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EDITORIAL

Shock wave boundary layer interaction

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1 Introduction

Shock wave boundary layer interaction (SWBLI) in high-speed aerodynamics has been the subject of several experimental and numerical studies in the past. Today, with the renewed interest in supersonic and hypersonic flights, the subject has become increasingly important, especially for aerospace applications (rockets, missiles, supersonic and hypersonic vehicles...).

The interaction of shock waves with boundary layers is a basic fluid-dynamics phenomenon that has both fundamental and practical importance. From a practical standpoint, the interaction of SWBL can have a significant influence on aircraft or rocket performance and often leads to extremely undesirable effects, such as drag rise, massive flow separation, shock unsteadiness and high wall heating. From the fundamental point of view, this problem involves the basic structure of a shock interacting with separated flows which represents one of the simplest occurrences of a strong viscous/inviscid interaction (see examples shown in Fig. 1), and therefore an ideal test case for Navier–Stokes solvers. In this problem, several phenomena related to viscous flows exist, such as boundary layers with adverse pressure gradients, induced separation, recirculation bubbles, shear layers and some of their salient features can be found in references given by Dolling [1], Settles and Dolling [2], Délery [3], Dolling and Dussauge [4].

Previous studies on supersonic wall bounded flows [4–24] have shown that shock wave boundary layer interaction occurring in many situations, such as ducts, wind tunnels, nozzles or ramps may exhibit strong unsteadiness that cause large wall pressure fluctuations. Those fluctuations associated to large shock excursions are prejudicial to the mechanical behavior and can subsequently cause fatigue or structural damages. From these studies, we have learned that the shock motion has a frequency much lower than the characteristic frequency of the turbulent boundary layer, and that the time scale associated with the low-frequency is of order of $\mathcal{O}(10\delta/U_\infty - 100\delta/U_\infty)$, in contrast to the characteristic time scale of the incoming boundary layer which is of $\mathcal{O}(\delta/U_\infty)$. Despite a large number of experimental and numerical studies devoted to the characterization of shock oscillations and large-scale turbulence identification, the cause of the low-frequency motion (influence of upstream or downstream conditions or intrinsic shock low-pass filter behavior) is still a debate question.

From numerical point of view, significant progress has been made in the development of both steady (RANS) or unsteady hybrid (RANS/LES) methods, which incorporate configuration-dependent flow physics. An assessment of RANS methods for SWBLI problems can be found in the AGARD report edited by Knight and Degrez [25]. In general, the majority of RANS models failed to capture the high level of unsteadiness in the shock system observed in the experiment and none of them provide a good prediction of *r.m.s.* (root-mean-square) fluctuating surface pressure and heat transfer. Recently, however, large-eddy simulation (LES) and direct numerical simulations (DNS) have been applied to the SWBLI problem with significant success [26–30] and subsequently some tentative of explanations of the origin of the low-frequency shock motion were given (see, for example, [31–33]).

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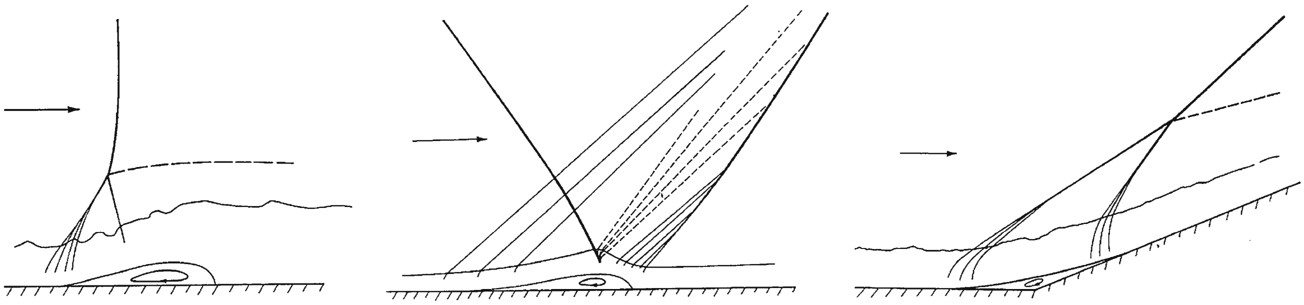

Fig. 1 Schematic representation of typical situations where SBLWI is encountered. Examples include transonic shock-boundary layer separation (**a**), oblique shock impinging turbulent boundary layer (**b**) and supersonic flow over a compression ramp (**c**)

In spite of many studies on the subject, the mechanisms of shock wave boundary layer interaction are quite complex. If much has been collected about the mean properties of SWBLI, at least in two-dimensional flows, the fluctuating aspects of the phenomenon has not received a comparable attention in spite of the important practical consequences of these fluctuations as concerns aeroelasticity, aeroacoustics and other fields. Recently, an attempt has been made to classify the frequency ranges of the shock motion, according to the type of interaction and the flow regime [34]. The results are encouraging and suggest that the frequencies can be only lower than in the incoming turbulence. However, this analysis is restricted to a limited number of geometries, typically two dimensional. Indeed, much effort should be spent towards the identification of the origin of the low-frequency shock movement as well as the physical mechanism that drive this phenomenon.

