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Estimation stochastique d'un écoulement compressible décollé

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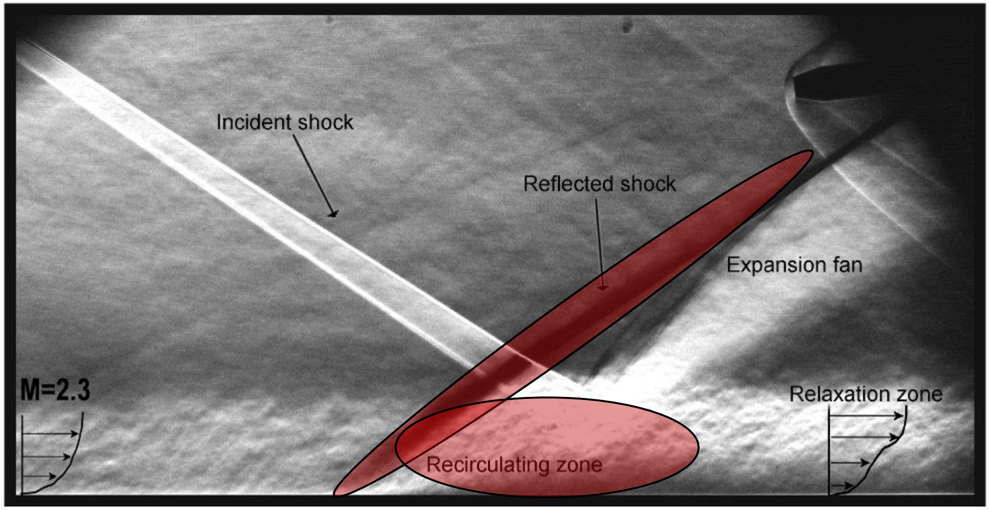
Motivations: unsteadiness in shock-induced separations

***M*=2**
***U*=550m.s^{-1}**
δ_0=11mm



Low frequencies (O(100Hz)) : mass entrainment process in the mixing layer?

Objectives

- Analysis of the dynamic of a shock wave / boundary layer interaction
- Understand the origin of the **low frequency unsteadiness** and the link with medium frequency phenomon
- ***Application of Linear Stochastic Estimation* in a complex compressible Flow**
  - Simultaneous Wall pressure - PIV measurements in a SWBLI

Experimental setup

IUSTI supersonic wind tunnel M=2

P_0=0,1–1 atm, T_0=290 K,
Continuous facility (5h)

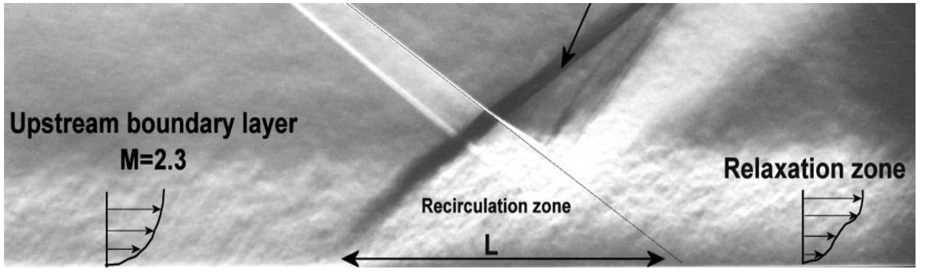
Low turbulence level:

➔ *0.1% u'* *1% p'*

Test section: 170 x 105 mm²

Reflected shock interaction

M=2, R_θ=5000, θ=8.5°



<u>Simultaneous and continous acquisition :</u>

- Wall Pressure signal(7 kulites) ($F_{sampling}$=100kHz)
- Trigger PIV
- PIV on the axis of the Wind Tunnel, ***not resolved in time***
  Dantec system
  ✓ 10,000 PIV vector fields

LINEAR ESTIMATION OF THE VELOCITY FIELD : POD & LSE

1/ **Snapshot POD** :

$$\mathbf{u}(\mathbf{x},t) = \sum_{n=1}^{N_{POD}} a_n(t) \cdot \Phi_n(\mathbf{x})$$

2/ **Linear stochastic estimation** of the *selected* **temporal modes, using wall pressure information *P***

$$\tilde{a}_n(t) = \sum_{k=1}^{N_{KUL}} A_{k,n} \cdot P_k(t + \Delta t_{k,n})$$

$A_{k,n}$: LSE coefficients
$P_k(t)$: pressure
K= 1..7 (kulites)

3/ **Field reconstruction** using The **POD decomposition** and the **estimated temporal modes** :

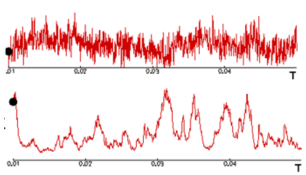
$$\tilde{\mathbf{u}}(\mathbf{x},t) = \sum_{n=1}^{N_{LSE}} \tilde{a}_n(t) \cdot \Phi_n(\mathbf{x})$$

POD + LSE

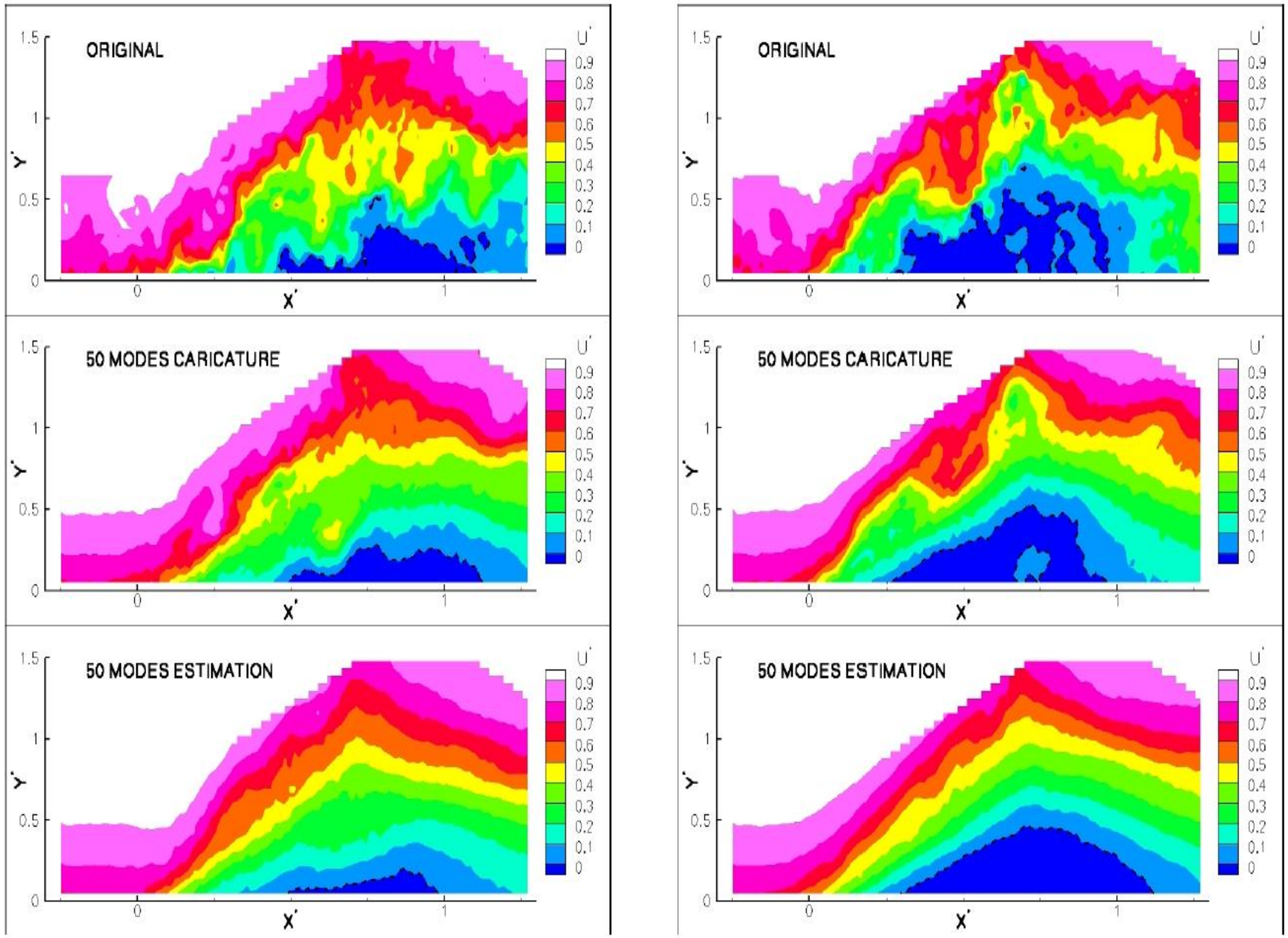
Database :
10 000 fields

• ***POD***

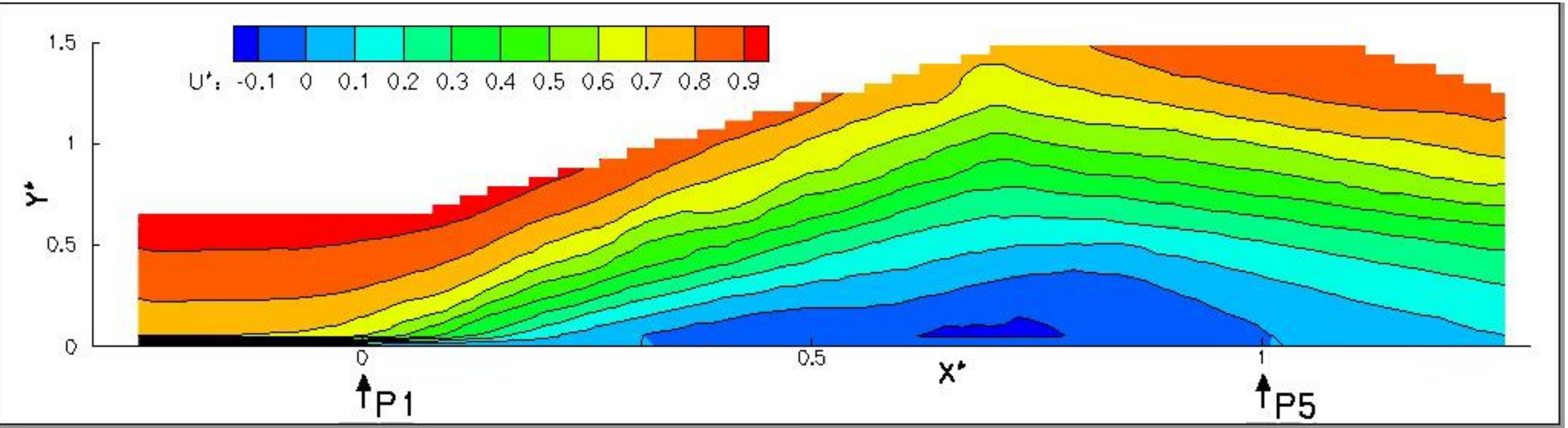
• *Flow Caricature*
Using 50 modes
≈ 40% of Total energy

