Readers' Forum

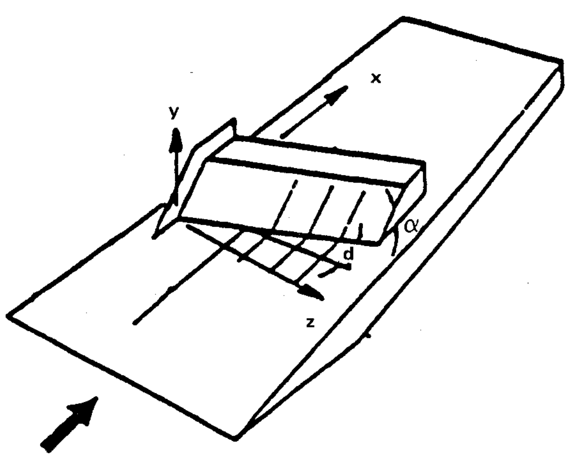
Brief discussion of previous investigations in the aerospace sciences and technical comments on papers published in the AIAA Journal *are presented in this special department. Entries must be restricted to a maximum of 1000 words, or the equivalent of one* Journal *page including formulas and figures. A discussion will be published as quickly as possible after receipt of the manuscript. Neither the AIAA nor its editors are responsible for the opinions expressed by the correspondents. Authors will be invited to reply promptly.*

Comment on "Critique of Turbulence Models for Shock-Induced Flow Separation"

Ching-Mao Hung*
NASA Ames Research Center,
Moffett Field, California

ERICSSON[1] suggests that the poor agreeement between Navier-Stokes computations and the experiment in Ref. 2, as shown in Fig. 1 (reproduced from Fig. 1 of Ref. 1), is caused by the computations not predicting the existence of a secondary separation. Contrary to this, I believe that the poor agreeement is caused by the computations not predicting the correct strength of the primary separation (vortex), as pointed out and discussed in Ref. 3. A weak secondary seapration may still occur near the corner, but would not carry (or entrain) enough momentum to cause a pressure peak of that magnitude between the two low pressure regions. Furthermore, the concept of attachment leading to a high pressure cannot explain the pressure decrease after the first pressure rise. A strong primary vortex adjacent to two walls will produce two low-pressure regions with a peak in between. These low-pressure (high-velocity) regions under the core of a vortex are phenomena typical of an "image or so-called ground effect" of the vortex near the walls. (The flow may be viscous, but the dominant mechanism is inviscid.)

The experimental pressure distribution shown in Fig. 1 is similar to the surface pressure along the line of symmetry for supersonic flow over a blunt fin (Fig. 2). The origin of s is set at the fin-plate juncture; negative s is on the flat plate and pos-



Case No.	Turb model	Leading edge	x_u/δ_∞	M_∞	δ_∞ (cm)	$Re_{\delta\infty}$	Total pressure (kPa)	Total temp. (deg K)
1	B-L	Straight	n/a	2.95	0.22	1.4×10^5	689	266
2	B-L	Straight	n/a	2.95	0.22	1.4×10^5	689	266
3	B-L	Swept	26.2	2.95	0.39	2.3×10^5	689	275
4	J-L	Swept	40.4	2.95	0.39	2.3×10^5	689	275
5	J-L	Swept	40.3	2.95	0.39	2.3×10^5	689	275

