Numerical Simulation of Shock Wave; Turbulent Boundary Layer Interaction

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Abstract

An analysis of the results shows an honest agreement with reference experiment in terms of mean quantities and turbulence structure. The machine knowledge makes sure theoretical and experimental results on fluctuation-amplification across the interaction region. Within the wake of the most shock a shedding of shocklets is discovered. The temporal behavior of the coupled shock-separation system agrees well with experimental knowledge. The simulation knowledge gives indications for a large-scale shock motion. In the present paper, it's discovered that the structural changes within the downstream separated flow are paying homage to bound global linear instability modes according within the literature, suggesting that an inherent instability of the separated flow may be the driving mechanism for the unsteadiness.

Keywords: Shock wave, Turbulent boundary, Boundary layer.

1. Introduction

The shock may be a variety of propagating disturbance. Once a wave moves quicker than the native speed of sound during a fluid, it's a wave. Like a normal wave, a wave carries energy and may propagate through a medium; but, it's characterized by abrupt, nearly discontinuous amendment in pressure, temperature and density of the medium. In supersonic flows, growth is achieved through growth fan, additionally called a Prandtl-Meyer growth fan.

Unlike solitons i.e., another quite nonlinear wave, the energy of a wave dissipates comparatively quickly with distance. Also, the related growth wave approaches and eventually merges with the wave, partly cancelling it out. Therefore the blast wave related to the passage of a supersonic craft is that the wave ensuing from the degradation and merging of the wave and therefore the growth wave made by the craft.

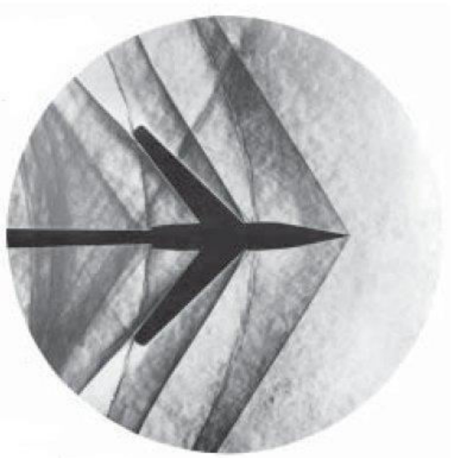

Figure 1. A schlieren photograph showing the compression in front of an unswept wing at Mach 1.2.

When a shock wave passes through matter, energy is preserved however entropy will increase. This alteration within the matter's properties manifests itself as a decrease within the energy which may be extracted as work, and as a problem force on supersonic objects; shock waves area unit powerfully irreversible processes. (Peter, 2011), (Wikipedia, 2017)

When object or disturbance moves quicker than the knowledge concerning it will propagate into the encompassing fluid, fluid close to the disturbance cannot react or "get out of the way" before the disturbance arrives. In an exceedingly blast wave, the properties of the fluid i.e., density, pressure, temperature, flow rate, Mach number amendment nearly in a flash. Measurements of the thickness of shock waves in air have resulted in values around two hundred nm i.e., about 10−5 in, that is on a similar order of magnitude because the mean free gas molecule path. In relevance the time, this means the blast wave are often treated as either a line or a plane if the flow field is two-dimensional or three-dimensional, severally.

Shock waves are shaped once pressure front moves at supersonic speeds and pushes on the encompassing air. At the region wherever this happens, sound waves traveling against the flow reach some extent wherever they cannot travel from now on upstream and therefore the pressure increasingly builds in this region; an air mass blast wave speedily forms.

The shock wave is one of several different ways in which a gas in a supersonic flow can be compressed. Some other methods are isentropic compressions, including Prandtl-Meyer compressions. The method of compression of a gas, results in different temperatures and densities for a given pressure ratio which can be analytically calculated for a non-reacting gas. A shock wave compression results in a loss of total pressure, meaning that it is a less efficient method of compressing gases for some purposes, for instance in the intake of a scramjet. The appearance of pressure-drag on supersonic aircraft is mostly due to the effect of shock compression on the flow. (Anderson, 2001), (Robert et al., 2003), (Settles, 2006).

Shock waves aren't typical sound waves; a blast wave takes the shape of a really sharp amendment within the gas properties. Shock waves in air are detected as a loud "crack" or "snap" noise. Over longer distances, a blast wave will amendment from a nonlinear wave into a linear wave, degenerating into a standard acoustic wave because it heats the air and loses energy. The acoustic wave is detected because the acquainted "thud" or "thump" of a shock wave, usually created by the supersonic flight of craft.