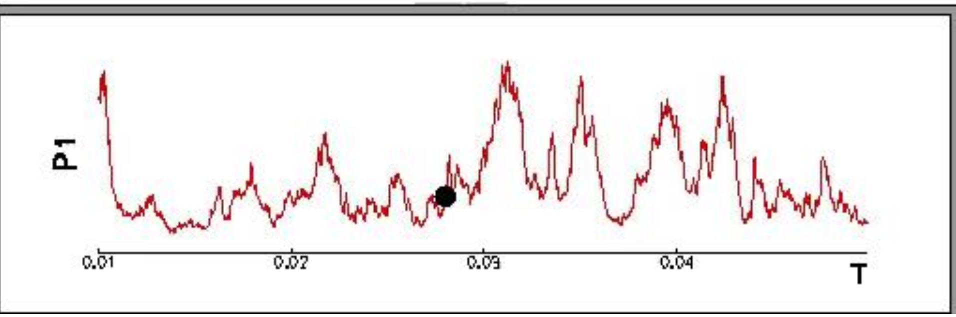


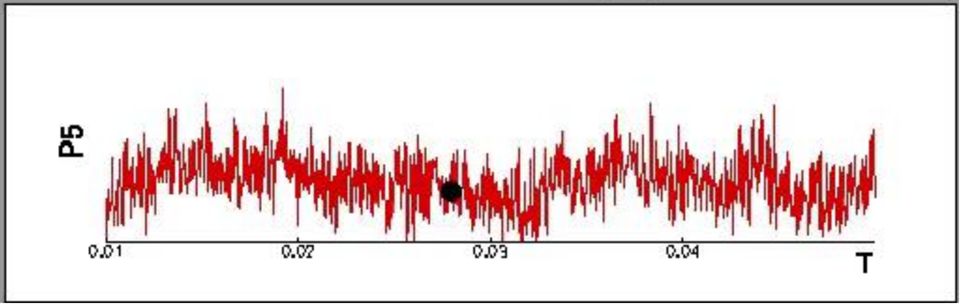
LSE *of the POD*
temporal coefficient



ANALYSIS OF TIME-RESOLVED ESTIMATED VELOCITY FIELDS







ANALYSIS OF TIME-RESOLVED ESTIMATED VELOCITY FIELDS

- Results coherent with previous studies
- Low frequency dynamic of the recirculating bubble

BUT

- LF is not modal in this type of flow
- No characteristic POD mode

➔ frequential information of the POD modes?

Improvments: POD + dual-PIV

dual-PIV / POD / unsteady wall pressure

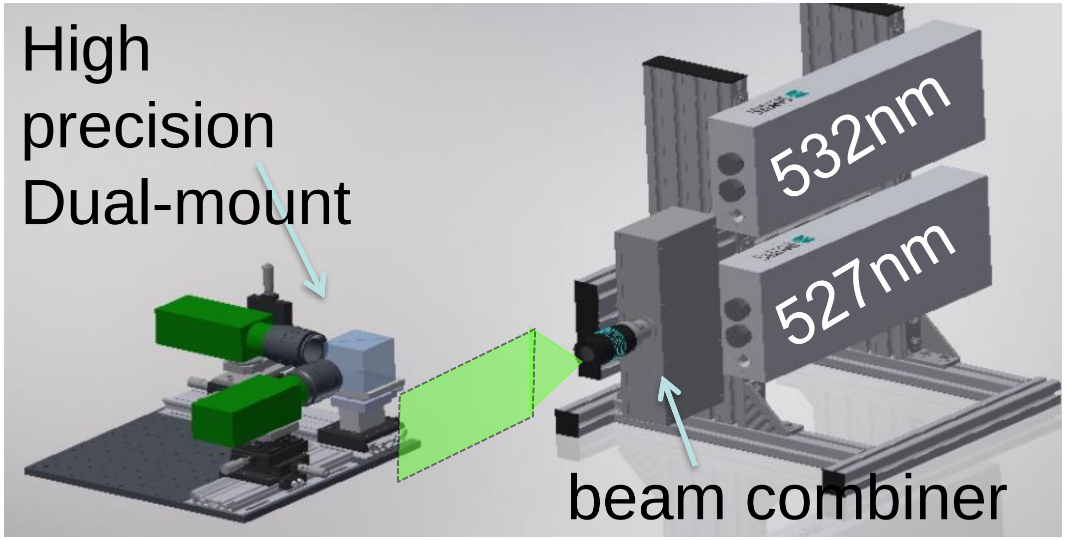
- from dual-PIV data: to identify the POD modes correlating low and medium frequencies in order to apply a space-time filter for the unsteady velocity fields.

- to analyse pressure / velocity correlations in frequential domain

Improvements: Dual PIV measurements

Dantec Dual-Piv system (2Hz)

2500 snapshots   *Schreyer et al., Expts. in Fluids, 2015*



2 cameras measuring the same field of view, with an adjustable time delay τ

τ=[0,5,10,20,…,3000] μs

+ simultaneous Pressure measurements

POD + dual-PIV

DUAL-PIV

$$u_1(x,t) = \sum_{n=1}^{N_{POD}} \left(a_{n,1}(t).\Phi_{n,1}(x) \right) \qquad u_2(x,t+\tau) = \sum_{n=1}^{N_{POD}} \left(a_{n,2}(t+\tau).\Phi_{n,2}(x) \right)$$

τ=[0,5,10,20,…,3000] μs

2 different spatial modes $\boldsymbol{\Phi_{n,1}(x)}$ and $\boldsymbol{\Phi_{n,2}(x)}$ describing the exact same flow

Projection of the data on a universal spatial mode distribution $\Phi_n(x)$

Time properties of the coefficients $a_n(t)$

$$R_{a_n}(\tau) = \frac{< a_n(t) a_n(t+\tau) >}{\sigma_{a_n(t)} \sigma_{a_n(t+\tau)}}$$

Time properties of the POD coefficients

Dual PIV :

$$R_{a_n}(\tau) = \frac{< a_n(t)a_n(t+\tau) >}{\sigma_{a_n(t)}\sigma_{a_n(t+\tau)}}$$

τ: *0, 5, 10... to 3000μs*

Time integral scale

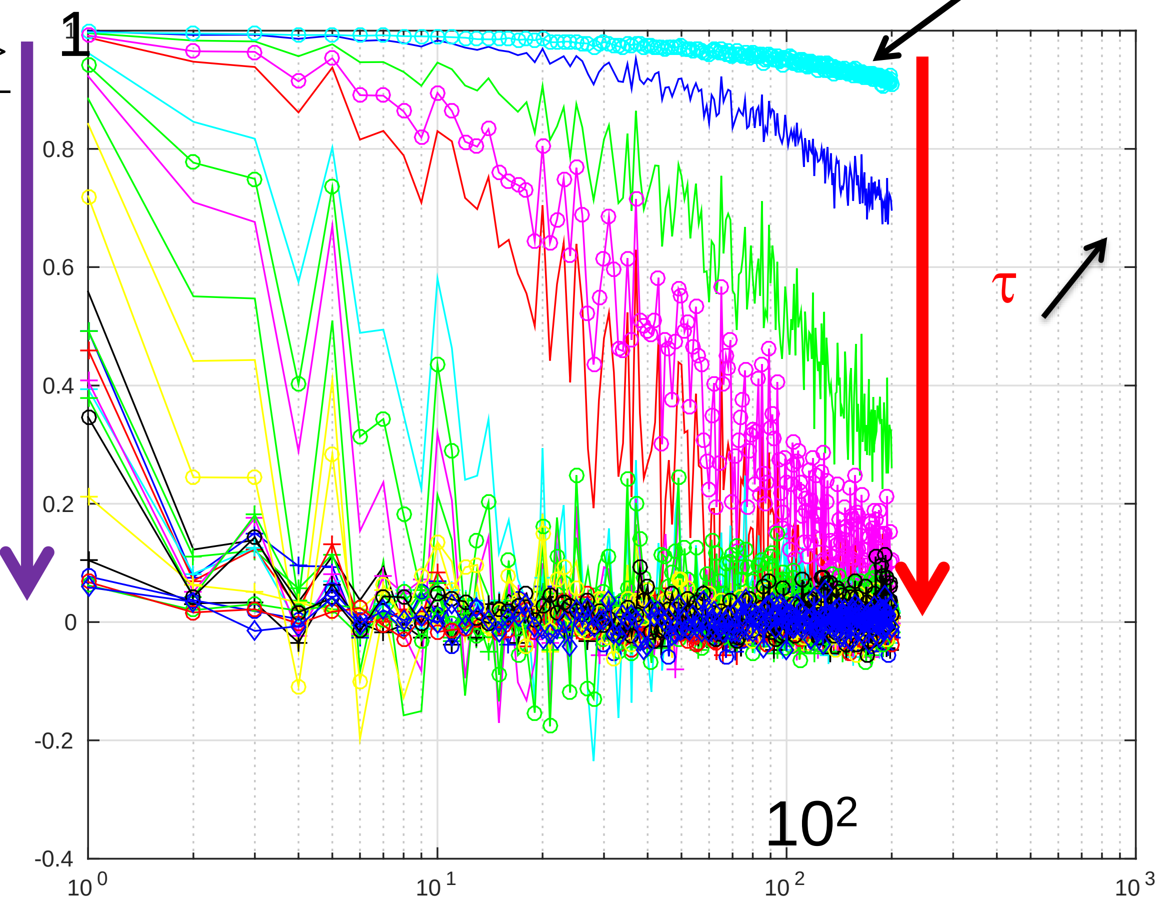
ζ_{an}

$$\zeta_{a_n} = \int_0^\infty R_{a_n}(\tau)d\tau$$

τ=0

process noise

(Dual PIV+ projection on a unique non optimal base)



