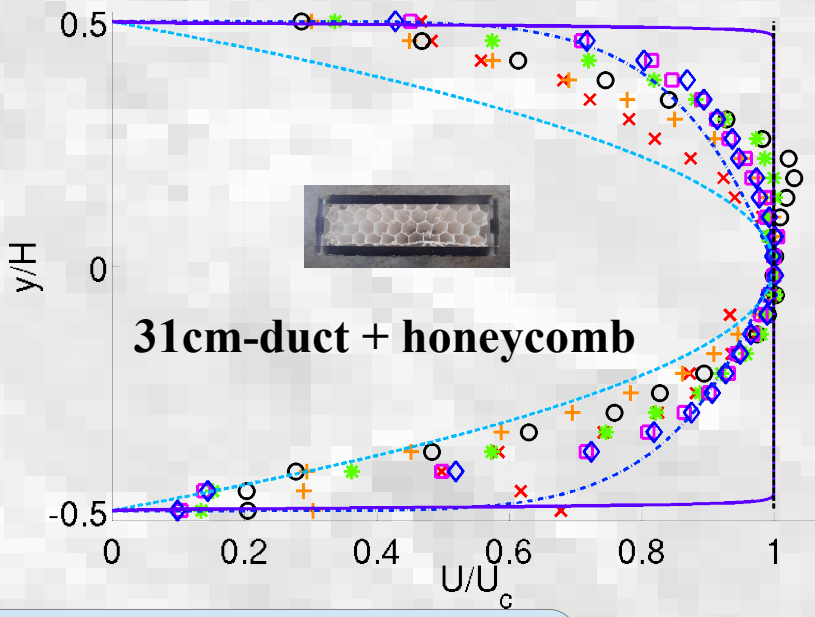
Transverse mean velocity profiles at (0, y, 0)





Effect of IC & Re

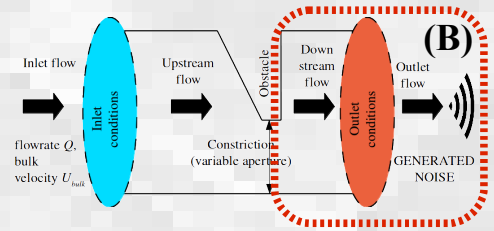




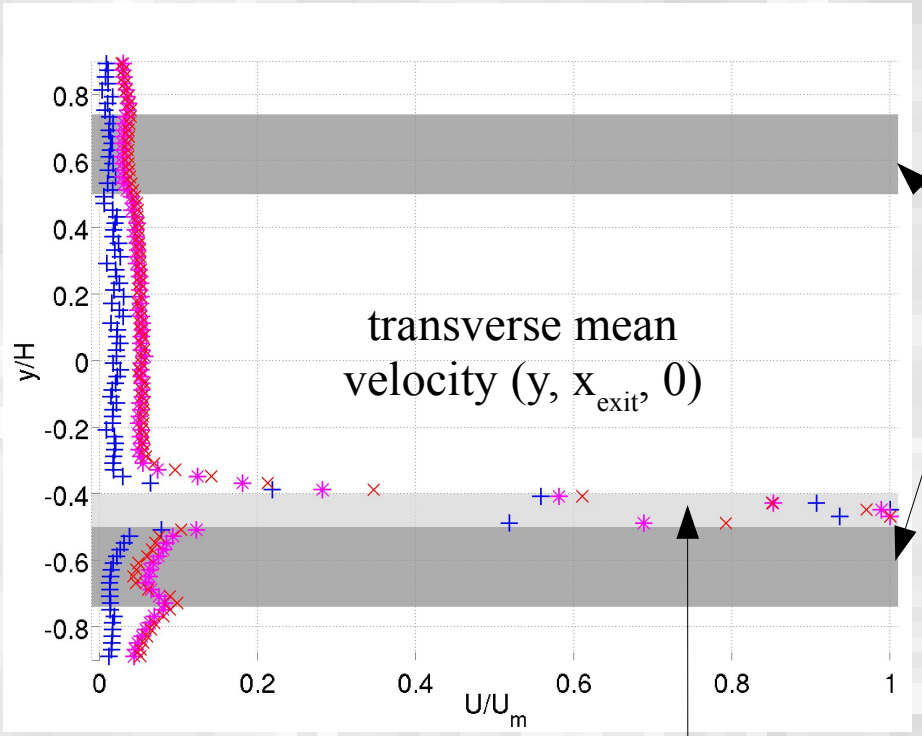
Reynolds numbers:

120 (×); 310 (+); 501 (o); 789 (*); 1167 (□); 1350 (◊)