The blast wave is one amongst many alternative ways during which a gas in a supersonic flow is compressed. Another ways are physical property compressions, together with Prandtl-Meyer compressions. The strategy of compression of a gas ends up in totally different temperatures and densities for a given pressure quantitative relation which may be analytically calculated for a non-reacting gas. A blast wave compression ends up in a loss of total pressure, which means that it's a less economical technique of pressing gases for a few functions, for example within the intake of a scramjet. The looks of pressure-drag on supersonic craft are usually thanks to the impact of shock compression on the flow. (Anderson, 2001), (Robert et al., 2003), (Settles, 2006).

At far back from the vanguard, the graceful streamline flow breaks down and transitions to a flow. From a tangle viewpoint, it's suggested to own the transition from stratified to flow as so much aft on the wing as attainable, or has an outsized quantity of the wing surface inside the stratified portion of the physical phenomenon. The low energy streamline flow, however, tends to interrupt down additional suddenly than the turbulent layer. Boundary layers develop because of the inherent viscousness or consistency of the fluid. As a fluid flows over a surface, the fluid sticks to the solid boundary that is that the supposed “no-slip condition”. As abrupt jumps in flow speed aren't attainable for flow continuity needs, there should exist a little region inside the fluid, near the body over that the fluid is flowing, wherever the flow speed will increase from zero to the thought speed.

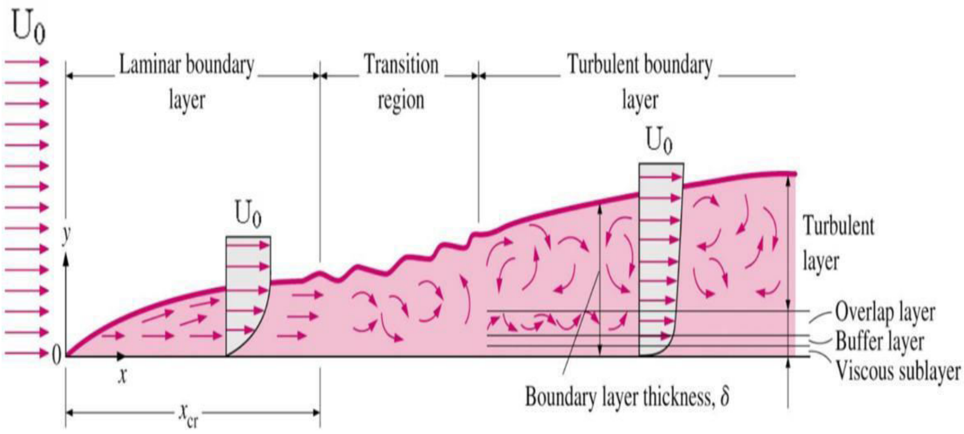

Figure-2 The turbulent boundary layer and thickness.

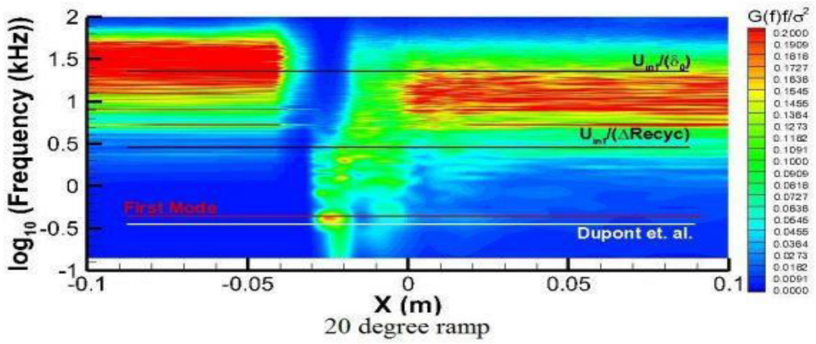

Figure-3 The Shock Wave / Turbulent Boundary Layer Interactions

(*From the Deptt. of Mechanical & Aerospace Engineering North Carolina State University Raleigh, NC 27695-7910 USA; https://www.mae.ncsu.edu/cfd/shock-wave-turbulent-boundary-layer- interactions/*).

This region is that the alleged physical phenomenon. The U-shaped profile of the physical phenomenon will be pictured by suspending a line of dye in water and permitting fluid flow to distort the road of dye. The gap of a distorted dye particle to its original position is proportional to the flow speed. The fluid is stationary at the wall, will increase in speed moving removed from the wall, then converges to the constant thought price at a distance capable the thickness of the physical phenomenon.

