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Characterizing the Flow Instability in Shockwave and Turbulent Boundary Layer Interactions

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14. ABSTRACT

The effort described here provides accurate in time and three-dimensional space datasets and analyses of attached and separated shock and turbulent boundary layer interactions at Mach numbers 3 to 10. In particular: 1) The scaling of the separation size was found to have a dependence on Reynolds number that prevents the collapse of the data on previously proposed scaling. Our understanding of the low-frequency physics supports the Reynolds number trend and shows promise of a data collapse. 2) The visualization of time- and space- accurate fields show how the induced flow mixing by large, long, streamwise aligned vortex pairs cause the cycle of depletion and replenishment of the separated region at low-frequency. 3) The large-eddy simulation of these flows at high Mach numbers requires models that are not purely dissipative and that can account for the conservative exchange of turbulent energy, i.e. simple eddy viscosity models are not good enough. 4) The STBLI database allows us to study shear layers at highly convective numbers and to provide shear layer statistics at those conditions for the first time. Others significant and relevant accomplishments are detailed for shock and isotropic turbulence interactions.

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Characterizing the Flow Instability in Shockwave and Turbulent Boundary Layer Interactions

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Shockwave and turbulent boundary layer interactions produce intense localized pressure loads and heating rates that can have a dramatic influence on the drag and heating experienced by a high-speed vehicle, and can significantly disrupt fuel mixing and combustion in propulsion systems. The lack of standardized and traceable databases prevents the calibration of computational fluid dynamic models to accurately represent these critical flow phenomena.

The effort described here provides accurate in time and three-dimensional space datasets of shock and turbulent boundary layer interactions at Mach numbers from 3 to 10. Direct numerical and large eddy simulation data was gathered, making the analysis (of the low-frequency unsteadiness, as well as of the mid-frequency that characterize the mixing layer over the separated flow and the range of frequencies of the turbulent flow) possible. Statistical evidence of the upstream and downstream influence in shock unsteadiness in fully separated configuration of boundary layer flow over a compression corner was detailed. We investigated the turbulence structures that are energetically dominant in the separation dynamics of shock-turbulent boundary layer interactions in interactions with supersonic to hypersonic freestream Mach numbers, with varying heat transfer and inviscid pressure jump. We examined the persistence of a separation-length scaling across the flow parameter space. And finally, we demonstrated that the conservative energy exchange that occurs in the highly compressible turbulent flows must be correctly accounted for by subgrid-scale models in large eddy simulations to obtain accurate results in STBLIs. These works have been submitted to the following journals:

1. Helm, C.M., and Martin, M.P., "Separation length scaling for hypersonic shock-separated flows," Under consideration for publication in **Physical Review Fluids**, **2019**.
2. Helm, C.M., and Martin, M.P., "Characterization of the shear layer in separated shock/turbulent boundary layer interactions," Under consideration for publication in **Journal of Fluid Mechanics, 2019**.
3. Priebe, S., and Martin, M.P., "Turbulence in a hypersonic ramp flow," Under consideration for publication in **Physical Review Fluids, 2019**.
4. Helm, C.M., and Martin, M.P., "Large eddy simulations of hypersonic shock-separated flows," in preparation for submission to **Physical Review Fluids, 2019**.

We also visualized the characteristic structure and the low-frequency cycle and mechanism that cause the low-frequency unsteadiness in closed separated STBLI flows.

1. Martín, M.P., Helm, C.M. and González-Kosasky, Sofía, "The Instability of Shock-Induced Separated Flows", Symposium on the Frontiers of Turbulent Flows, Denver, Co. November 2017.
2. Martin, M.P., Priebe, S., and Helm, C.M., "Upstream and Downstream Influence on STBLI Instability", AIAA Paper No. 2016-3344, Washington DC, June 2016.

In addition, this grant served to fund in part other relevant work of shock and turbulence interactions in the context of isotropic turbulence and shockwaves interactions. This work was extraordinarily productive and lead to substantive results. In particular, we have enabled accurate numerical simulations of highly compressible shock and isotropic turbulent interactions with unprecedentedly high turbulent Mach numbers up to 0.69 and up to 15% of turbulent kinetic energy in the dilatational modes. Enabling these calculations requires significant expertise in turbulence and numerical methods that very few people have acquired, if at all. We have formulated a new and simpler derivation of Linear Interaction Analysis (LIA) that is general and allows us to account for solenoidal and (nonzero) dilatational modes consistently. We have formulated a new theory, QIA (Quadratic Interaction Analysis), that allows for the prediction of shock jumps for turbulent and noisy signals, for the first time. With our unprecedented data and analysis, we have been able to understand the physics of the anisotropy in post-shock Reynolds stresses, and we have developed a physics-based model for the anisotropic, which will be significant to RANS. Previously proposed 'universal scaling' (Donzis) for the turbulence amplification across a shock are not universal. The previously proposed scaling (Larson) that the deviation of the mean post-shock flow from the Rankine-Hugoniott jump condition is isentropic is not correct, thus the proposed isentropic scaling for the deviation does not hold. These works have been submitted for publication to the following journals:

1. Grube, N.E., and Martin, M.P., "Mean Shock Jump Relations for Turbulent or Noisy Flows," in preparation for submission to **Nature**, **2019**.
2. Grube, N.E., and Martin, M.P., "Reynolds stress anisotropy in shock and isotropic turbulence interactions," Under consideration for publication in **Journal of Fluid Mechanics**, **2019**.
3. Grube, N.E., and Martin, M.P., "Interactions of highly compressible isotropic turbulence with shock waves," Under consideration for publication in **Journal of Fluid Mechanics**, **2019**.
4. Grube, N.E., and Martin, M.P., "Direct numerical simulations of shock and highly compressible isotropic turbulence," Under consideration for publication in Physics **Review Fluids, 2019**.

