[7]Ericsson, L. E. and Reding, J. P., "Scaling Problems in Dynamic Tests of Aircraft-Like Configurations," AGARD Symposium on Unsteady Aerodynamics, Ottawa, Canada, Sept. 26-28, 1977, Paper 25, AGARD CP-227.

[8]Ericsson, L. E. and Reding, J. P., "Reynolds Number Criticality in Dynamic Tests," AIAA Paper 78-166, AIAA 16th Aerospace Sciences Meeting, Huntsville, Ala., Jan. 1978.

[9]Reding, J. P. and Ericsson, L. E., "Review of Delta Wing Space Shuttle Vehicle Dynamics," *Proceedings Space Shuttle Aerothermodynamics Conference*, NASA Ames RC, Moffett Field, Calif., Dec. 15-16, 1971, Vol. III, pp. 861-931 (NASA TMX-2508).

[10]Reding, J. P. and Ericsson, L. E., "Effects of Delta Wing Separation on Shuttle Dynamics," *Journal of Spacecraft and Rockets*, Vol. 10, July 1973, pp. 421-428.

[11]Reding, J. P. and Ericsson, L. E., "Unsteady Aerodynamic Analysis of Space Shuttle Vehicles, Part IV: Effect of Control Deflections on Orbiter Unsteady Aerodynamics," NASA CR-120125, Aug. 1973.

Reply by Author to L.E. Ericsson and J.P. Reding

H. Ikawa*
Rockwell International, Downey, Calif.

ERICSSON and Reding[1] commented that application of the quasi-three-dimensional methodology (QTDM) to predict the control surface effectiveness[2] without considering three-dimensional effects is a disservice to vehicle designers. It appeared that Ericsson and Reding drew these conclusions without careful examination of the paper[2] and the comparison data. The author was well aware of the importance of the three-dimensional separated flow phenomena generated by surface deflections prior to undertaking this task. However, sound engineering judgement was exercised to determine that a quasi-three-dimensional approach is valid for the Space Shuttle Orbiter (SSO) control surface effectiveness analysis when the flap/elevon is deflected into the windward flowstream.

The paper[2] did not claim that the QTDM is universally applicable to any re-entry vehicle control surface analysis. On the contrary, the application of the strip theory is limited to "hypersonic winged vehicles" as described in the paper. Furthermore, it stated that "the effects of flow spillage and cross flow components normally associated with three-dimensional viscous interaction problems are *minimized* (did not imply nonexistent) by the deflected surfaces having *unswept hinge lines*." The flow spillage due to flap end effects is minimized when the aspect ratio of elevon/flap is large. The application of this QTDM subsequently showed that the effects of the three-dimensional flow phenomena can be approximately simulated for the SSO configuration.

Based on the aforementioned assumptions, the conclusion drawn by Ericsson and Reding based on application of the present methodology to axisymmetric data[3] (cylinder-frustum configuration of Apollo/Saturn) and the older Shuttle vehicle having control surfaces with a highly swept-back hinge line[4] are unjustified. In these configurations, strong three-dimensional flow exists and the contribution arising from the crossflow component of the interacting flowfield cannot be neglected as stated by Ericsson and Reding.

The current SSO configuration consists of a flat wing lower surface, and large-aspect-ratio elevon and flap (4.5 and 2.2, respectively) with unswept hinge lines. Therefore, three-dimensional flow separation effects are minimized, meeting the aforementioned criteria.

Ericsson and Reding also discounted the effectiveness of the QTDM by quoting the experimental results of delta wings with unswept hinge lines obtained by Whitehead and Keyes. Laminar-turbulent transitional flow (mixed)[5] separation data were used to construct their argument. However, Ericsson and Reding must be well aware of the fact that the mixed separated flow phenomena cannot be predicted by either two- or three-dimensional theory unless proper turbulent transitional criteria are incorporated. For fully developed turbulent flow separation, Whitehead and Keyes stated: "For the spanwise stations on the flap of 70 degrees swept wing data, the centerline pressure is lowest and the pressure increases as the distance from the centerline increases. This behavior is just the reverse of that shown for the pressure distribution on the flap of the mixed flow separation case." The predicted spanwise pressure distribution for the reattachment region of laminar flow separation on the SSO elevon follows precisely the same qualitative three-dimensional trend observed in the turbulent experiment[5] (see Fig. 7 and discussion of Spanwise Distribution of Peak and Plateau Pressures, Ref. 2). This is to be expected since the observed phenomena in which separation length increases with Reynolds number follows the same trend for both laminar and turbulent flow separations.[5] Therefore, this observation gives credence to the QTDM for predicting the SSO control surface effectiveness, provided the viscous interaction does not occur in the laminar turbulent transitional regime and the criteria for the applicability of the present QTDM are not violated.

It should be noted that the criticism is centered on the fact that the four test data points shown on the $\alpha = 40$ deg data (Fig. 8 of Ref. 2) did not agree with the prediction. This apparent discrepancy was allegedly credited to the flow spillage at the wingtip, where in fact the observed disagreement is due to wall cooling effects. The predicted values were omitted in Fig. 8 for clarity, as discussed later. As a result of this misunderstanding, the overall merit of the QTDM is discredited by Ericsson and Reding.

Although Ericsson and Reding have qualitatively interpreted the correctness of the separated flow phenomena, they are unable to predict the exact separation and reattachment points of their arguments. Ericsson and Reding failed to recognize that the separation-reattachment points and pressure recovery are influenced by many factors other than the three-dimensional nature of separated flows, e.g., Reynolds number, Mach number, finite flap chord length, wall cooling, etc. The rigorous arguments which led to the results of Fig. 1 of Ref. 1 is simply demonstrated in Figs. 11 and 12 of Ref. 2 for the different reasons.

Due to the page limitation imposed on the paper a detailed discussion of the experimental data (Fig. 8, Ref. 2) was omitted, leading to Ericsson and Reding's misinterpretation of the results. The experimental data shown in Fig. 8 of Ref. 2 were obtained from the two experimental sources. The data points shown in open triangle and square symbols were obtained from AEDC wind tunnel tests, in which the model was heated to produce an adiabatic wall test condition ($S_w = 0$). Hence, the agreement of test and predicted data made with $S_w = 0$ is good. The open circle data points were gathered from the short-duration test conducted at CALSPAN which produced nonadiabatic wall test conditions ($S_w = -.8$). These short-duration tests were subjected to model vibration, which may account for the data scatter. The separated zone is reduced by wall cooling and control becomes more effective as compared with the adiabatic case shown in Fig. 12 of Ref. 2. Figure 2 shown by Ericsson and Reding[1] is a reproduction of the $\alpha = 40$ deg data, Fig. 9 of Ref. 2 with four data points taken from Fig. 8 of Ref. 2. However, Ericsson and Reding failed to include the predicted nonadiabatic data points ($S_w = -.8$ data also shown in black circle symbols which were

Received Feb. 13, 1978.

Index categories: Supersonic and Hypersonic Flow; Jets, Wakes, and Viscid-Inviscid Flow Interactions.

*Member of the Technical Staff. