Reply by Authors to S.M. Bogdonoff and S. Wang

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WE thank Prof. Bogdonoff and Mr. Wang for their comments on our work,[1] although we disagree with them. We did not use selected test results, but based our conclusions on the data set obtained by F.K. Lu during his Master's thesis research.[2] Subsequent work by Goodwin[3] using fins at larger angles of attack also substantiated our conclusions. If conflicting data have been obtained at Princeton in the interim, we are unaware of them. We are willing to consider conflicting data if any exist.

Bogdonoff and Wang question our assertion that conical flow symmetry exists in the outboard region of swept shock/boundary-layer interactions generated by fins. This assertion is supported not only by our data, but by a number of experimental and computational studies conducted in several countries.[4-10] To our knowledge no form of far-field symmetry other than conical has ever been observed in fin-generated interactions.

The matter of the spanwise growth of incoming boundary-layer thickness is admittedly not completely understood. The preponderance of known experiments has used rectangular flat plates that naturally generate boundary layers which grow in the spanwise direction at the upstream limit of a swept interaction. However, in one experiment,[11] the flat-plate leading edge was intentionally swept back 45 deg in order to check such boundary-layer growth effects. The results showed the surface pressure footprints of 4- and 10-deg fin interactions at Mach 3 to be invariant to leading-edge sweepback of the flat plate. We find this to be a plausible result; the scale of the incoming boundary layer apparently having exerted its influence only in the establishment of the inception zone, according to dimensional arguments.[12]

In further support of conical symmetry, note that the outer inviscid flow is naturally conical. The interaction requires an equilibrium between an outer conical flow and an inner viscous layer. This layer is extremely thin at high Reynolds numbers compared to the dimensions of the fin (as was the case in Ref. 1). Therefore, if the viscous layer refuses to respond to the symmetry of the outer flow, enormous gradients would have to be supported by this thin wall layer. Thus, it seems clear that swept shock/boundary-layer interactions must rapidly adopt the symmetry imposed by the outer flow. The length required for this to occur is the inception length referred to in our paper.[1] This argument has been quantified in an order-of-magnitude analysis by Inger.[13]

As for the inception length itself, our description in Ref. 1 was admittedly preliminary. This was not the primary subject of our work, and at that time no one had studied inception lengths per se. More recent work[12] clarifies this issue. It is clear that the inception zone merges gradually into the outboard region of conical symmetry in all fin interactions we are aware of. As long as a consistent criterion such as that proposed in Ref. 12 is used to choose inception lengths from the shape of the interaction upstream influence line, we believe there is little ambiguity here. We thus maintain that our proposed model of an inception zone followed by a region of conical symmetry stands unaltered.

Bogdonoff and Wang further object to our description of some of the interactions in Ref. 1 as separated flows. In particular, the laser light-sheet photograph shown in Ref. 1 is questioned on the basis that the seeding particles do not flow within the plane of the light sheet. Such is not required by the principle of light-sheet visualization, which is a well-known and powerful tool to visualize and understand three-dimensional flows by taking two-dimensional cuts. In the case in question, the seeding of the flow was, in fact, controlled by allowing the liquid seed material to flow along the separation line on the surface, whence it was dispersed into an aerosol in the free shear layer, as shown in Fig. 2 of Ref. 1. This figure is one of many examples of still photgraphs and videotaped light-sheet visualizations obtained in this family of flows, which (to us) demonstrate clearly the separated nature of the majority of the fin interactions in question.

In a wider sense, the ability of sufficiently strong swept shocks to provoke three-dimensional boundary-layer separation has been demonstrated in a variety of past studies too numerous to quote here. We believe that a controversy over whether or not such separation occurs is no longer useful, if it ever was.

Finally, Bogdonoff and Wang cite flowfield unsteadiness as a further objection to Ref. 1. We fail to see the relevance of this comment to our work, which dealt with the mean flow behavior of fin interactions rather than their fluctuating character. In any case, the fluctuations occurring in swept shock/turbulent boundary-layer interactions do not invalidate the use of a mean flow model such as our conical similarity model. This statement includes consideration of the recent research on unsteadiness cited by Bogdonoff and Wang.

In conclusion, though conical similarity is not an elaborate flow model describing every detail of fin-generated interactions, we believe it remains a viable framework for this family of interactions despite the objections raised by Bogdonoff and Wang. Since they have not proposed an alternate model supported by any known experiments, computations, or analyses, we stand by conical similarity as originally put forth in Ref. 1.

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References

[1]Settles, G.S. and Lu, F.K., "Conical Similarity of Shock/Boundary-Layer Interactions Generated by Swept and Unswept Fins," *AIAA Journal*, Vol. 23, July 1985, pp. 1021-1027.

[2]Lu, F.K., "An Experimental Study of Three-Dimensional Shock Wave/Boundary Layer Interactions Generated by Sharp Fins," M.S. Thesis, Princeton University, Princeton, NJ, Rept. MAE 1584-T, March 1983.

[3]Goodwin, S.P., "An Exploratory Investigation of Sharp Fin-Induced Shock Wave/Turbulent Boundary-Layer Interactions at High Shock Strength," M.S. Thesis, Princeton University, Princeton, NJ, Rept. MAE 1687-T, Nov. 1984.

[4]Zubin, M.A. and Ostapenko, N.A., "Structure of Flow in the Separation Region Resulting from Interaction of a Normal Shock Wave with a Boundary Layer in a Corner," *Izvestiya Akademii Nauk SSSR, Mekhanika Zhidkosti i Gaza*, May-June 1979, pp. 51-58.

[5]Law, C.H., "Three-Dimensional Shock Wave/Turbulent Boundary Layer Interactions at Mach 6," ARL-TR-75-0191, June 1975.

[6]Zheltovodov, A.A., "Properties of Two- and Three-Dimensional Separation Flows at Supersonic Velocities," *Izvestiya Akademii Nauk SSSR, Mekhanika Zhidkosti i Gaza*, May-June 1979, pp. 42-50.

[7]Degrez, G. and Ginoux, J.J., "Surface Phenomena in a Three-Dimensional Skewed Shock Wave/Laminar Boundary Layer Interaction," *AIAA Journal*, Vol. 22, Dec. 1984, pp. 1764-1769.

[8]Dolling, D.S., "Upstream Influence in Conically Symmetric Flow," *AIAA Journal*, Vol. 23, June 1985, pp. 967-969.

[9]Knight, D.D., "A Hybrid Explicit-Implicit Algorithm for the Three-Dimensional Compressible Navier-Stokes Equations," *AIAA Journal*, Vol. 22, Aug. 1984, pp. 1056-1063.

[10]Horstman, C.C., "Computation of Sharp Fin-Induced Shock Wave Turbulent Boundary Layer Interactions," to be published in *AIAA Journal*.

[11]Dolling, D.S., Cosad, C.D., Bogdonoff, S.M., and Vas, I.E., "A Three-Dimensional Study of Fin-Induced Shock Wave Turbulent Boundary Layer Interaction," Interim Technical Report on U.S. Army Research Office Grant DAAG29-76-G-0269, Gas Dynamics Laboratory, Princeton University, Princeton, NJ, July 1977.

[12]Settles, G.S., "On the Inception Lengths of Swept Shock Wave/Turbulent Boundary-Layer Interaction," Presented at the IUTAM Symposium on Turbulent Shear-Layer/Shock Wave Interactions, Palaiseua, France, Paper No. 4.3, Sept. 1985.

[13]Inger, G.R., "Spanwise Propagation of Upstream Influence in Conical Swept Shock/Boundary Layer Interactions," submitted for publication in *AIAA Journal*.