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## Role of the recirculation bubble dynamics on the unsteadiness of the Shock Wave Boundary Layer Interaction.

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**Summary** The aim of the present work is to contribute to a better understanding of the physical mechanism causing the low frequency oscillations of the Shock Wave Boundary-Layer Interaction (SWBLI) by analyzing data from highly resolved unsteady numerical simulations. Results show that the low frequency reflected shock-wave motion is mainly driven by the low frequency breathing of the separation bubble that comes from a modulation of the successive enlargements and shrinkages of the separated zone (medium frequency flapping of the shear-layer); the oscillations of the reflected shocks foot being in phase with the motion of the separation point.

### INTRODUCTION

The Shock-Wave Boundary-Layer Interaction (SWBLI) is a recurrent physical phenomenon present in aeronautical and space systems. If the shock wave is strong enough, the subsequent adverse pressure gradient can lead to a separation of the boundary layer. A separation bubble is then created surrounded by a complex system of shock waves. The highly 3-D separation bubble leads to a steep increase of the drag force, heat fluxes and pressure fluctuations at the wall. Previous studies have additionally shown that the recirculation bubble as well as the reflected shock wave are subjected to a low frequency streamwise motion called the unsteadiness of the SWBLI. This unsteadiness subjects structures to oscillating loads that can damage their integrity, justifying the importance of a careful study of SWBLIs and particularly its low frequency unsteadiness.

Even if this phenomenon is well known, the mechanism leading to the SWBLI unsteadiness is still not well understood. Mainly two kind of mechanisms have been referred to in order to explain the existence of the SWBLI unsteadiness [1]. The first one consists in an excitation of the SWBLI by the large scales of the incoming turbulent boundary layer. The second one is provoked by the dynamics of the recirculation zone that drives the unsteadiness of the whole SWBLI system. Despite arguments in favor of each mechanism, no definitive explanation has been yet provided. The aim of the present work is then to perform well resolved DNS of SWBLIs and analyze results in order to contribute to a better understanding of the SWBLI unsteadiness and the physical mechanism causing these low frequency oscillations. To this end, the canonical configuration of an oblique shock wave impinging a boundary layer developing on a flat plate is considered.

### NUMERICAL APPROACH

The Navier-Stokes equations are solved by using a high order finite volume approach on cartesian meshes. The Euler part is discretized by means of a high-order one-step Monotonicity Preserving scheme, namely the OSMP7 scheme [2], based on a Lax-Wendroff approach, which ensures a 7th-order accuracy in both time and space in the regular regions. Monotonicity-Preserving (MP) constraints, first developed by Suresh and Huynh [3] and further extended in [2], are applied; they locally relax the TVD constraints near extrema. The resulting OSMP7 scheme recovers the 7th-order accuracy in both time and space everywhere, except near discontinuities where the scheme is Monotonicity-Preserving. Besides, the discretization of the diffusive fluxes is obtained by means of a classical centered 2nd-order scheme. These numerical schemes are implemented in the in-house parallel (MPI) Finite Volume DNS solver (code CHORUS) that has been developed at LIMSIS-CNRS. This numerical tool has intensively been validated on the simulation of high Reynolds number turbulent and shocked flows [5]. Results demonstrate the correct accuracy of the numerical approach to predict turbulent features and the great efficiency of the MP procedure to capture discontinuities without spoiling the solution at an almost negligible additional cost (at most 2.5 %).

### RESULTS ON SWBLI CONFIGURATIONS

In order to better understand the mechanisms leading to the unsteadiness of the SWBLI, it has been chosen to first perform a SWBLI simulation suppressing one of the two suspected mechanisms leading to the unsteadiness. By simulating the interaction between a *laminar* boundary layer and an incident oblique shock wave, the suspected influence of the large scale turbulent structures within the incoming boundary layer on the SWBLI unsteadiness has been suppressed. The only remaining suspected cause of the unsteadiness would be the dynamics of the separation bubble.

#### Shock-Wave Laminar Boundary-Layer Interaction:

We first chose to simulate a 3-D test-case similar to the one designed by Degrez *et al.* [4] ( $M_\infty = 2.15$ ;  $Re_{x_{sh}} = 10^5$ ) with however a higher shock angle ( $\sigma = 33.8^\circ$ ) to recover an unsteady behavior of the recirculation bubble that exhibits 3-D flow patterns. Results (Fig. 1-left) have shown that the separation point of the recirculation bubble and the foot of the reflected shock wave have a fixed location along time. This result shows that, in this configuration, the SWBLI unsteadiness has not been observed. Analyses of the dynamics of the recirculation bubble has been performed. Two

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regions have been identified in the recirculation bubble: the first part of the separation, upstream of the incident shock wave impingement and the second part downstream of the impingement. Although SWBLI unsteadiness has not been observed (no motion of the reflected shock wave), the characteristic low frequency of the SWBLI unsteadiness has however been recorded that characterizes the dynamics of the whole recirculation bubble: low frequency breathing ( $St_L \simeq 0.03 - 0.04$ ) of the recirculation bubble and medium frequency flapping ( $St_L \simeq 0.12 - 0.15$ ) of the shear layer in whole of the bubble, in addition to higher frequencies ( $St_L \simeq 0.5 - 0.6$ ) characterizing the vortex shedding from the shear layer in the second part of the recirculation bubble. In particular, the reattachment location is sensitive to the instabilities of the recirculation bubble, namely the breathing, the flapping and the Kelvin-Helmholtz frequencies. Even though present in the first part, the low frequency activity is not intense enough to provoke the oscillations of the separation point and the subsequent oscillations of the reflected shock foot.

### Shock-Wave Turbulent Boundary-Layer Interaction:

In order to reproduce and analyze the SWBLI unsteadiness, the simulation of the interaction between a incident shock wave and a *turbulent* boundary layer has secondly been undertaken (Fig. 1-right). In this context, the accurate simulation of a turbulent compressible incoming boundary layer is of great importance. A Synthetic Eddy Method (SEM) (Jarrin et al. [2006]) that we adapted to compressible flows, has efficiently been employed at the inlet boundary to generate a fully developed flat plate turbulent boundary layer ( $M_\infty = 2.33$ ;  $Re_\theta = 2539$ ) upstream of the impingement of the oblique shock-wave without a prohibitive additional computational cost. In the turbulent case, the SWBLI unsteadiness has clearly been recorded. The frequencies characterizing motion of the reattachment point are characteristic of the low ( $St_L \simeq 0.03 - 0.04$ ) and medium frequency flapping ( $St_L \simeq 0.12 - 0.15$ ) of the separation zone, while the frequencies of the separation point are characteristic of the low frequency flapping of the separation zone. Besides, the foot of the reflected shock wave oscillates in phase with the separation point. Motions of separation and reattachment points are mainly in opposite phase indicating successive enlargements and shrinkages of the recirculation bubble; the shrinkage phase being associated with a shedding of a large amount of fluid from the separated zone to downstream. This medium frequency flapping have been shown to be irregular in time; the maximum size of the recirculation bubble being submitted to discrepancies between successive cycles. This behavior of the separation bubble is responsible for the low frequency temporal modulation of the amplitude of the separation and reattachment points and thus to the low frequency breathing of the separation bubble.

### CONCLUSION

We here show that the reflected shock-wave is passive and the SWBLI unsteadiness is related to the low frequency breathing of the recirculation bubble (and not the large scales of the incoming turbulent boundary layer); the oscillations of the reflected shocks foot being in phase with the motion of the separation point. This low frequency activity of the recirculation bubble also seems to be at play in the laminar case. Although in the laminar case the behavior in the second part of the recirculation bubble is the same as in the turbulent case, the low frequency activity in the laminar regime is counter-currently damped towards the first part of the bubble as the length of the bubble is much greater than in the turbulent case. It is then not intense enough to excite, in the first part of the bubble, the separation point and the subsequent oscillations of the reflected shock foot.



Figure 1: Q criterion colored by the magnitude of the longitudinal velocity. Shock waves are highlighted by isosurfaces of  $\nabla \cdot \mathbf{u}$ : laminar case on the left, turbulent case on the right.

### References

- [1] Délery, J. and Dussauge, J.-P. *Some physical aspects of shock wave/boundary layer interactions*. Shock waves, **19**(6): 453, 2009.
- [2] Daru, V. and Tenaud, C. *High order one-step monotonicity-preserving schemes for unsteady compressible flow calculations*. Journal of Computational Physics, **193**(2): 563–594, 2004.
- [3] Suresh, A. and Huynh, H.T. *Accurate monotonicity-preserving scheme with Runge-Kutta time stepping*. Journal of Computational Physics, **136**(1): 83–99, 1997.
- [4] Degrez, G.; Boccadoro, C. H. and Wendt, J. F. *The interaction of an oblique shock wave with a laminar boundary layer revisited. An experimental and numerical study*. Journal of fluid mechanics, **177**(13), 247–263, 1987.
- [5] Ben Hassan Saidi, I.; Tenaud, C.; and Fournier, G. *Solving three dimensional turbulent compressible flows using a high order One Step Monotony Preserving scheme*. 10th International Conference on Computational Fluid Dynamics (ICCFD 2018), Barcelone, Spain, 2018.