Workshop on

Shock-Boundary Layer Interaction (SBLI)

CFD research and applications

IIT Bombay, 15th May 2012

Convenor: Prof. Krishnendu Sinha

Preamble

Interaction of shock waves with turbulent boundary layers is important in many aerospace applications. Examples in external aerodynamics include control surfaces, wing body junctions, and multi-body aerodynamics. In high-speed propulsion systems, shock-boundary layer interaction (SBLI) can occur in intakes, supersonic combustion chambers and nozzles. Computational fluid dynamics (CFD) is routinely used to study SBLI flows and predict such interactions in geometries of practical interest.

Simulation of SBLI flows in engineering applications rely mostly on Reynolds-averaged Navier Stokes (RANS) methods. The reliability of the CFD results are primarily determined by the accuracy of the turbulence model used in the computation. Traditional turbulence models, even with compressibility corrections, often fail to predict dominant features in SBLI flows accurately. These include flow separation and reattachment, peak pressure and heat transfer. Several modifications are proposed in literature, but their performance vary from one test case to another.

The interaction of turbulent fluctuations with a shock wave involves complex physical processes. General purpose turbulence models do not account for many of these mechanisms, and therefore lead to inaccurate predictions. For example, most RANS models treat the shock wave as steady and neglect the effect of unsteady shock oscillation in an otherwise steady mean flow. Upstream temperature fluctuations, inherent in a high-speed boundary layer, result in additional physics which is usually not modeled.

Research is underway at IIT Bombay to systematically study different aspects of shock-turbulence interaction and model the underlying physics.[1-3] Most notably, the effect of unsteady shock oscillations has been modeled in a simple and physically consistent way. The new model has been validated against experimental measurements available in literature for a range of Mach numbers and geometric configurations. It has shown good potential in matching the experimental data on separation bubble size, shock structure and wall pressure distribution.[4-6]

Additional aspects of SBLI flows that are of practical relevance are currently under investigation. These include three dimensional effects, numerical implementation issues, and surface heat transfer rates. Such indigenous efforts at developing and validating turbulence models for targeted CFD application can be valuable to the relevant space and defense programmes. Close interaction and feedback between industry and academia can harness the full potential of these developments. The SBLI meeting at IIT Bombay is an effort in this direction.

Objectives

- To identify SBLI configurations of interest to the Indian space and defense programmes.
- To identify SBLI prediction capabilities crucial to specific applications, e.g. flow separation, shock structure and surface heat flux.
- To guide indigenous turbulence model development to address critical industry requirements.

Participants

The attendees from academia included faculty, current and past students of IIT Bombay. From the industry side, there was representation from all the major SBLI related activities in the country. These include scientists from DRDL, ISRO, NAL and ADA. A list of attendees is given in Annexure I.

Technical presentations

The workshop consisted of a series of technical presentations from academia and industry, followed by discussion. The workshop programme is attached. The first set of presentations were from students and faculty of IIT Bombay, which highlighted some of the recent advances and ongoing work in the area of shock boundary layer interaction (SBLI). Prof. Sinha set the stage with an introduction to SBLI challenges and an overview of the research activities spanning almost a decade. The key elements -- flow physics, turbulence modeling, CFD implementation, experimental validation and practical application -- and the connection between them were brought out in the talk.

Subsequently, current and past students of IIT Bombay presented further details of the research work. Russell Quadros described fundamental studies in shock-turbulence interaction to highlight the physics of unsteady shock oscillations in a turbulent flow. The theoretical analysis and its subsequent use to model the damping effect of unsteady shock oscillations was presented. Comparison with DNS data showed good match of the turbulence amplification across a normal shock.[1-3]

The implementation of the shock-unsteadiness modification to standard one- and two-equation turbulence models was described by Dr. Amjad Ali Pasha. The new models were applied to SBLI configurations ranging from supersonic to hypersonic Mach numbers. Significant improvement over existing models was reported in predicting the size of the separation bubble in these SBLI flows. The resulting shock structure and pressure distribution showed good match with experimental data.[4-6]

Ongoing work on three-dimensional effects in SBLI flows was presented by Sarvesh Sundaram. Simulation results for both canonical and practical geometries were described.[7-9] A systematic analysis of the shock structure, flow separation and vortex formation were used to gain insight into the complex three-dimensional flowfield computed in realistic scramjet inlet configurations. Finally, a description of the in-house parallel implicit CFD code was given by Balasridhar. The current capabilities of the code and a representative set of published results from the in-house simulations were also presented.