2 Thematic issue on SWBLI

The thematic issue on SWBLI focuses on the integration of physical analysis, modelling, and experiments for the study of basic shock-wave interactions with turbulent boundary layer over an adiabatic plate, and helps provide a basis for future work in this area. This issue includes seven original papers from experts in the various aspects of SWBLI (physical description, advanced measurements and numerical simulations). Roughly half of the contributions are experimental investigations, and the other half is dedicated to numerical simulations. Some of the selected papers have been presented in short versions at the 18th International Shock Interaction Symposium (ISIS18), 15–18 July 2008 Rouen, France (see http://isis18.coria.fr) and the other have been proposed by different authors in reply to our call for contributions. It should be mentioned that all manuscripts have been strictly peer-reviewed according to the SWJ procedure and policy.

In this framework, several experimental techniques have been used with different flow configurations (flat plate, transonic channel and ramp) to elucidate the phenomenon of boundary-layer separation and shock interactions. For example, Debiève et al. [35] presented an experimental study of the dynamics of the interaction of an oblique shock with a fat plate turbulent boundary layer. Optical resolutions as well as pressure information have been used to highlight the important characteristics of this unsteady flow with emphasis on the low-frequency movements of the separated shock. The authors proposed a scenario to explain the coupling between the separation shock motion and the separated bubble pulsation in a shock reflection. On the other hand, Délery and Dussauge [36] summarized the essential features of nominally two-dimensional shock wave boundary layer interactions, using a mixture of techniques including experimentation and calculation (characteristics methods) to analyse several shock configurations with more insight into the physics of SWBLI in general.

From a more practical standview and towards the study of passive-flow control of SWBLI, two different experimental investigations were presented. In Blinde et al. [37], micro-ramps devices based on a PIV technique are used to analyse the manipulation of separation in an interaction produced by an impinging oblique shock wave, whereas Bur et al. [38] have dedicated their study to boundary-layer separation control inside a transonic channel flow with a bump shape at the lower wall, in which various vortex generation configurations are tested with different arrangements and sizes. The experimental data are obtained through flow visualizations (schlieren, laser-sheet, surface oil flow visualizations) and pressure measurements at the wall (average and instantaneous wall pressure sensors) and results are presented for both an unforced case and for a forced oscillation configuration. The main finding is that vortex generators are effective in delaying flow separation both in the forced and unforced case.

From a computational and modelling point of view, compressible flows, in general, and shock/boundary-layer interaction, in particular, pose substantial challenges. Although some features of this interaction are also encountered in other boundary layers subjected to smoothly varying adverse pressure gradient, there are aspects which make particularly difficult the prediction of shock-affected flows. There is, first, the question of numerical accuracy and shock-capturing methods in which the representation of wave characteristics is of considerable importance. Modern low-dissipative high-order methods, based on Riemann solvers and high-order WENO interpolations, are now generally regarded as offering an accurate and stable numerical framework. However, studies (see e.g. [39–41]) indicated that these high-order shock-capturing schemes are still too dissipative for capturing fine scale turbulence fluctuations. Their excessive numerical dissipation, especially when applied to strong steady shocks or unsteady turbulence/shocklet interaction, has encouraged the use of hybridizing (switching) between spectral or high-order compact schemes and high-resolution shock-capturing methods (switch to shock-capturing methods at discontinuities) [30,33,42,43]. As regards turbulence, it might be assumed that only the most elaborate turbulence models, specifically those resolving dynamically the interaction between various energetic scales and its interplay with the flow anisotropy as well as the shear stresses, would be able to give a well-adapted representation of the complex interaction processes in shock-affected flows.

In this context, Touber and Sandham [44] used an advanced CFD code in conjunction with large-eddy simulation techniques based on a dynamical subgrid model to study the physical mechanism related to the dynamics of the recirculation bubble downstream of the shock that drives the low-frequency shock oscillations in conjunction with the unsteady coherent large scales that are well-identified. Additionally, the unsteady aspects of SWBLI are correctly reproduced in agreement with previous experimental data and the 3-D flow topology is clearly highlighted. Also, Pirozolli et al. [45] presented a numerical analysis of shock boundary layer interaction under conditions of incipient separation by means of both LES and RANS methods and showed in this case the importance of incoming turbulence. On the other hand, Garnier [46] reported results of an advanced CFD investigation using a Stimulated Detached Eddy Simulation (SDES) methodology on the unsteadiness aspects of the 3-D SWBLI. DES stands as a promising solution for computing complex geometries, since it combines the efficiency of a Reynolds-averaged turbulence model near the wall with the fidelity of Large-Eddy Simulation (LES) in separated regions.