The above work builds upon AFOSR previously sponsored research FA9550-090-1-0464, where we accomplished the development and validation against experiments at the same flow and boundary conditions of direct numerical simulations of shock and turbulent boundary layer interactions. We pioneered the development of a unique numerical capability that allows the accurate and detailed three-dimensional turbulence data at a reasonable turn-around time at hypersonic Mach numbers well beyond 6. In turn, parametric studies of fundamental flow physics are feasible, for the first time. By accurate, it is meant that the numerical uncertainty is within the experimental error. By reasonable turn-around time, it is meant that the computational time is comparable to the experimental turn-around-time. The numerical methods, the simulations and their validation against experimental data have been published in the following journal papers:

- Taylor, E.M., Wu, M., and Martín, M.P., "Optimization of Nonlinear Error Sources for Weighted Non-Oscillatory Methods in Direct Numerical Simulations of Compressible Turbulence," *Journal of Computational Physics*, **223**, 384-397, 2007.
- Wu, M., and Martín, M.P., "Direct Numerical Simulation of Shockwave and Turbulent Boundary Layer Interaction induced by a Compression Ramp," *AIAA Journal*, **45**, 4, 879-889, 2007.
- Ringuette, M., Wu, M., and Martín, M.P., "Coherent Structures in DNS of Turbulent Boundary Layers at Mach 3," *Journal of Fluid Mechanics,* **594**, 59-69, 2008

The unsteady motion of STBLI has been analyzed using the DNS data and this work has been published in:

- Wu, M. and Martín, M.P., "Analysis of Shock Motion in STBLI using Direct Numerical Simulation Data," *Journal of Fluid Mechanics,* **594**, 71-83, 2008.

In addition, the data analysis using the DNS of Wu & Martin suggest that low-Reynolds number shock-wave turbulent boundary layer interactions exhibit differences with previous measurements at high Reynolds number. The low Reynolds number effects are due to the greater influence of viscosity, and result in a smaller peak in the RMS of the wall pressure fluctuations, an enriched intermittency of the wall-pressure signal, and a substantially larger separation zone. Unlike previous studies at high Reynolds number, the richer wall-pressure signal of the low-Reynolds number data cannot be used to determine the location of the shock wave. The primary shock wave does not penetrate as deeply into the boundary layer as for the high Reynolds number flows, so it is more accurate to determine the low-Reynolds number shock location in the outer region of the boundary layer. Despite the difference between the low and high Reynolds number data, the low-frequency shock motion (relative to the high-frequency that characterizes the undisturbed boundary layer) reported for high Reynolds number flows, and the turbulence amplification across the interaction region, are not affected by the low Reynolds number condition. These findings have been published in the following journal articles:

- Wu, M., and Martín, M.P., “Direct Numerical Simulation of Shockwave and Turbulent Boundary Layer Interaction induced by a Compression Ramp,” *AIAA Journal*, **45**, 4, 879-889, 2007.
- Ringuette, M.J., Wu, M., and Martín, M.P., “Low Reynolds Number Effects in a Mach 3 Shock Turbulent Boundary Layer interaction,” *AIAA Journal*, **46**, 7, 2008.

Also, as part of this effort, accurate wall-pressure data for Mach 3 interactions at low Reynolds numbers, accessible to DNS and LES, have been gathered and published in the following journal article:

- Ringuette, M.J., Bookey, P., Wychham, C., Smits, A.J., “Experimental Study of a Mach 3 Compression Ramp Interaction at Re_θ = 2400”, *AIAA Journal*, **47**, 2 2009.

For the first time, we provided accurate statistical evidence of the upstream and downstream influence in shock unsteadiness in a fully separated configuration of boundary layer flow over a compression corner at Mach 2.9. The dominant scales in the flow were investigated by spectral analysis, and the statistical link between the low-frequency shock motion and the upstream and downstream flow were investigated. Strong coherence, at the low frequencies of the shock motion, is observed with the downstream, separated flow. The coherence with the upstream, undisturbed boundary layer is shown to be statistically significant, but weak. The findings were reported in

- Priebe, S., and Martin, M.P., “Direct Numerical Simulation of Shockwave and Turbulent Boundary Layer Interactions”, *AIAA Paper 2009-0589, 47th AIAA Aerospace Science Meeting and Exhibit*, Orlando, FL, January 2009.

A direct numerical simulation of a reflected shock and turbulent boundary layer interaction was also characterized using DNS during this period effort and appears in:

- Priebe, S., Wu, M., and Martin, M.P., “Direct Numerical Simulation of a Reflected Shockwave and Turbulent Boundary Layer Interactions”, *AIAA Journal*, **7***, 5, 2009.*

Conclusions

The effort described here provides accurate in time and three-dimensional space datasets and analyses of attached and separated shock and turbulent boundary layer interactions at Mach numbers 3 to 10. In particular: 1) The scaling of the separation size was found to have a dependence on Reynolds number that prevents the collapse of the data on previously proposed scaling. Our understanding of the low-frequency physics supports the Reynolds number trend and shows promise of a data collapse. 2) The visualization of time- and space- accurate fields show how the induced flow mixing by large, long, streamwise aligned vortex pairs cause the cycle of depletion and replenishment of the separated region at low-frequency. 3) The large-eddy simulation of these flows at high Mach numbers requires models that are not purely dissipative and that can account for the conservative exchange of turbulent energy, i.e. simple eddy viscosity models are not good enough. 4) The STBLI database allows us to study shear layers at highly convective numbers and to provide shear layer statistics at those conditions for the first time. Others significant and relevant accomplishments have been achieved for shock and isotropic turbulence interactions.

We are grateful for the support of AFOSR and the supervision by Dr. Ivett Leyva.