On the application side, presentations were made by representative from DRDL, ISRO and NAL. Dr. Krishnamoorthy from DRDL Hyderabad gave a talk on their in-house CFD code development and applications. He described simulation of multi-body aerodynamics, like air launch of ASTRA missile and stage-separation in missiles. These flows are characterized by multiple shock waves and their interaction with the boundary layer on the vehicle surface.

Mr. Rajnikant from Project HSTDV at DRDL Hyderabad presented SBLI work and challenges related to their scramjet programme. CFD results showing SBLI during cowl opening process leading to inlet unstart were discussed. He also presented the effect of wall temperature on the computed shock structure and SBLI in the inlet duct resulting in variation in flow properties at combustor entry. The changes in control effectiveness of the rear cowl during engine ON/OFF conditions and multi-body aerodynamics involved in the opening of the panels enclosing the HSTDV cruise vehicle were also highlighted.

Mr. Subramaniam from VSSC, ISRO, presented results from scramjet intake unstart studies and flow visualization inside the inlet duct and combustor. The surface flow pattern between the fuel injection struts clearly show a *Double Fin* crossing-shock boundary layer interaction. Another configuration highlighted in the talk was that of umbilical protrusion on a launch vehicle. The SBLI occurring due to these flow obstructions lead to unsteady pressure loads that are detrimental to the vehicle.

Mr. Sai Ganesan from VSSC, ISRO gave a presentation on the work being carried out in the Air-breathing propulsion project (ABPP) at ISRO. Shock-boundary layer interaction and shock-shear layer interactions occurring in the combustor were highlighted. He also discussed issues related to the upcoming flight test of the scramjet modules.

Dr. Manoj Nair from CTFD Division at NAL gave the final presentation. He described ongoing work on high-order and high-resolution numerical methods for simulating hypersonic SBLI flows. The computational cost and challenges involved in parallelization of these numerical schemes for realistic applications were highlighted.

Discussion

The discussion was initiated by listing down the practical applications highlighted in the presentations by DRDL and ISRO scientists. See Annexure II for details. The SBLI issues relevant to the configurations of interest, and the CFD prediction capabilities desired were also discussed. It was found that predicting shock-induced boundary layer separation is important in a variety of applications. These include deflected control surfaces, protrusion on launch vehicles and scramjet intakes and combustors.

In his talk, Dr. Pasha from IIT Bombay had described the limitation of existing turbulence models like k-epsilon, k-omega and Spalart-Allmaras models in shock-dominated flows. The advantages of the in-house shock-unsteadiness modification in improving the separation bubble predictions were also highlighted. Prof. Sinha presented recent simulations of a practical scramjet intake, where the shock-unsteadiness correction applied to the Spalart-Allmaras model was used to predict the SBLI occurring in the inlet duct. The shock-unsteadiness model parameter was calibrated to existing experimental data for canonical configuration, and the predicted separation bubble size was further validated against available data. The experimental data for a range of SBLI configurations were used, along with established scaling laws, to make the best possible prediction of the separation bubble size.[10]

The above approach was proposed to be extended to other cases of practical interest, where experimental data at matching free-stream and geometric conditions is currently unavailable. It will be beneficial to identify problems of common interest among different research and application groups active across the country. Tailoring turbulence models to match experimental data for a range of conditions that are practically relevant can provide well-validated CFD methodology for industry applications.

Summary and future direction

The presentations made during the one-day SBLI workshop highlighted the need to predict flow separation accurately in a variety of configurations of practical interest. The new physics-based turbulence models, being developed at IIT Bombay, have shown good potential in predicting boundary layer separation in SBLI flows. They are also amenable to simple implementation into existing CFD codes based on one- and two-equation turbulence. The models have been validated against experimental data for canonical SBLI and applied to geometries of practical interest. It is proposed to calibrate the turbulence model parameters to available experimental data relevant to current and future applications. This may require pooling of resources from different groups active in this area.