Finally, it should be recalled that substantial additional research in 3-D shock wave turbulent boundary layer interactions is needed to achieve greater understanding of the flow physics and to improve the accuracy of numerical simulations. Since the main finding is revealing the unsteady nature of the flow separation, which is not easily accessible by experiments in real configurations, the quantitative data of the CFD, if well validated through selected benchmark calculations, should help to understand and explain such flow behavior.

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References

1. Dolling, D.S.: Fifty years of shock-wave/boundary-layer interaction research: what next? AIAA J. **39**, 1517–1531 (2001)
2. Settles, G.S., Dolling, D.S.: Swept shock wave/boundary layer interactions—tutorial and update. AIAA Paper 90-0375 (1990)
3. Délery, J., Marvin, J.G.: Shock-wave boundary layer interactions. AGARDograph No. 280, ISBN 92-835-159-6 (1996)
4. Dolling, D., Dussauge, J.P.: Fluctuating wall-pressure measurements. In: Fernholz, H.H., Smits, A.J., Dussauge, J.P., Finley, P.J. (eds.) A Survey of Measurements and Measuring Techniques in Rapidly Distorted Compressible Turbulent Boundary Layers, AGARDograph, 315, NATO, Neuilly s/Seine (1989)
5. Kistler, A.L.: Fluctuating wall pressure under a separated supersonic flow. J. Acous. Soc. Am. **36**(3), 543–550 (1964)
6. Humble, R.A., Scarano, F., van Oudheusden, B.W.: Particle image velocimetry measurements of a shock wave/turbulent boundary layer interaction. Exp. Fluids **43**, 173–183 (2007)
7. Kim, J., Sung, H.J.: Wall pressure fluctuations in a turbulent boundary layer over a bump. AIAA J. **44**(7), 1393–1401 (2006)
8. Erengil, M.E., Dolling, D.S.: Unsteady wave structure near separation in a Mach 5 compression ramp interaction. AIAA J. **29**(5), 728–735 (1991)
9. Baresh, S.J., Clemens, N.T., Dolling, D.S.: Relationship between upstream turbulent boundary-layer velocity fluctuations and separation shock unsteadiness. AIAA J. **40**(12), 2412–2422 (2002)
10. Selig, M.S., Smits, A.J.: Effect of periodic blowing on attached and separated supersonic turbulent boundary layers. AIAA J. **29**(10), 1651–1658 (1991)
11. Hou, Y.X., Unalmis, O.H., Bueno, P.C.: Effects of boundary-layer velocity fluctuations on unsteadiness of blunt-fin interactions. AIAA J. **42**(12), 2615–2619 (2004)
12. Ganapathisubramani, B., Clemens, N.T., Dolling, D.S.: Effects of upstream boundary layer on the unsteadiness of shock-induced separation. J. Fluid Mech. **585**, 369–394 (2007)
13. Dupont, P., Haddad, C., Debiève, J.-F.: Space and time organization in a shock-induced separated boundary layer. J. Fluid Mech. **559**, 255–277 (2006)
14. Sajben, M., Bogar, T.J., Kroutil, J.C.: Forced oscillation experiments in supercritical diffuser flows. AIAA J. **22**(4), 465–474 (1984)
15. Nguyen, A.T., Deniau, H., Girard, S., Alziary de Requefort, T.: Unsteadiness of flow separation and end-effects regime in a thrustoptimized contour rocket nozzle. Flow Turb. Combust. **71**, 121 (2003)
16. Wong, H.Y.: Overview of flow oscillations in transonic and supersonic nozzles. J. Propuls. Power **22**(4), 705–720 (2006)
17. Hadjadj, A., Onofri, M.: Nozzle flow separation. Shock Waves **19**, 163–169 (2009)
18. Papamoschou, D., Zill, A., Johnson, A.: Supersonic flow separation in planar nozzles. Shock Waves **19**, 171–183 (2009)
19. Verma, S.B.: Shock unsteadiness in a thrust optimized parabolic nozzle. Shock Waves **19**, 193–212 (2009)