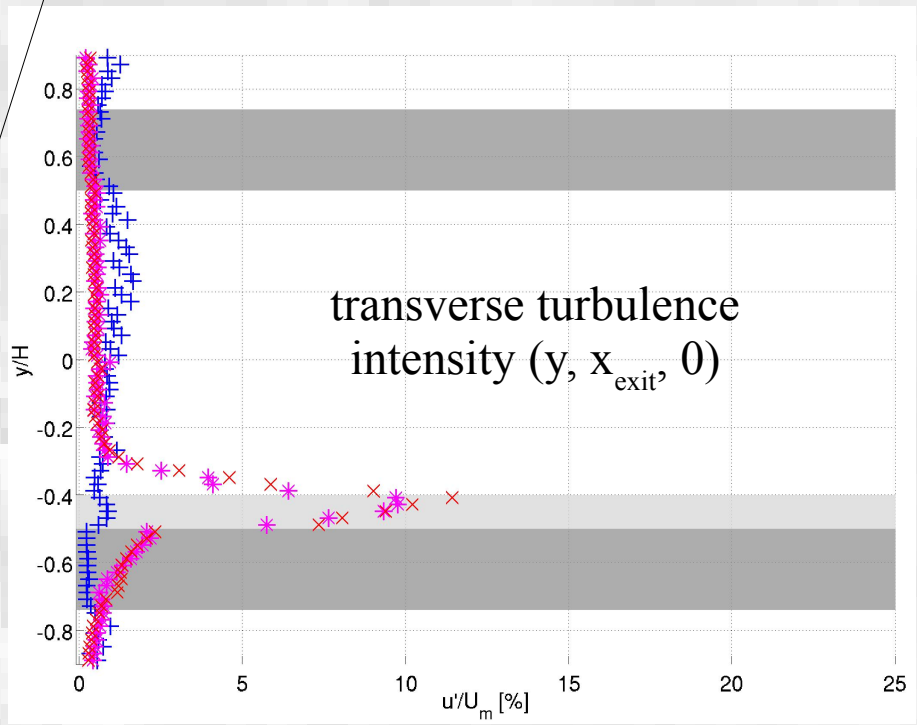
Jet transverse profiles: $H_c/H = 10\%$ + honeycomb



Effect of Re



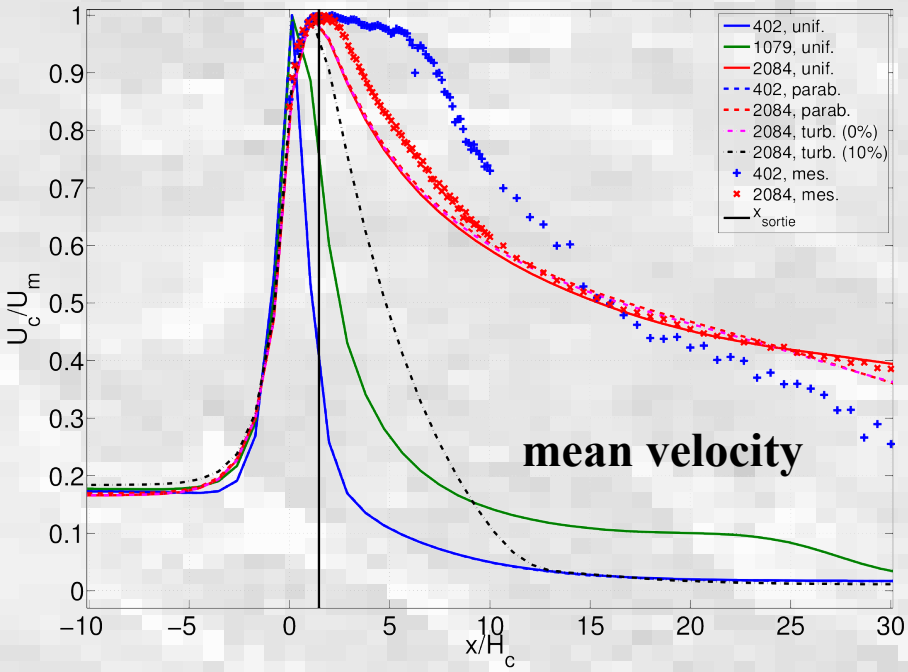
duct walls transverse regions



constriction transverse region (**below obstacle**)

Reynolds numbers:
+: 402
×: 1079
*: 2084

Comparison of longitudinal mean center velocity profiles
for several inlet conditions & Reynolds numbers (aperture degree $H_c/H = 30\%$)



× & +: measured data