Study of low-frequency unsteadiness in shock/turbulent boundary layer interaction using LES database

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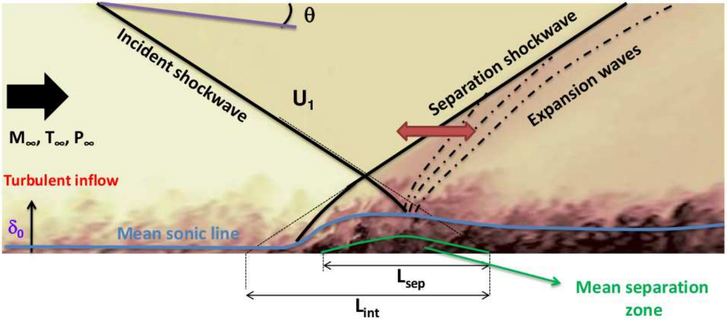
GDR Turbulence (GDR 2865 CNRS)
15-17 october 2012 Poitiers, France

ANR – SPICEX

Context & Objectives

- **Objectives** : to understand the dynamics of the interaction between an oblique shockwave and turbulent boundary-layer developing on flat plate.
- Under certain conditions, the interaction exhibits a self-sustained oscillations.



- High frequency activities : $t_{turb} \simeq \delta_0/U_\infty$ (turbulence origin) ;
- Medium frequency activities : $t_{sep} \simeq 10 t_{turb}$ (mainly located in separated zone) ;
- Low frequency activities : $t_{int} \simeq 100 t_{turb}$ (oscillations of the separated shock).

Numerical Tools

To investigate the self-sustained oscillations in SWTBLI a compressible Large Eddy Simulation is used.

- Finite-difference scheme with good spectral properties (DRP scheme) (Bogey & Bailly (2004)) ;
- Explicit time integration : low-storage optimized six-step Runge-Kutta scheme ;
- The high-order explicit filtering (Bogey & Bailly (2004)) ;
- Inflow condition : Synthetic-Eddy-Method (Pamiès *et al.* (2009)) ;
- Shock capturing : ANSF method (Bogey *et al.* (2009)) ;
- Nonreflecting boundary conditions (Thompson (1987)) ;
- Parallel solver in 3 directions (MPI method).

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Numerical Parameters

- Pirozzoli & Grasso (2006) case
- $M_\infty = 2.25$ and $Re_\theta = 3725$;
- Angle of flow deflector : $\phi = 8^o, 9^o$.

Runs	ϕ	L_x/δ	L_y/δ	L_z/δ	Δx^+	Δy^+	Δz^+	N_x	N_y	N_z
SWTBLI1	8^o	58	17.6	2.94	40-9-40	1.8	14	1100	250	150
SWTBLI2	8^o	26	15.1	3.5	42	1.7	17	400	200	154
SWTBLI3	9^o	26	15.1	3.5	42	1.7	17	400	200	154

	SWTBLI1	**SWTBLI2**	**SWTBLI3**
$\Delta t U_\infty/\delta$	0.0024	0.0023	0.0023
Time integration (in U_∞/δ)	1200	920	7000
number de traversees de domaine	20	36	280
number of proc.	294	32	32
CPU time	200000h	27000h	220000h
Recovery time	$\simeq$ 15 days	$\simeq$ 16 days	$\simeq$ 4 months

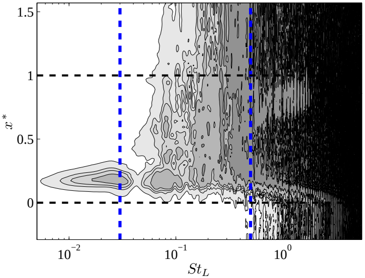
$\hookrightarrow$ Only SWTBLI-3 is discussed in this talk.

Wall Pressure Analysis

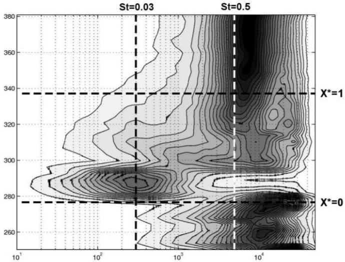
- Definition of Strouhal number $St_L = fL_{int}/U_1$
- 41600 plans wall pressure recorded every $50\Delta t$
- resolution $St_{L_{max}} = 18$ and $St_{L_{min}} = 0.00085$

premultiplied PSD $fE(f)$ of the wall pressure (arbitrary scale)

SWTBLI3 (LES)



IUSTI Experiments



$\hookrightarrow$ broad-band pressure fluctuations at the foot of the separated shock

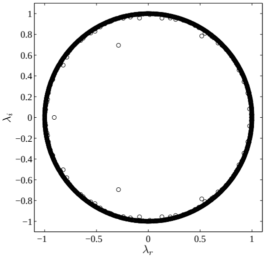
$\hookrightarrow$ low-frequency activity centered on $St_L = 0.03$

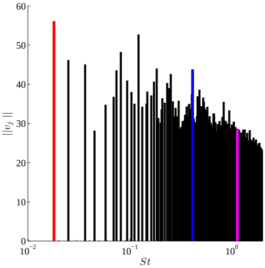
What are the spatial supports of the observed frequencies ?