Index of the spatial mode Φ_n

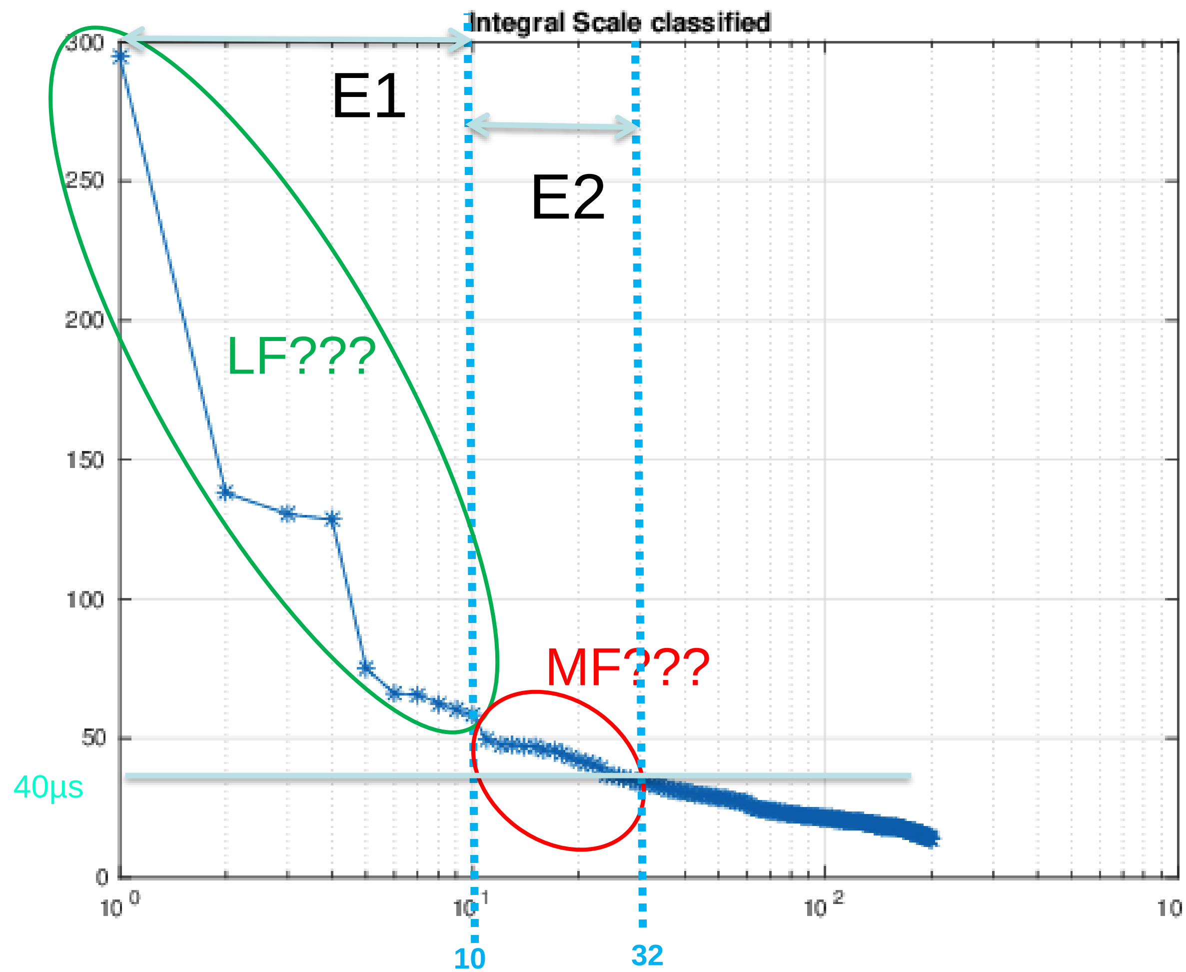
Time properties of the POD coefficients

Identification des modes BF et MF

• Only 32 modes have a time integral scale > 40µs

•two subsets of modes:
•E1= [1:10]: LF?
•E2= [10:32]: MF?

•Compute band-passed pressure and POD-filtered velocity fields for validation



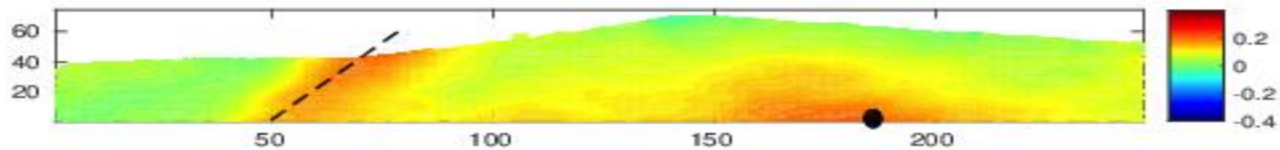
Low Frequency pressure – velocity correlations