B-L Baldwin-Lomax; J-L Jones-Launder; n/a not applicable

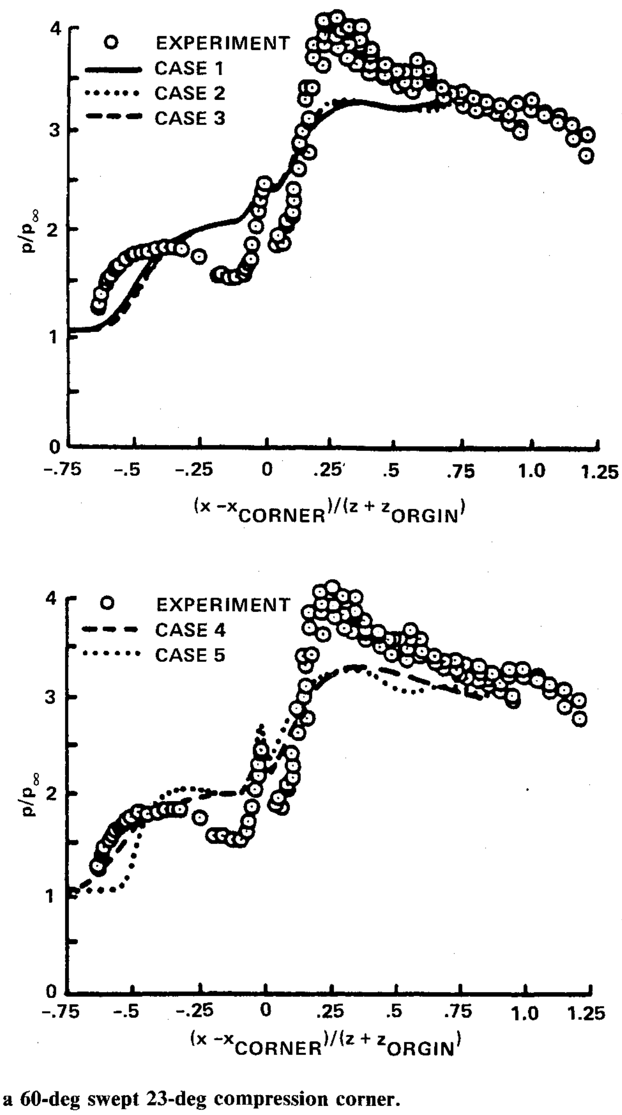


Fig. 1 Supersonic turbulent flow at Mach 3 past a 60-deg swept 23-deg compression corner.

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*Research Scientist, Computational Fluid Dynamics Branch. Associate Fellow AIAA.

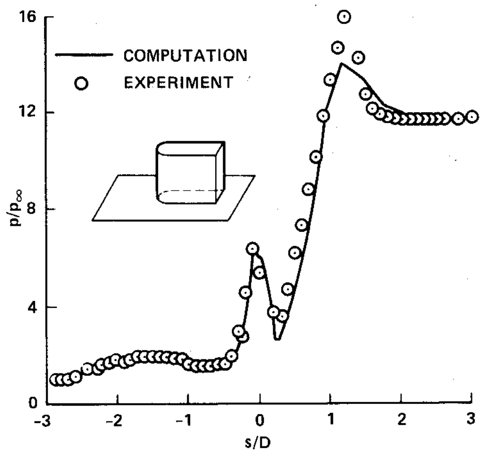

Fig. 2 Supersonic turbulent flow at Mach 3 past a blunt fin on a plate ($\delta/D = 1.0$).

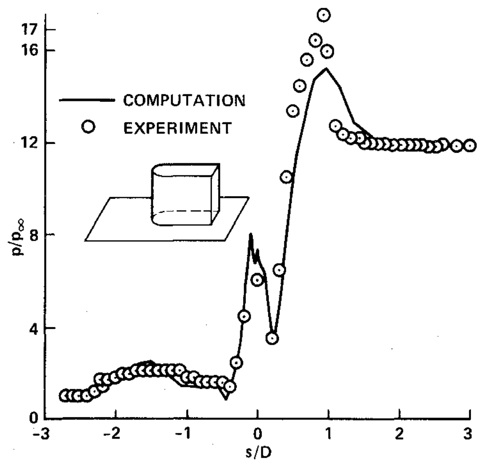

Fig. 4 Supersonic turbulent flow at Mach 3 past a blunt fin on a plate ($\delta/D = 0.26$).