- Koopman mode decomposition is an interesting tool to answer this question.
  - Nonlinear,
  - One mode by frequency,
  - Dynamic Mode Decomposition (Schmid, JFM, 2010).

Koopman modes

eigenvalues and amplitudes





- almost all eigenvalues on the unit circle : system statistically steady ;
- frequencies obtained in accordance with the linear spectral analysis ;
- continuous distribution of modes with similar amplitudes ; 3 modes are considered : $St_L = 0.018$ ( ), $St_L = 0.41$ ( ), $St_L = 1.1$ ( )

Spatial support of modes

Low-frequency modes at $St_L = 0.018$

Iso-u (dotted sonic line)

Iso-u with mean flow

- spatial support localized in upstream part of decelerated area,
- low frequency mode dynamics : cyclical breathing of decelerated area associated with a back-and-forth the separated shock.
- The shock of separation is a slave of the decelerated area (shear-layer and separated zone).

Spatial support of modes

modes at medium and high frequencies

$St_L \approx 0.41$ $St_L \approx 1.1$

- high and low frequencies activities are decoupled,
- selectivity of the shear-layer at medium frequencies,
- convective nature of the medium and high frequencies.

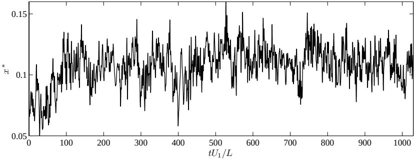
What is the dynamics of the separated zone ?

- Study of different filtered dynamics at low and medium frequencies :
  - Dynamics of separated point,
  - Dynamics of reattachment point,
  - Evolution of the mass of the recirculation zone.

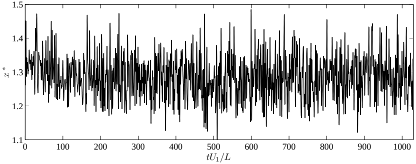
Dynamics of the separated zone – (1)

Separated and reattachment points

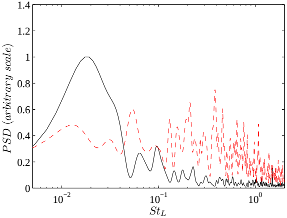
Separated point



Reattachment point



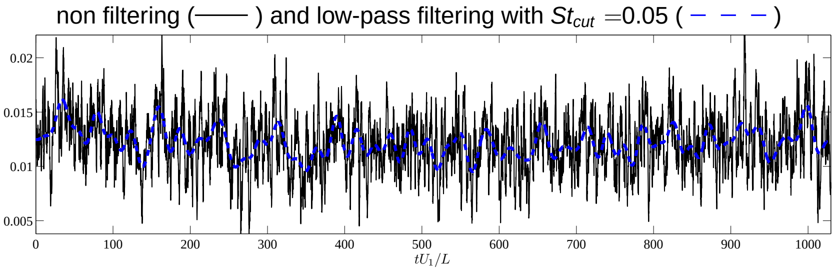
PSD : Separated point (——)
Reattachment point (– – –)

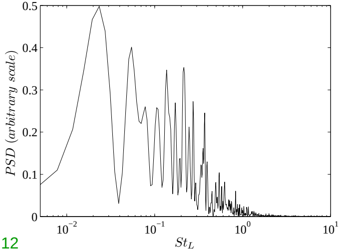


- Dynamics of separated zone splited in 2
  - The first part is mainly dominated by low-frequency ;
  - The second part by low and medium-frequency.

Dynamics of the separated zone – (2)

Mass of the separated zone – (1)



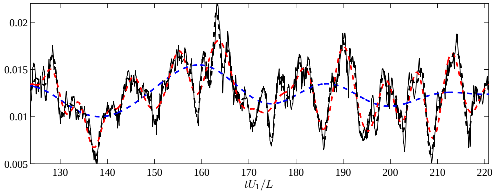


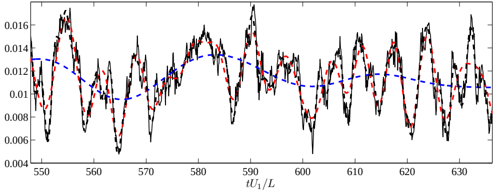
- no regular low-frequency activity (broadband acticity).
- Inside to separated zone : low and medium frequency activities.