LF unsteady pressure

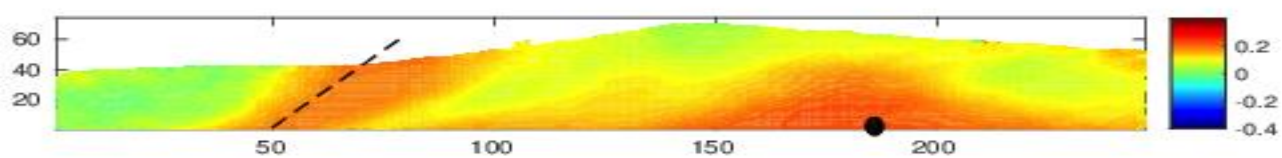
100modes

subset E1

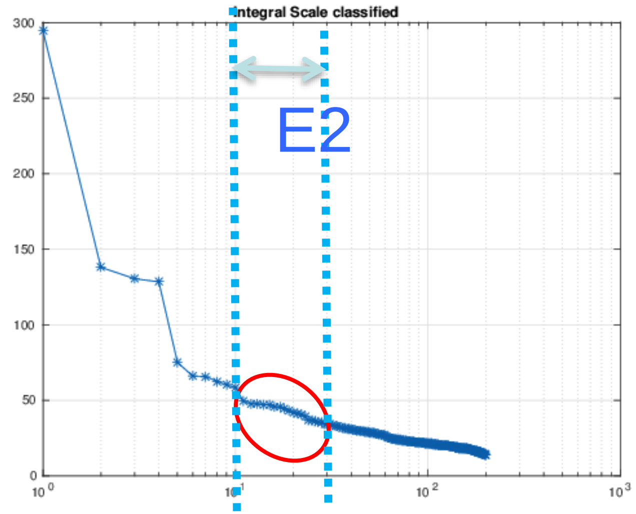
LF ; $d\tau$ = 0ms



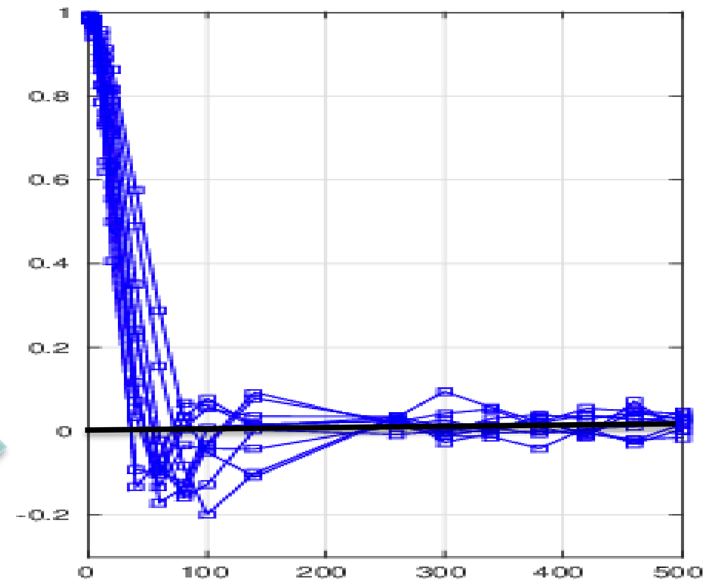
E1, LF ; $d\tau$ = 0ms

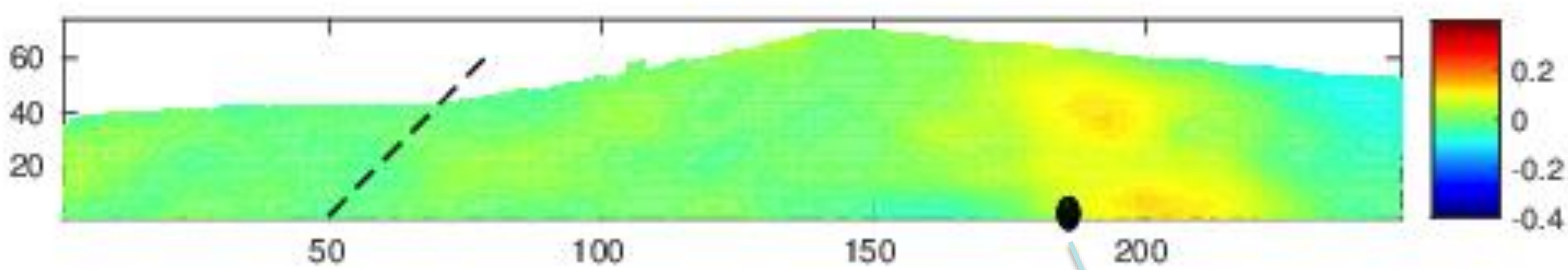


Medium Frequency pressure – velocity correlations



from E2: subset E’2 with oscilating $Ra_n(\tau)$

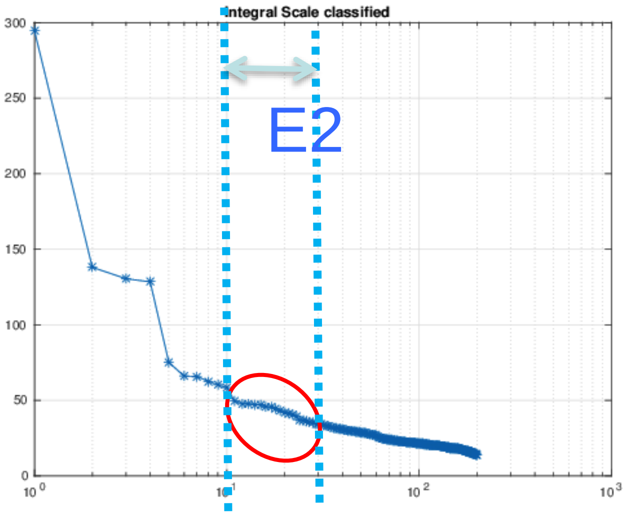




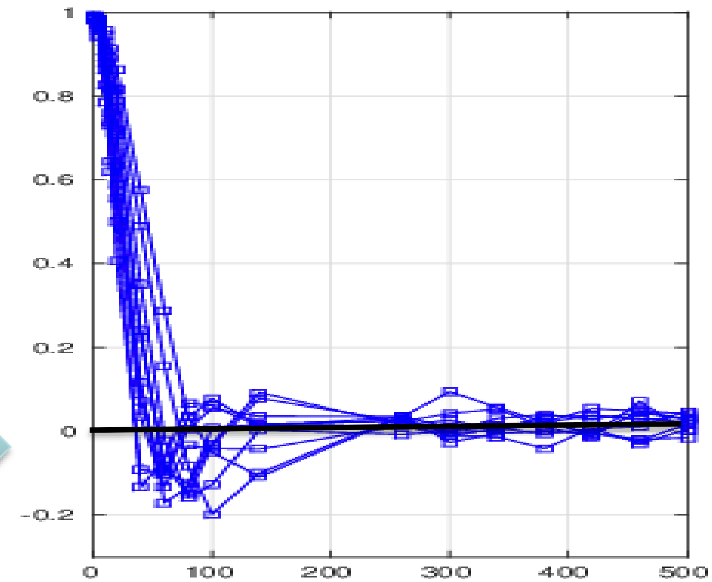
100 modes MF, dτ=0ms

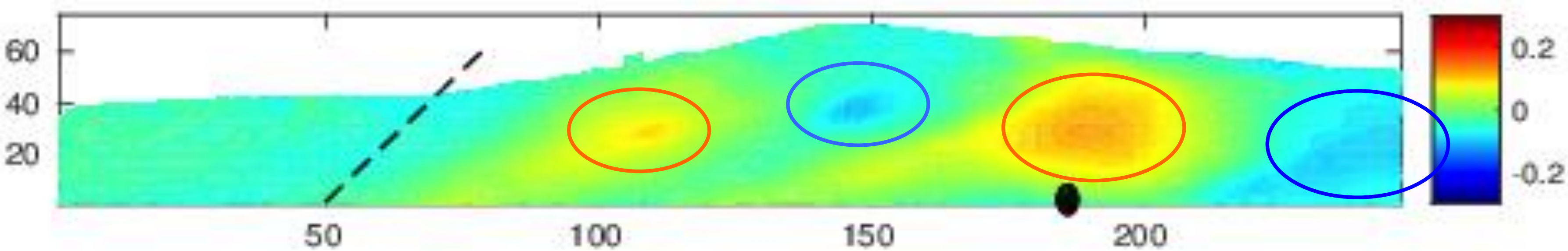
reference sensor

Medium Frequency pressure – velocity correlations



from E2: subset E’2 with oscilatin g $Ra_n(\tau)$



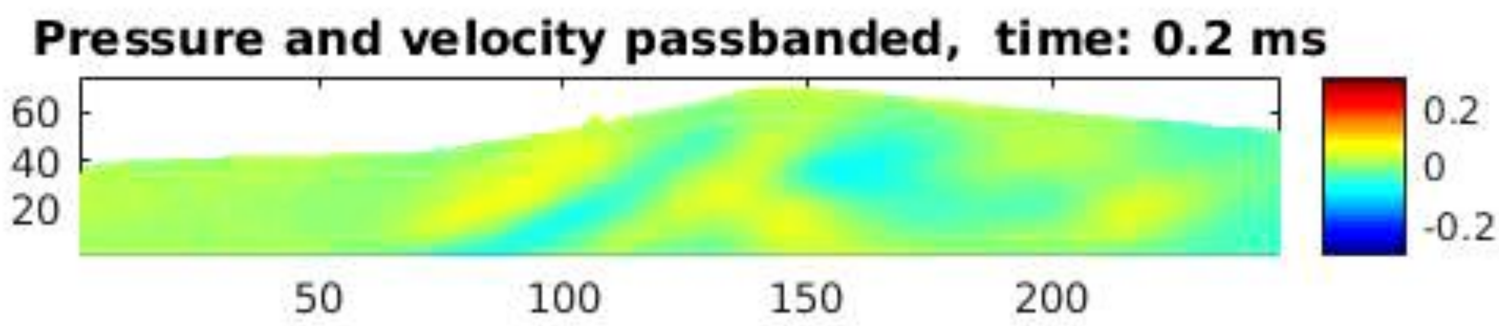


E’2: périodic structures

convection?

Medium Frequency pressure – velocity correlations

E’2, velocity- MF pressure fluctuations, 0.2ms > dτ >-0.1ms



Convective structures with $V_{MF} \approx 160 m.s^{-1}$
As derived from 2points unsteady wall pressure

Conclusions and perspectives

- First attempt to develop space-time filters from dual-PIV data (selected subsets of modes)
- improved velocity-pressure correlations
- Low frequency unsteadiness described with 9 modes
- Evidence of convective structure on a reduced basis

- Spectral properties of the time coefficients
- “band passed” velocity intercorrelations
- Linear Stochastic Estimation with subsets modes: LF and MF dynamics

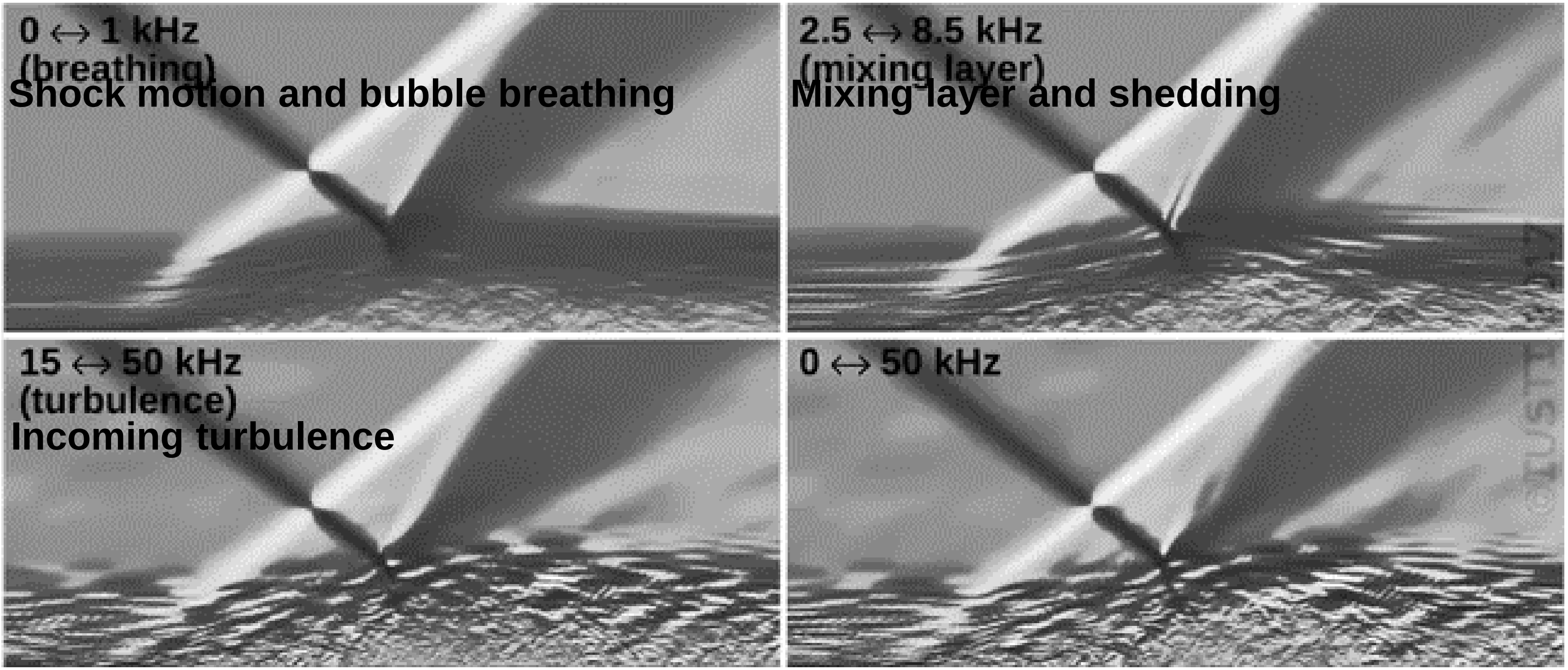
thank you for your attention

Objectives

- Analysis of the dynamic of a shock wave / boundary layer interaction
- Understand the origin of the **low frequency unsteadiness** and the link with medium frequency phenomon
- ***Application of Linear Stochastic Estimation in a complex compressible Flow***
  - Simultaneous Wall pressure - PIV measurements in a SWBLI