2. Review Literature

We investigate the interaction of an oblique shock generated by a wedge with a turbulent boundary-layer at a free-stream Mach number of $Ma_\infty = 3.0$ and a Sir Joshua Reynolds range supported the incoming boundary-layer thickness of $Re_{\delta 0,I} = 205.103$. Large-eddy simulations (LES) are performed for two configurations that disagree within the treatment of the wind-tunnel wall and shock generator movement inside the experiment: a hard and fast panel with a static shock generator that deflects the flow by $\theta = 20^0$, and therefore the transient interaction of a pitching shock generator with an elastic panel. Besides mean and instant flow quantities, we have a tendency to investigate unsteady aspects of the interaction region by suggests that of wall-pressure spectra and supply comparison with experimental information whenever attainable (Pasquariello et al., 2015).

Past and current work on direct numerical simulations of shockwave and turbulent physical phenomenon interactions at the Laboratory at Princeton University is given. Direct numerical simulations of compression ramp and reacted shock configurations are mentioned, with explicit stress on the validation of the simulations against experiments at matching flow conditions. The low-frequency motion of the shock system is analyzed. A 'long-time' DNS of a philosopher three physical phenomenon, which can functions a condition for future STBLI simulations, is given. In an attempt to increase the simulations to higher, hypersonic philosopher numbers, the DNS of a philosopher eight physical phenomenon is additionally shortly given.

Numerical solutions of the Navier-Stokes equations are given for the interactions of a wave and a turbulent physical phenomenon. The turbulent closure is provided by a relaxation eddy viscousness model that approximates the response of turbulence to a severe pressure gradient. The eddy viscousness model is verified by work shock impingement on a turbulent physical phenomenon. Computations were performed for shock generators varied from 7.93^0 to 12.17^0, at a free-stream ratio of 2.96 and a painter range of twelve million. Numerical results obtained with Mack Cormack's theme were compared with experimental measurements of the surface pressure distribution and therefore the location of the separation and reattachment points. The density distribution throughout the complete interacting flow field was additionally compared with experimental results obtained from holographic interferograms. All essential options of the experimental observation were duplicated by the numerical computation (Shang et al., 1976).

3. Numerical approach

The governing equations for the fluid domain are the compressible Navier-Stokes equations. The Adaptive Local Deconvolution Method (ALDM) is employed for the discretization of the convective fluxes and provides a physically consistent sub grid-scale turbulence model for implicit LES. Using a shock device to find discontinuities and put on the shock-dissipation mechanism, ALDM will capture shock waves whereas sleek waves and turbulence area unit propagated accurately while not excessive numerical dissipation. The disseminative fluxes are discretized employing a second order central distinction theme, and a third order Runge-Kutta theme is employed for the time integration. The flow convergent thinker operates on mathematician grids for a high parallel performance. The elastic wall boundary is diagrammatical by a cut-element immersed boundary methodology. The structural field is ruled by the weak type of the linear-momentum balance, describing equilibrium of the forces of inertia, internal and external forces. A hyper-elastic Venant-Kirchhoff material model is chosen. The structural field is discretized with the Finite part methodology. The totally separate nonlinear structural system is resolved iteratively by a Newton-Raphson methodology. The tactic of increased assumed strains (EAS) is employed so as to avoid protection phenomena. For time integration, the generalized tetragon rule or one-step-θ theme is utilized. We tend to create use of a classical Dirichlet-Neumann partitioning in conjunction with a traditional Serial Staggered procedure for coupling of the two domains. Our framework inevitably results in a non-matching discretization of the interface between each subdomain. Load transfer is established by an even Mortar methodology, that preserves linear and momentum. So as to resolve the various time-scales of each sub-domain and increase the general efficiency, sub-cycling among the fluid domain is employed.

The chosen sub-cycling time-step is

$$\Delta t_s = 2 \text{ X} 10^{-6} \text{ s},$$

which on the one hand leads to a sampling factor of 2250 with respect to the first structural eigen frequency found in the experiment (f_1 = 222 Hz) and on the other hand guarantees that high-frequency fluctuations associated to the TBL i.e.,

$$f_{TBL} = \frac{\delta_{0.1}}{U_\infty} = 7.5X10^{-6}$$

are still resolved (Hick et al., 2006), (Hick et al., 2014), (Örley et al., 2015), (Pasquariello et al., 2015).