Dynamics of the separated zone – (3)

Mass of the separated zone – (2)

no filtering (——), low-pass filtering with St_{cut} =0.5 (– – –), St_{cut} =0.2 (– – –), St_{cut} =0.05 (– – –)



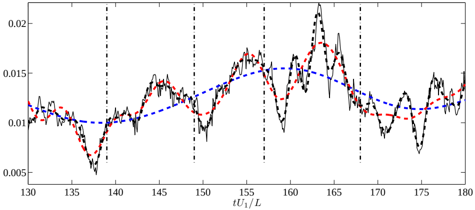


- Dynamics of the separated zone at medium frequency.
- Modulated dynamics at low-frequency.

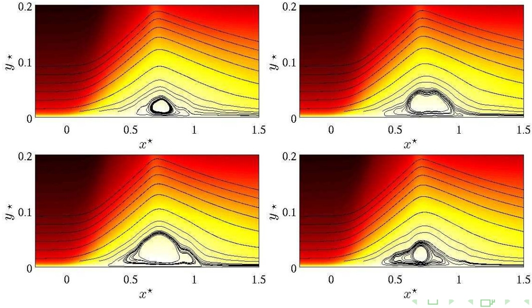
- What kind of structures is associated with this dynamics cycles ?

Dynamics of the separated zone – (4)

Low-pass filtered field with a cutoff $St_{cut} = 0.1$

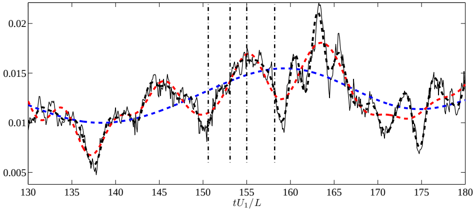


4 filtered fields describing a low-frequency cycle associated with $St_L = 0.05$ (— — —)

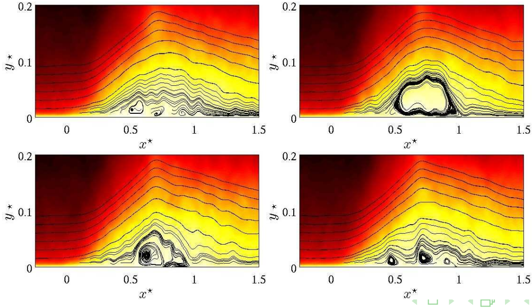


Dynamics of the separated zone – (5)

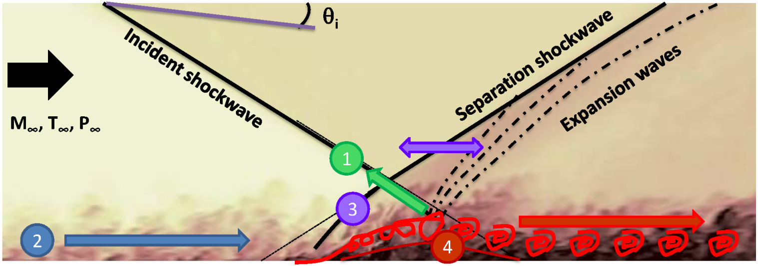
Non filtered field



4 non-filtered fields describing a medium-frequency cycle associated with $St_L = 0.2$ (— — —)



Summary of main effects



1 Generation and growth of the adverse gradient pressure which generate the interaction zone,

2 This interaction zone is continuously forcing by upstream turbulence : $E(\kappa,\omega)$,

3 Separated shock is a low-pass filtering, perturbations is amplified crossing the shock, and the shear-layer is deflected.

4 The shear-layer and separated zone develop instabilities which limit 1 .

1 and 4 Two opposing effects !

- The dynamics is the result of the continuous forcing and these two opposite effects.

Outlooks

- **Summary** :
  - The spatial support of a typical LF mode is concentrated in the first part of the recirculation bubble, mainly along the shear-layer.
  - The low-frequency dynamics is mainly localized (energetically) near the separated shock foot and in separated zone ;
  - The dynamics of separated zone is mainly dominated by medium frequency : $St_L \in [0.1; 0.5]$;
  - The low-frequency dynamics is a modulation of medium frequency dynamics ;
  - Two antagonist effects : Incident shock creates and increases the adverse pressure zone and the instabilities that develop in this region contribute to the reduction of the area.

- **Future work** :
  - Detection of structures responsible for medium frequency dynamic.
  - Characterization of scales (time, length) controlling low-frequency dynamics.
  - Analysis of 3-D structure of the flow.

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