Motivations: unsteadiness in shock-induced separations

Band pass filtered schlieren
(Large Eddy Simulations)



Low frequencies (O(100Hz)) : several mecanisms proposed

- upstream perturbations
- noise amplifier
- mass entrainment process in the mixing layer
- low pass filter

Necessity to obtain highly resolved in space and time data: LES validation/physical mecanisms

POD : define an optimal basis, in term of energy, of a sptio-temporal database.
Considering u(x,t) the velocity field obtained by PIV (for example), POD consists in determining a basis of function ϕ, such as:

$$\mathbf{u}(\mathbf{x},t) = \sum_{n=1}^{N_{POD}} a_n(t) \cdot \Phi_n(\mathbf{x})$$

an(t) are the temporal modes of the POD.

linear Stochastic Estimation

Principe : to make an estimation of a flow, based on a conditionnal information in one or several points, in a field where the 2 points statistics is known

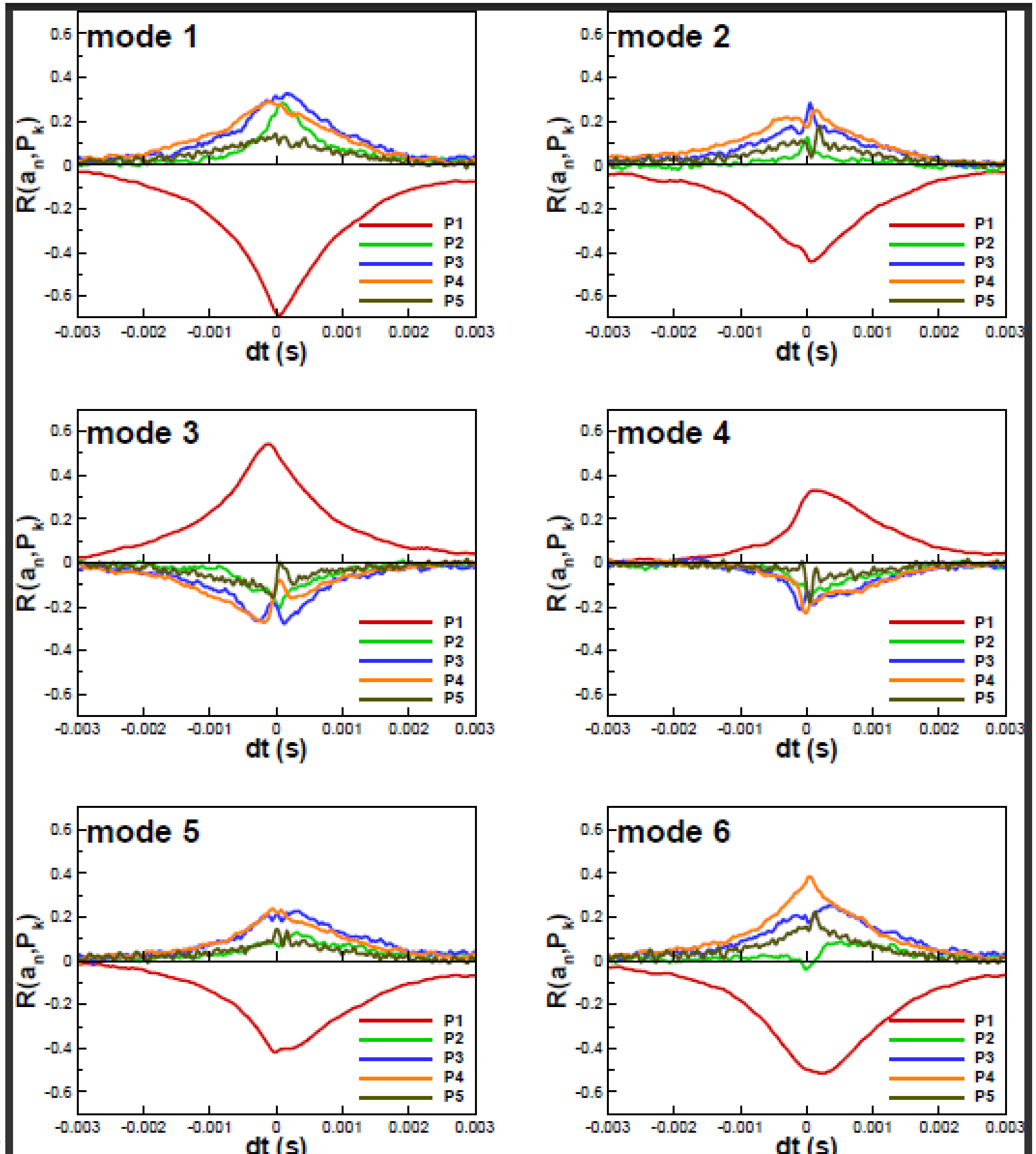
Signals of differents nature (Pressure, velocity, etc..)

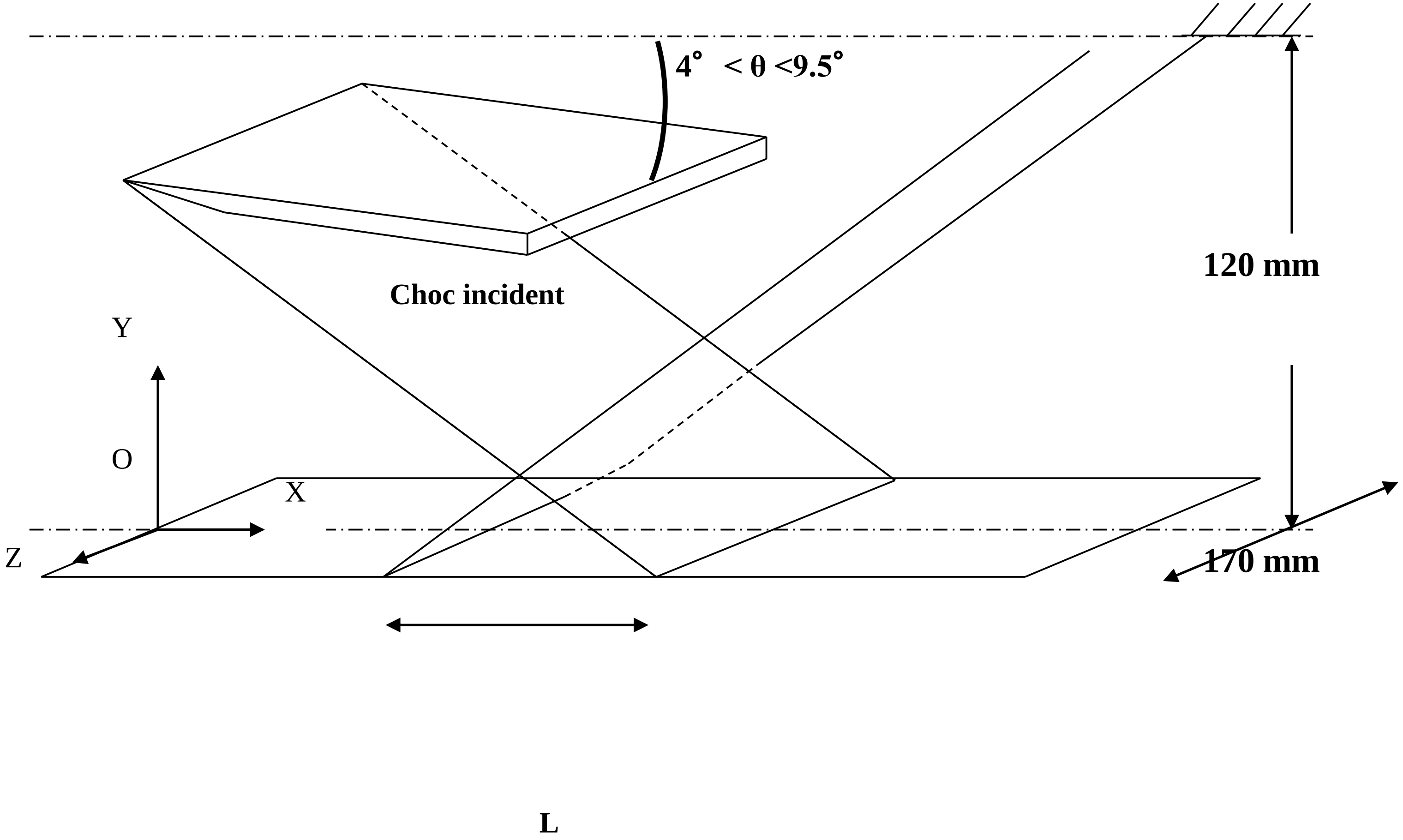
$$\tilde{a}_n(t) = \sum_{k=1}^{N_{KUL}} A_{k,n} \cdot P_k(t + \Delta t_{k,n})$$

Le calcul des coefficients A_k^n est effectué en cherchant à minimiser l'erreur quadratique moyenne entre les a_n et les $\tilde{a_n}$. Le système à résoudre aux moindres carrés est donc :

$$\langle a_n(t) \cdot P_{k'}(t + \Delta t_{k',n}) \rangle = \sum_{k=1}^{N_{KUL}} A_k^n \cdot \langle P_k(t + \Delta t_{k,n}) \cdot P_{k'}(t + \Delta t_{k',n}) \rangle \qquad (1.12)$$