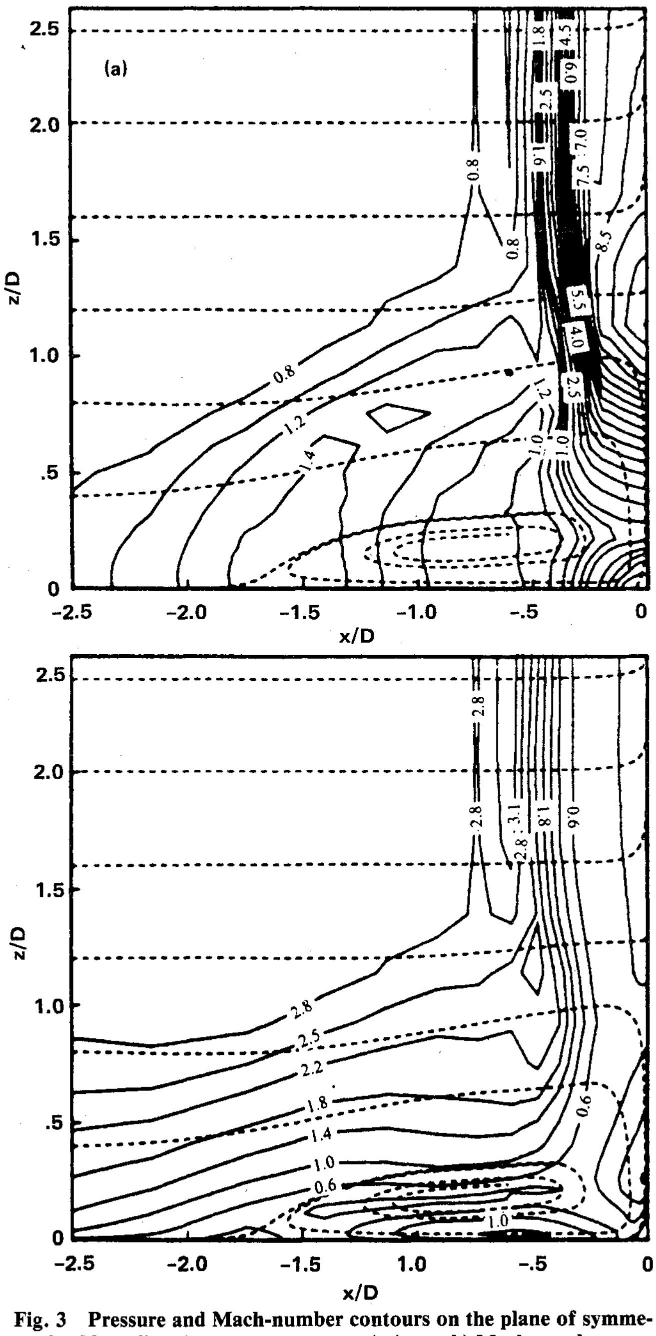

Fig. 3 Pressure and Mach-number contours on the plane of symmetry for blunt fin: a) pressure contours ($p/\gamma p_\infty$; b) Mach-number contours.

itive s is along the fin leading edge. Actually, Fig. 2 is a replot of Figs. 5a and 7a of Ref. 4, for the case of a thick incoming boundary layer, $\delta/D = 1.0$. In Fig. 2, the agreement between computations and experimental data of Ref. 5 is very good. The underprediction of the last peak pressure, around $s/D = 1.2$, in the computation is due to a coarse grid resolution in the direction along the fin leading edge. The controlling mechanism for the pressure distribution here is the shock-induced flow separation with its resulting horseshoe vortex ahead of the blunt fin, to be discussed later. Since the features depicted in the experiment results for the swept corner (Fig. 1) all appear for the blunt-fin case (Fig. 2), the controlling mechanism for the swept corner is similar to that for the horseshoe vortex ahead of the blunt fin.

To explain the role of the flow separation and horseshoe vortex, pressure and Mach number contours in the plane of symmetry are shown in Figs. 3a and 3b with particle paths superimposed. The fin bow shock induces the incoming boundary layer to separate from the plate, resulting in a horseshoe vortex ahead of the blunt fin. The horseshoe vortex, which is the primary vortex for the blunt-fin case, brings an abundance of fresh high-momentum fluid into the separation region. As the high-momentum fluid accelerates due to the ground effect, it results in two high-speed low-pressure regions, one on the fin, with Mach number as high as 1.2, and the other on the plate, with Mach number up to 1.4. The first pressure rise around $s/D = -1.5$ is caused by the flow separation. The two low-pressure regions separated by a spike are due to ground effects on the plate and the fin of the primary vortex, as previously discussed. The last pressure peak, $s/D = 1.2$, is caused by the attachment of flow through multiple compression. These observations were discussed in Ref. 4.