20. Dussauge, J.P.: Compressible turbulence and energetic scales: what is known from experiments in supersonic flows? Flow Turbul. Combust. **66**, 373–391 (2001)
21. Müller, J., Mümmler, R., Staudacher, W.: Comparison of some measurements techniques for shock-induced boundary layer separation. Aerosp. Sci. Technol. **5**(6), 383–395 (2001)
22. Kiya, M., Sasaki, K.: Structure of a turbulent separation bubble. J. Fluid Mech. **137**, 83–113 (1983)
23. Palko, C.W., Dutton, J.C.: A method for separating shock wave motion and turbulence in LDV measurements. Exp. Fluids **26**, 358–370 (1999)
24. Knight, D., Yan, H., Panaras, A.G., Zheltovodov, A.: Advanced in CFD prediction of shock wave turbulent boundary layer interactions. Progr. Aerosp. Sci. **39**, 121–184 (2003)
25. Knight, D., Degrez, G.: Shock wave boundary layer interactions in high Mach number flows—a critical survey of current CFD prediction capabilities. AGARD AR-319 2 (1998)
26. Adams, N.A.: Direct simulation of the turbulent boundary layer along a compression ramp at $M = 3$ and $R_{e_\theta} = 1685$. J. Fluid Mech. **420**, 47–83 (2000)
27. Stolz, S., Adams, N.A., Kleiser, L.: The approximate deconvolution model for large-eddy simulations of compressible flows and its application to shock-turbulent boundary-layer interaction. Phys. Fluids **13**(10), 2985–3001 (2001)
28. von Kaenel, R., Kleiser, L., Adams, N.A., Vos, J.B.: Large-eddy simulation of shock turbulence interaction. AIAA J. **42**(12), 2516–2528 (2004)
29. Urbin, G., Knight, D., Zheltovodov, A.A.: Compressible large eddy simulation using unstructured grid: supersonic turbulent boundary layer and compression corner. AIAA Paper, 99-0427, 37th AIAA Aerospace Sciences Meeting and Exhibit, Jan. 11–14, Reno, NV (1999)
30. Garnier, E., Sagaut, P.: Large eddy simulation of shock/boundary-layer interaction. AIAA J. **40**(10), 1935–1944 (2002)
31. Pirozzoli, S., Grasso, F.: Direct numerical simulation of impinging shock wave/turbulent boundary layer interaction at $\mathrm{M} = 2.25$. Phys. Fluids **8**, 1–17 (2006)
32. Wu, M., Martn, M.P.: Analysis of shock motion in STBLI using direct numerical simulation data. J. Fluid Mech. **594**, 71–83 (2008)
33. Touber, E., Sandham, N.D.: Large-eddy simulation of low-frequency unsteadiness in a turbulent shock-induced separation bubble. Theor. Comput. Fluid Dyn. **23**(2), 79–107 (2009)
34. Dupont P., Debive J.F., Dussauge J.P.: Shock wave unsteadiness in shock boundary layer interactions. In: Babinssky, H. (ed.) Shock boundary layer interaction. Cambridge University Press, Cambridge, to be published (2009)
35. Debiève, J.F., Dupont, P.: Dependence between the shock and the separation bubble in a shock wave boundary layer interaction. Shock Waves, present issue (2009)
36. Délery, J., Dussauge, J.P.: Some physical aspects of shock wave/boundary layer interactions. Shock Waves, present issue (2009)
37. Blinde, P.L., Humble, R.A., van Oudheusden, B.W., Scarano, F.: Effects of micro-ramps on a shock wave/turbulent boundary layer interaction. Shock Waves, present issue (2009)
38. Bur, R., Coponet, D., Carpels, Y.: Separation control by vortex generator devices in a transonic channel flow. Shock Waves, present issue (2009)
39. Garnier, E., Mossi, M., Sagaut, P., Comte, P., Deville, M.: On the use of shock-capturing schemes for large-eddy simulation. J. Comput. Phys **153**, 273–311 (1999)
40. Mittal, R., Moin, P.: Stability of upwind-based finite difference schemes for large-eddy simulation of turbulent flows. AIAA J. **35**, 1415–1417 (1997)
41. Blin, L., Hadjadj, A., Vervisch, L.: Testing numerical schemes for large eddy simulations of thrust-reversers. AIAA paper 99-0787. The 37th AIAA Aerospace Sciences Meeting and Exhibit, Reno, NV (1999)
42. Adams, N.A., Shariff, K.: A high-resolution hybrid compact-ENO scheme for shock-turbulence interaction problems. J. Comp. Phys. **127**, 27–51 (1996)
43. Dubos, S., Hadjadj, A.: Large-eddy simulation of a supersonic boundary layer at $M = 2.25$. In: Proceedings of the 15th Int. Symp. Turbulence and Shear Flow Phenomena, August 27–29, München, Germany (2007)
44. Touber, E., Sandham, N.D.: Comparison of three large-eddy simulations of shock-induced turbulent separation bubbles. Shock Waves, present issue (2009)
45. Pirozzoli, S., Beer, A., Bernardini, M., Grasso, F.: Computational analysis of impinging shock-wave boundary layer interaction under conditions of incipient separation. Shock Waves, present issue (2009)
46. Garnier, E.: Stimulated Detached Eddy Simulation of three-dimensional shock/boundary layer interaction. Shock Waves, present issue (2009)