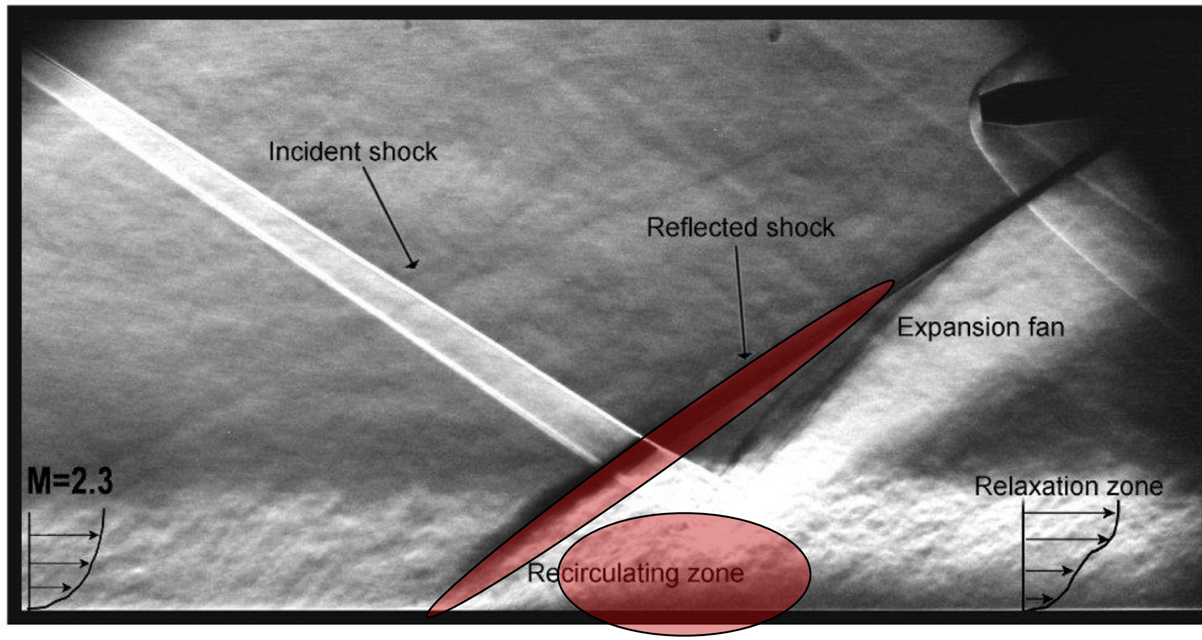
LSE using time delay correlation




4° < θ <9.5°
120 mm
Choc incident
Y
O
X
Z
170 mm
L

Motivations: unsteadiness in shock-induced separations

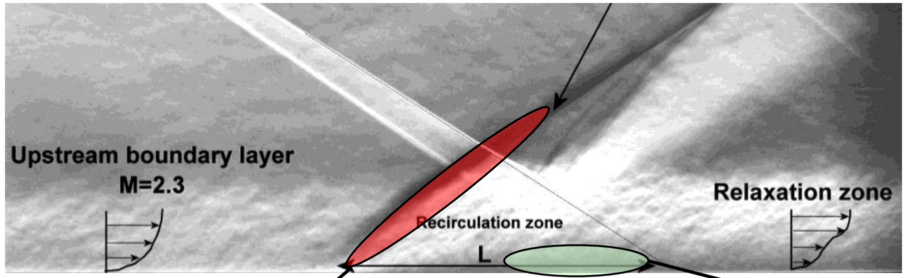
M=2
U=550m.s^{-1}
δ_0=11mm



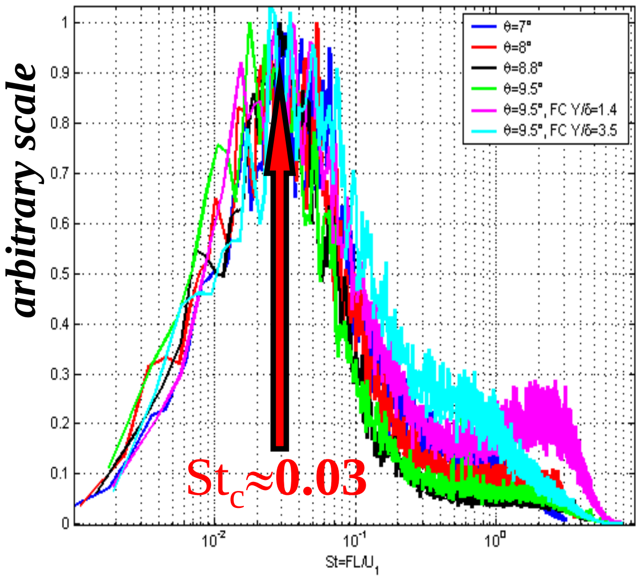
Low frequency Unsteadiness : (200Hz – 400Hz)

➔ Séparation shock Motion

➔ Pulsation of the recirculating buble



0.6<X*<0.8

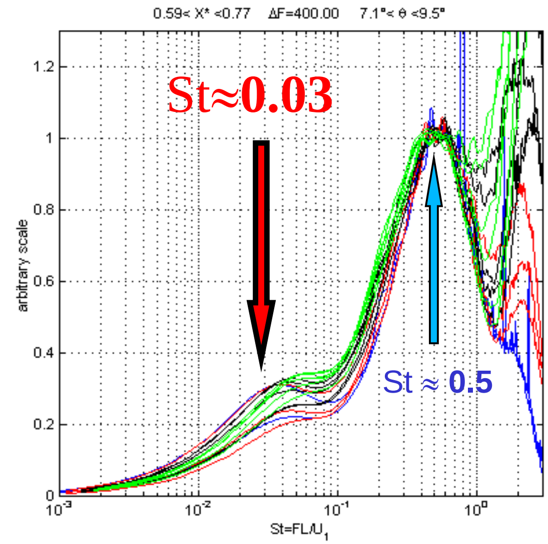


Power Spectral density

$7° < \theta < 9.5°$

$0 < y/\delta_0 < 3.5$

$$\boxed{S_t = f_c L / U_1}$$



Dupont, P., Haddad, C., and Debiève, J. F. (2006).
Space and time organization in a shock induced boundary layer. JFM

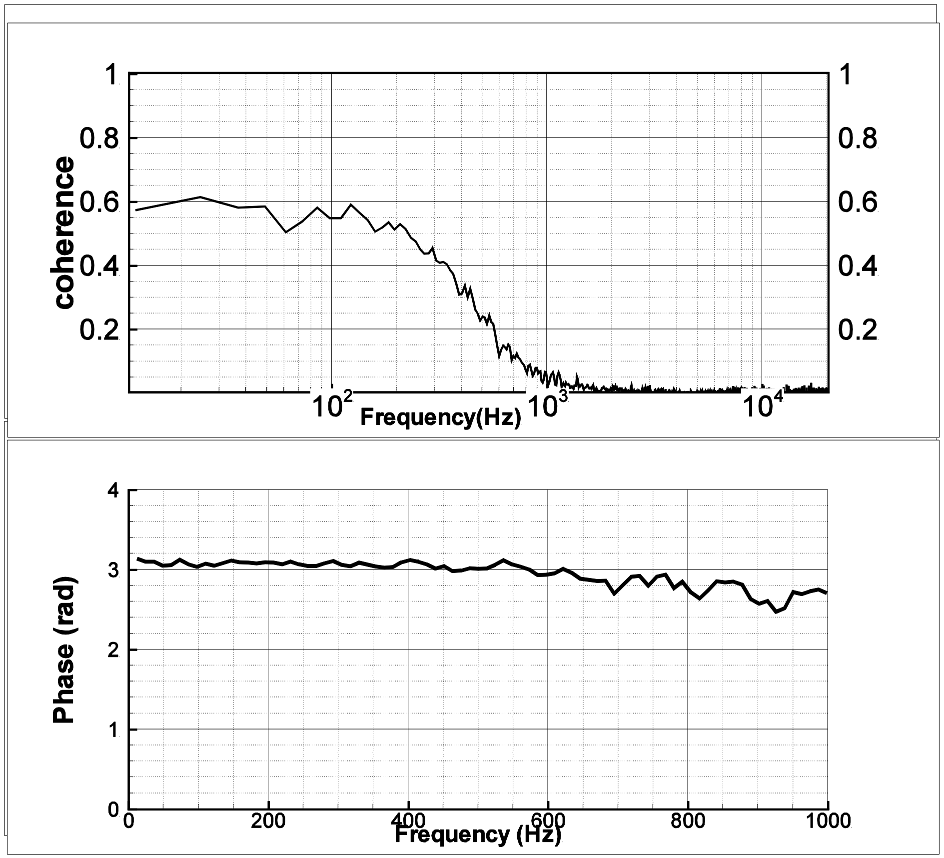
Experimental setup

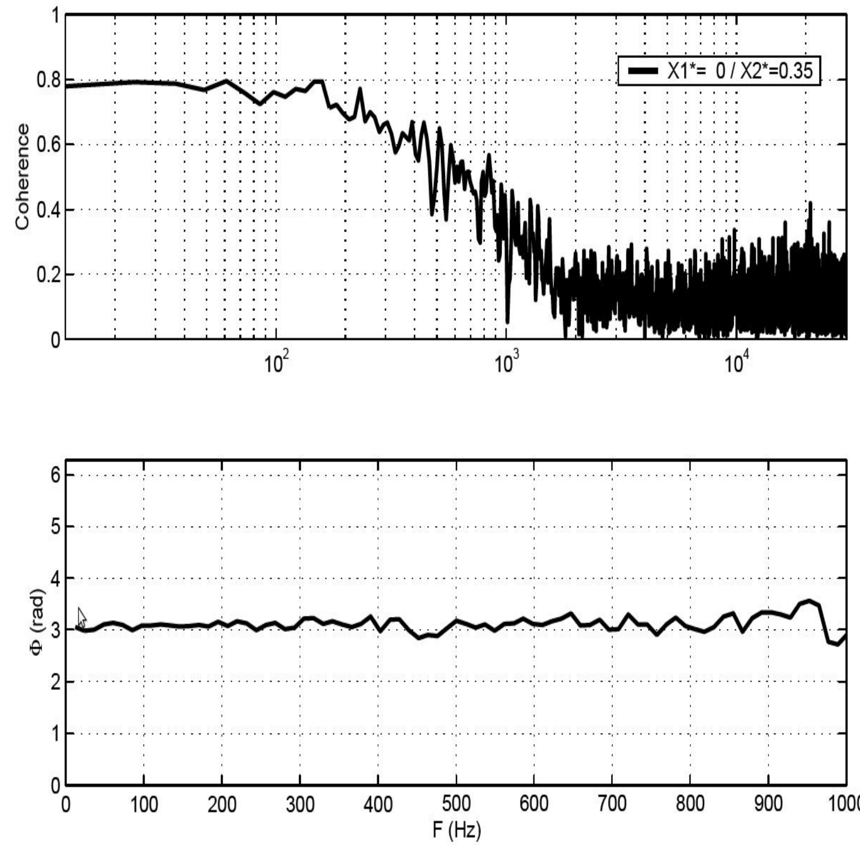
- Experiments using the Supersonic wind tunnel of the IUSTI laboratory, **M=2.3**
- Dantec PIV system, using a **30 mJ ND:YAG** Laser
- **PIV measurements in a vertical plane**, on the axis of the wind tunnel.
- ***10 000 Instantaneous PIV vector fields*** in one run.
- Seeding particles : **Incens smoke, F_r = 200Khz**
- **5 miniature Kulites** XCQ-062, **F_s=100KHz**