Relevant publications

1. Sinha, K., Mahesh, K., and Candler, G.V., "Modeling Shock Unsteadiness in Shock/Turbulence Interaction", *Physics of Fluids*, Vol. 15, No. 8, 2003.
2. Veera, V.K. and Sinha, K., "Modeling the Effect of Upstream Temperature Fluctuations in Shock/ Turbulence Interaction," *Physics of Fluids*, Vol.21, No.2, 2009.
3. Sinha, K., "Evolution of Enstrophy in Shock/Homogeneous Turbulence Interaction," *Journal of Fluid Mechanics*, manuscript under review.
4. Sinha, K., Mahesh, K., and Candler, G.V., "Modeling the Effect of Shock Unsteadiness in Shock-wave/ Turbulent Boundary Layer Interactions", AIAA Journal, Vol. 43, No. 3, 2005.
5. Pasha, A.A., and Sinha, K., "Shock-unsteadiness Model Applied to Oblique Shock Wave / Turbulent Boundary-layer Interaction," *International Journal of Computational Fluid Dynamics*, vol. 22, Issue 8, September 2008.
6. Pasha, A.A., and Sinha, K., "Simulation of Hypersonic Shock/Turbulent Boundary-layer Interactions using Shock-Unsteadiness Model," *Journal of Propulsion and Power*, Vol. 28, No. 1, Jan-Feb 2012.
7. Pawar, V., Rane, N., and Sinha, K., "Three-dimensional Shock/Turbulent Boundary Layer Interaction in a Simulated Scramjet Inlet," Fourth Symposium on Applied Aerodynamics and Design of Aerospace Vehicles, Bangalore, India, Dec. 2009.
8. Rane, N., Pawar, V., and Sinha, K., "Effect of Geometric Variations on Three-dimensional Flow Separation in a Practical Scramjet Inlet," 12th Annual AeSI CFD Symposium 2010, Indian Institute of Science, Bangalore, India, Aug. 2010.
9. Sinha, K., Rane, N.J. and Pawar, V., "Numerical Investigation of Three Dimensional Shock/boundary-layer Interaction in a Hypersonic Inlet", 28th International Symposium on shock waves, The University of Manchester, United Kingdom, 17-22 July 2011.
10. Pasha, A.A., Vadivelan, C., and Sinha, K., "Simulation of a Practical Scramjet Inlet using Shock-unsteadiness Model" 28th International Symposium on Shock Waves, The University of Manchester, United Kingdom, 17-22 July 2011.

Annexure I

List of Attendees

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Annexure II

SBLI problems of interest:

Application	**Problem/issues**	**Relevant SBLI characteristics***
Hypersonic intakes	Starting problem	Interaction of multiple shocks with boundary layer in the inlet duct; large separation bubble can be formed; specifically important during cowl opening configurations
Hypersonic intakes	Flow uniformity at intake exit station	Size of separation bubble affects downstream shock structure and the flow quality at intake exit. Wall temperature boundary condition can also alter boundary layer and shock pattern leading to variation in flow uniformity at exit.
Cross-flow injection	Combustion upstream of injection	Shock wave formed due to obstruction of the supersonic cross flow; separation bubble upstream of injection point; trapped fuel can burn in the separation region.
Protrusion on launch vehicles	Unsteady pressure levels; localized high surface heat flux	Shock induced flow separation due to umbilical protrusion; separation bubble formed ahead of protrusion; unsteady pressure levels highest at separation and reattachment points. Enhanced heat transfer rate due to SBLI; peak heating at shear layer reattachment.
Multi-body aerodynamics	Aerodynamic loads & moments	Location and magnitude of peak pressure due to shock impingement and SBLI; separation and reattachment locations; possible shock-shock interaction.
Deflected control surfaces	Control effectiveness for unstable cruise vehicles	Oblique shock generated by deflected control surface can cause flow separation; size of separation bubble and associated surface pressure distribution affect control effectiveness. Engine on/off condition can alter the forces and moments generated by the rear cowl in HSTDV cruise vehicle.
Shock train formed in a scramjet isolator. Consecutive SBLI due to wing, fins, etc.	Boundary layer going through multiple SBLI interactions	Length scale associated with flow separation, reattachment and subsequent recovery of the boundary layer may determine the characteristics of subsequent interactions.
Scramjet combustor	Enhanced mixing due to shock-shear layer interaction	Turbulence amplification across a shock wave; effect of upstream temperature fluctuations.

*Key issues in CFD prediction are underlined.