Note that there does exist a weak secondary separation near the corner for the blunt-fin case.[4] However, all of the previously discussed features have almost nothing to do with the secondary vortex. When the strength of the secondary vortex increases, the shape of the pressure spike will change. This is demonstrated in Fig. 4 where the pressure distribution along the line of symmetry for the case of a thinner incoming boundary-layer, $\delta/d = 0.26$, is shown. Figure 4 is a replot from Figs. 12 and 13a of Ref. 4. The results of the computations show that, due to the additional ground effect generated by the secondary vortex, the pressure spike splits into two. Similarly, the ground effect of a vortex causing low pressure can also explain the flowfield features observed in flows about delta wings,[6] in flows over a cone at high angles of attack,[7] and in flows over sharp and blunt fins.[8]

I agree with Ericsson that turbulence models for shock-induced flow separation are very important. A similar turbulence model, the Baldwin-Lomax model, was used in Ref. 4

and cases 1–3 in Ref. 2. One can speculate that for the case of supersonic flow over a blunt fin,[4] at least in the region ahead of the blunt fin, the flow is strongly dominated by the geometry and other inviscid mechanisms. The strength of the primary vortex was closely predicted; hence so were the main features. For the case of supersonic flow over a swept corner,[2] the mechanism for generating the primary vortex was probably not correctly simulated; hence so were not the strength of the vortex and its associated features.

References

[1]Ericsson, L. E., "Critque of Turbulence Models for Shock-Induced Flow Separation," *AIAA Journal*, Vol. 27, No. 11, 1989, pp. 1648–1650.

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[3]Hung, C. M., "Computation of Three-Dimensional Shock Wave and Boundary-Layer Interactions," NASA TM 86780, Aug. 1985.

[4]Hung, C. M., and Buning, P. G., "Simulation of Blunt-Fin-Induced Shock-Wave and Turbulent Boundary-Layer Interaction," *Journal of Fluid Mechanics*, Vol. 154, 1985, pp. 163–185.

[5]Dolling, D. S., and Bodgonoff, S. M., "Blunt Fin-Induced Shock Wave/Turbulent Boundary Interaction," *AIAA Journal*, Vol. 20, No. 12, 1982, pp. 1674–1680.

[6]Ganzer, U., and Szodruch, J., "Vortex Formation over Delta, Double-Delta and Wave Rider Configurations at Supersonic Speeds," AGARD-CD-428, Nov. 1987.

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[8]Fomison, N. R., and Stollery, J. L., "The Effects of Sweep and Bluntness of Glancing Shock Wave Turbulent Boundary Layer Interaction," AGARD-CP-428, Nov. 1987.

Reply by Author to C.-M. Hung

L. E. Ericsson*

Lockheed Missiles & Space Company, Inc., Sunnyvale, California 94089

THE claim made by Hung[1] that the separated flow phenomenon on a highly swept wedge, discussed in Ref. 2, is similar to that for a blunt fin at zero sweep, analyzed by him,[3] is based solely on the similarity in the measured pressure distributions (compare Figs. 1 and 2 of Ref. 1). This is where the similarity ends. It is well-documented that the separated flow structures are very different, as different at least as those for blunted and sharp fins.[4] Thus, it is true that the dominant mechanism is inviscid for the blunt fin in Ref. 1, as demonstrated by the insignificant effect of a factor of four difference in the thickness of the approaching turbulent boundary layer (compare Figs. 2 and 4 in Ref. 1). This contrasts sharply with the large effect of Reynolds number exhibited by the experimental swept-wedge pressure distributions (compare Fig. 1 of Ref. 1 with the following Fig. 1).

Another demonstration of the fact that the separated flow structures causing apparently similar separated flow effects (Figs. 1 and 2 of Ref. 1) are very different, is the large effect of sweep angle in the case of the swept wedge.[5,6] When the sweep was decreased from 60 to 40 deg, the large effect of Reynolds number on the correlation between predicted and experimental pressure distributions essentially disappeared (compare Fig. 1 of Ref. 1 with the following Fig. 2). It is suggested in Ref. 2 that, as in the case of delta wings, the sweep has to be increased beyond 50 deg before a strong vortical structure develops which contains a secondary vortex of significant size and strength, as in the low Reynolds number case shown in Fig. 1 of Ref. 1.