- **Pressure Taps at the exact position of the PIV Laser sheet.**
- **Simultaneous acquisition** using a ETEP system

Data validation

Coherence and phase shift between the separtion shock wave and the recirculation (X*=0 and X*=0.35)



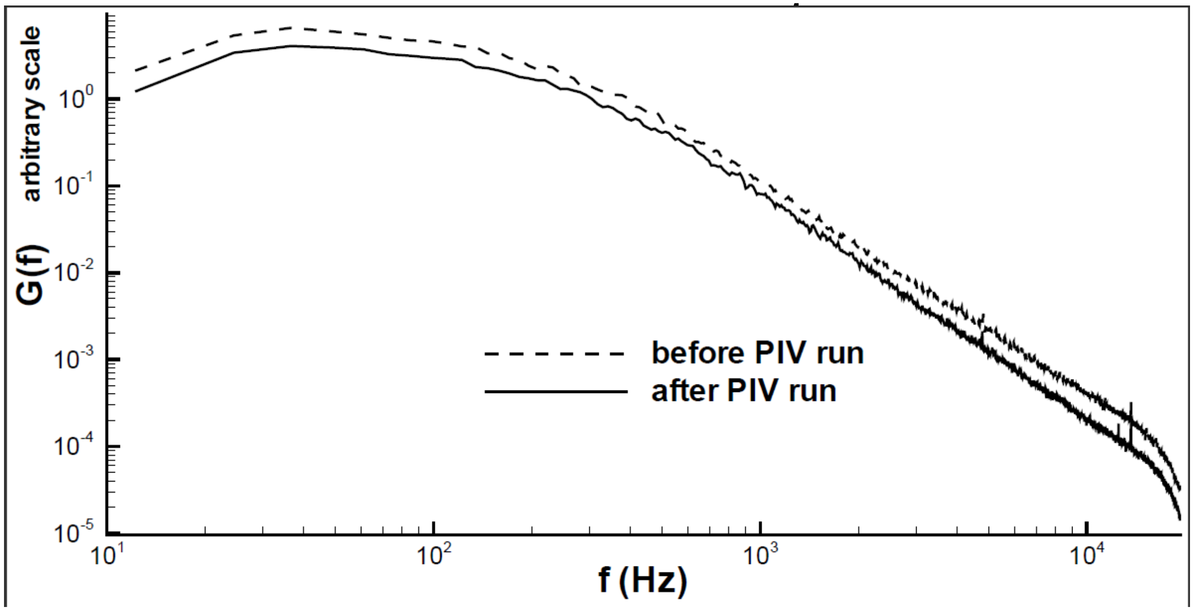


Current, 2011

Hadad, 2005

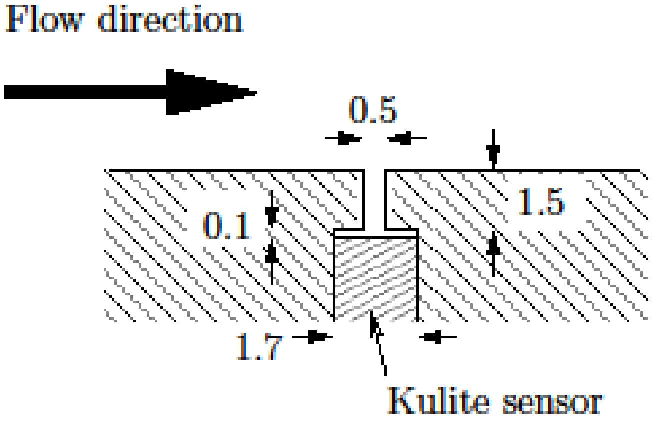
Data validation

Effect of the Incense smoke on Pressure, X*=0



Clogging effect
(1 run = 12 min)
Linear Correction of the signal

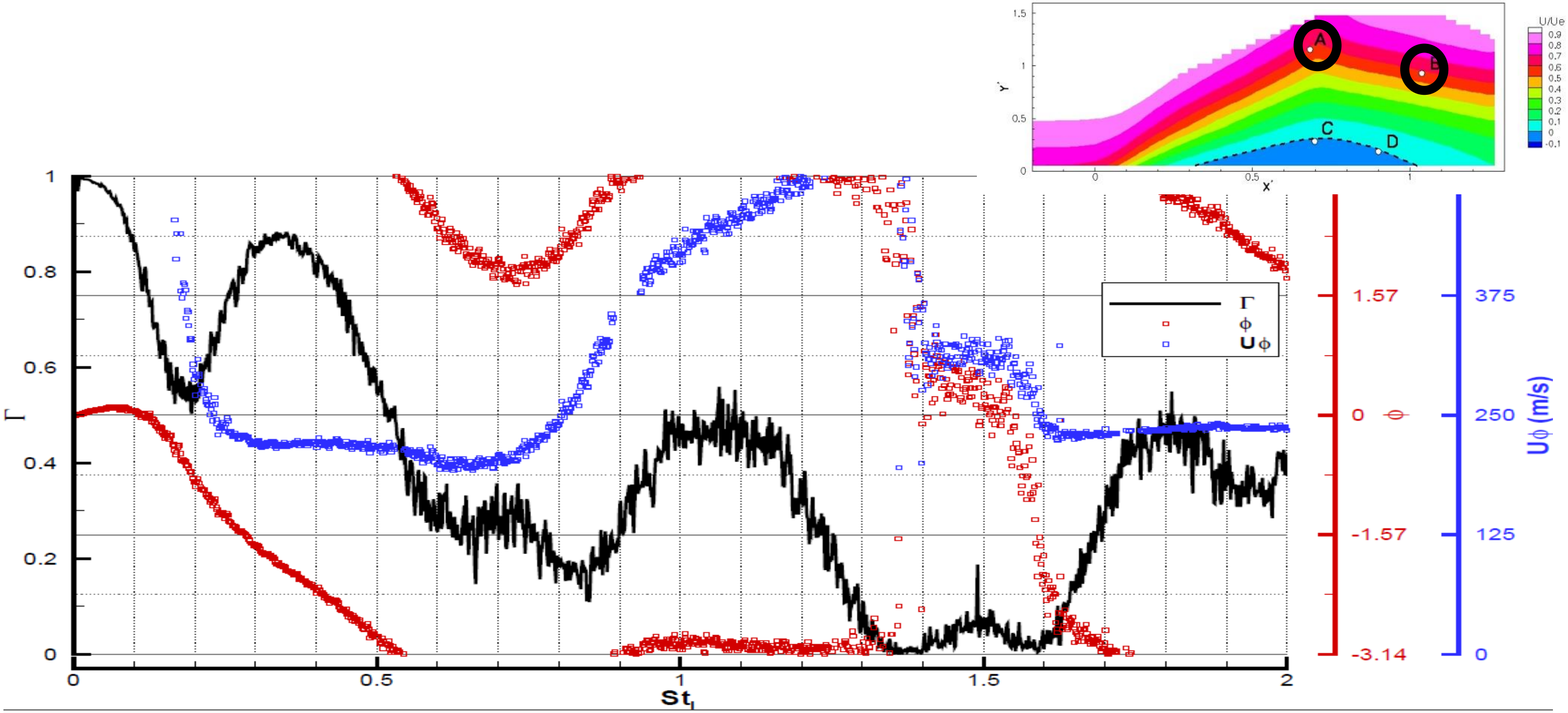
- No significant Phase shift and Damping
- Only one transducer affected by clogging
  - ➔ Correction *a posteriori of the signal*



Kulites behind a cavity

According to tidjemann &al, no significant damping and phase shift of the signal up to 8khz