4. Results and discussion

Since no direct activity of the skin-friction is out there for this flow configuration, the incompressible skin friction distribution obtained from the van-Driest II transformation is compared to pure mathematics incompressible relations, numerous DNS and experimental knowledge for a large vary of Mach numbers. The computed incompressible skin friction coefficient is in smart agreement with the DNS results. Now, we offer a comparison between experiment and LES in terms of ram-pressure measured at the stream wise location x = 0.15 m. so as to account for the shock-losses generated by the Pitot rake, the LES pressure is corrected in keeping with the Rayleigh Pitot tube formula wherever Ma denotes the native ratio. The nice agreement between experiment and LES confirms the proper boundary-layer thickness evolution inside the simulation and justifies the belief of a completely TBL. For any validation, the van-Driest reworked mean-velocity profile in conjunction with the RMS of Sir Joshua Reynolds stresses in Morkovin scaling at identical stream wise position x =0.15m are conferred and compared with DNS knowledge for an analogous friction Reynolds range i.e., $Re\tau_{;LES}$ =840, $Re\tau_{;DNS}$ =900. Note that the DNS includes a totally different ratio of Ma_∞ =2.0 and a lower Reynolds range of $Re\tau_{;DNS}$ =55170. The speed profile is in smart agreement with the power law of the wall and therefore the DNS knowledge. Tiny variations within the wake region are attributable to the next Reynolds range within the LES. The Reynolds stresses are in smart agreement with the DNS knowledge within the near-wall region, whereas larger deviations occur within the power and wake region. The spatial extent of the separation is sensitive on the amount of turbulence within the incoming TBL. Thus, before the SWBLI simulations are thought of, a spatially developing TBL simulation while not shock generator has been conducted, that covers the experimental Pitot rake position settled at x =0.15 m.

5. Conclusions

We have studied the interaction of associate oblique shock with a turbulent boundary-layer (TBL) victimization well-resolved large eddy simulation (LES) and experimental information. The flow is deflected by a mobile shock generator at a free-stream Mach number of Ma = 3.0. The painter range upstream of the interaction region is $Re_{\delta 0;I}$ = 205 X 10^3. Two configurations are investigated: the primary one considers a gentle shock generator with a deflection angle of $\theta = 20^0$. The second setup investigates the fluid-structure interaction (FSI) arising from a pitching shock generator, whose incident shock interacts with a versatile panel. The validity of the incoming TBL has been assessed through an on the spot comparison between LES results and information from direct numerical simulation found within the literature. Associate overall smart agreement may well be found in terms of van-Driest reworked mean speed, painter stresses and incompressible skin-friction evolution. Experimental stagnation pressure measurements before the interaction region confirmed the validity of the incoming TBL.

References

1. Anderson, J. D. Jr., 2001, Fundamentals of Aerodynamics (3rd ed.), McGraw-Hill, Science/Engineering/Math, ISBN 0-07-237335-0.
2. Hickel, S., Adams, N. A. and Domaradzki, J. A., 2006, An adaptive local deconvolution method for implicit LES. Journal of Computational Physics, 213:413–436.
3. Hickel, S., Egerer, C. P. and Larsson, J., 2014, Subgrid-scale modeling for implicit large eddy simulation of compressible flows and shock-turbulence interaction. Physics of Fluids, 26:106101.
4. Krehl, Peter O. K., 2011, "Shock wave physics and detonation physics — a stimulus for the emergence of numerous new branches in science and engineering", European Physical Journal H, 36: 85. doi:10.1140/epjh/e2011-10037-x.
5. On Boundary Layers: Laminar, Turbulent and Skin Friction, 2016, AERODYNAMICS, GENERAL AEROSPACE. http://aerospaceengineeringblog.com/boundary-layers/

6. Örley, F., Pasquariello, V., Hickel, S. and Adams, N. A., 2015, Cut-element based immersed boundary method for moving geometries in compressible liquid flows with cavitation. Journal of Computational Physics, 283:1–22.
7. Pasquariello, V., Hammerl, G., Örley, F., Hickel, S., Danowski, C., Popp, A., Wall, W. A. and Adams, N. A., 2015, A cut-cell Finite Volume – Finite Element coupling approach for fluid-structure interaction in compressible flow. Journal of Computational Physics (in review).
8. Pasquariello, V., Hickel, S. and Adams, N. A., 2015, Coupled simulation of shock-wave/turbulent boundary-layer interaction over a flexible panel. http://elib.dlr.de/97850/1/Pasquariello_2015_EUCASS.pdf
9. Priebe, S. and Martin, M. P., 2009, Direct Numerical Simulation of Shockwave and Turbulent Boundary Layer Interactions. http://croccolab.umd.edu/publications/conf-docs/AIAA_2009_0589.pdf
10. Robert, W. F. and McDonald, A. T., 2003, Introduction to Fluid Mechanics Fourth Edition, ISBN 0-471-54852-9.
11. Shock wave, 2017, From Wikipedia, the free encyclopedia. https://en.wikipedia.org/wiki/Shock_wave
12. Settles, G. S. (2006), High-speed Imaging of Shock Wave, Explosions and Gunshots, 94 (1), American Scientist, pp. 22–31.
13. Shang, J. S., Hankey, W. L. Jr. and Law, C., 1976, "Numerical Simulation of Shock Wave - Turbulent Boundary-Layer Interaction", AIAA Journal, Vol. 14, No. 10, pp. 1451-1457.