Hung's colleague, Horstman, found that his Navier-Stokes calculations could detect a secondary seapration in the case of a highly swept sharp fin, provided the grid was refined enough.[7] However, the secondary vortex structure was of insignificant size and could not explain the upstream influence observed experimentally, and "the reasons for this discrepancy remain a mystery." In his plans to solve this mystery through improving the computational method, Horstman does not discuss any efforts to improve the prediction of the primary vortex structure, which Hung thought "was probably not cor-

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*Senior Counseling Engineer. Fellow AIAA.

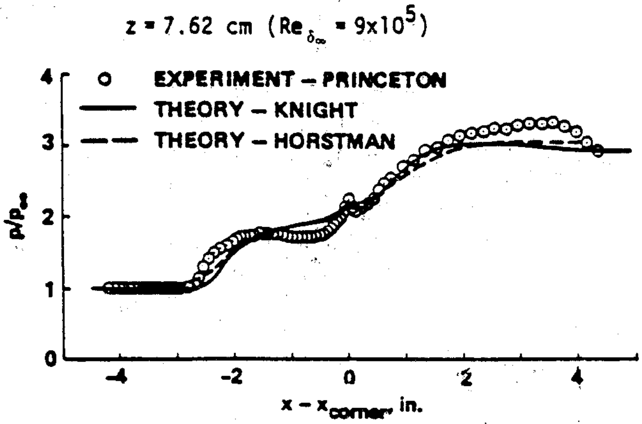

Fig. 1 Pressure distribution for the 60-deg swept 23-deg compression corner at $M_\infty = 3$ and high Reynolds number.[5]

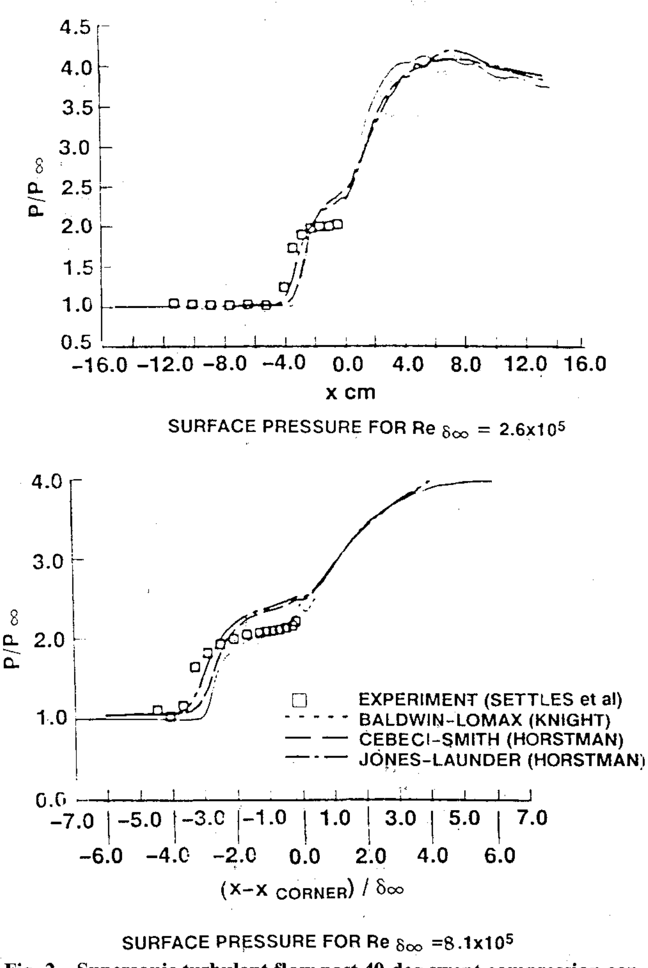

Fig. 2 Supersonic turbulent flow past 40-deg swept compression corner at $M_\infty = 3$.[6]