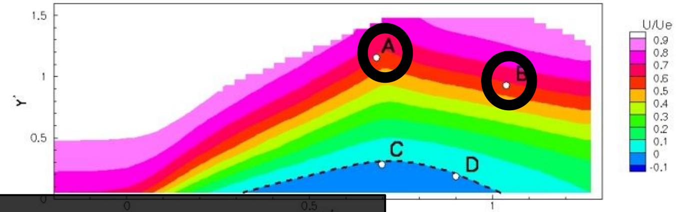
ANALYSIS OF TIME-RESOLVED ESTIMATED VELOCITY FIELDS

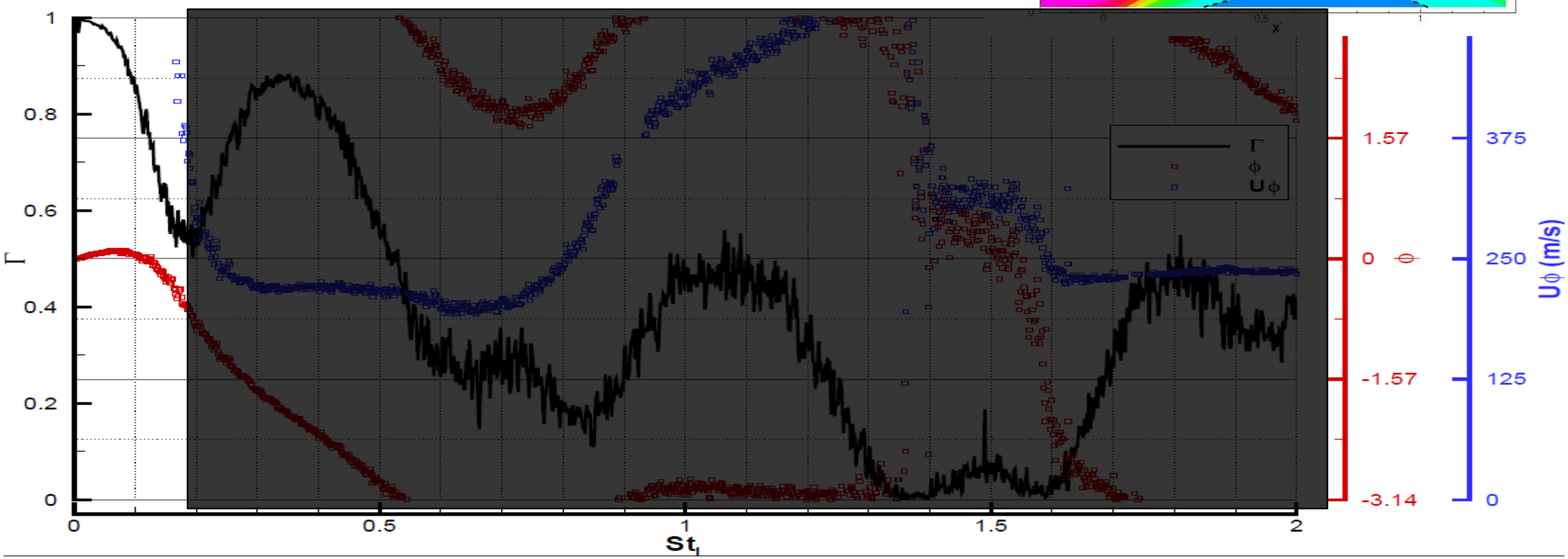


Coherence, Phase velocity, phase shift between points *A* and *B*

ANALYSIS OF TIME-RESOLVED ESTIMATED VELOCITY FIELDS

Low frequency unsteadiness, in phase

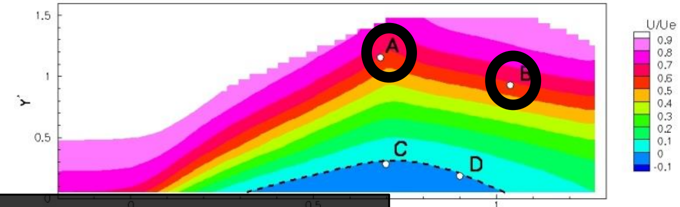


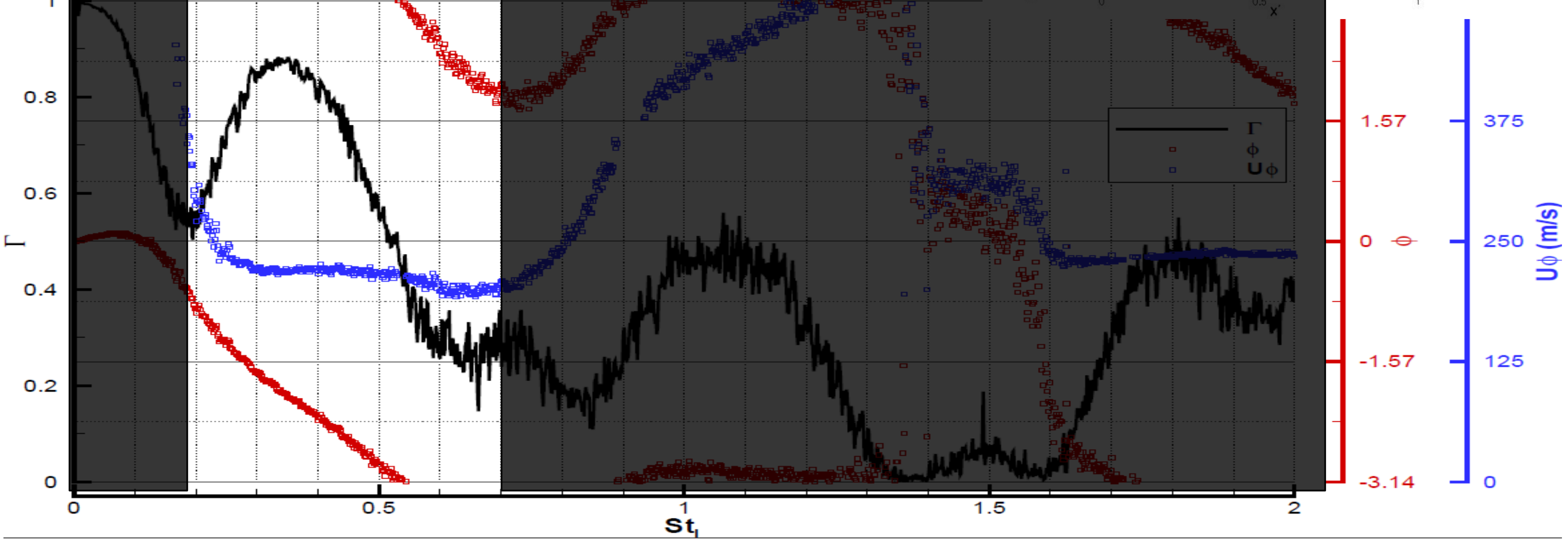


Coherence, Phase velocity, phase shift between points *A* and *B*

ANALYSIS OF TIME-RESOLVED ESTIMATED VELOCITY FIELDS

linear variation of ϕ, $U\phi$=250m/s : KH instability





— Coherence, — Phase velocity, —phase shift between points *A* and *B*

Pressure-velocity correlations

single basis, all τ
(non optimal)

$$R = \frac{\langle P,V\rangle}{\sqrt{\langle P,P\rangle\langle V,V\rangle}} = \frac{\langle P,V\rangle}{\sigma_P \sigma_V} = \frac{1}{\sigma_P\sigma_V}\sum_{k}^{n_{modes}} \langle P,a_k\rangle \Phi_k$$

Dual-PIV = 2X PIV

subset ←→ filter

$u(\overrightarrow{x}, t_j)$ et $u(\overrightarrow{x}, t_j + \tau)$

$$u(\overrightarrow{x}, t_j) = \sum_{n}^{N_{modes}} a_n(t_j)\Phi_n(\overrightarrow{x})$$

$$u(\overrightarrow{x}, t_j + \tau) = \sum_{n}^{N_{modes}} a_n(t_j + \tau)\Phi_n(\overrightarrow{x})$$

criteria to select the modes???

$$R_{a_n}(\tau) = \frac{< a_n(t)a_n(t+\tau) >}{\sigma_{a_n(t)}\sigma_{a_n(t+\tau)}}$$

Time properties of the coefficients $a_n(t)$

Band passed pressure-velocity correlations

<u>Process</u>:

1. correlations are computed $R_{q_i u}(\mathbf{x}, \mathbf{y}, \tau)$

Kulites – PIV fields

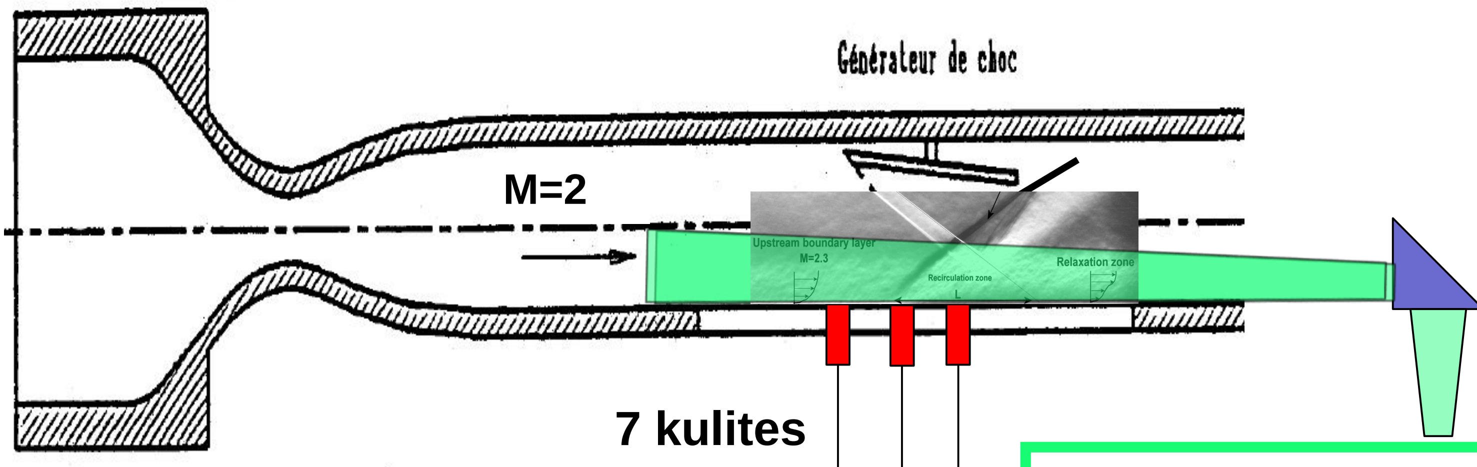
2. band pass filtering q_i' $\rightarrow$ $R_{q_i u}(\mathbf{x}, \mathbf{y}, \tau, \Delta f)$

3. how to apply a band pass filter on velocity fields ???

- Fourier filter not faisable (no TR – aliasing for TR)
- using POD to define a filter

$$\longrightarrow \quad u(\vec{x}, t) = \sum_{k}^{n_{modes}} a_k(t) \Phi_k(\vec{x})$$

Experimental setup



- PIV on the axis of the Wind Tunnel, *not resolved in time*
- ***Dantec*** system
- ND:YAG laser
- Incense Smoke

<u>Simultaneous and continous acquisition :</u>

- Kulites signal (Fs=100kHz)
- Trigger PIV

✓ 10,000 PIV vectors fields

✓ 12 min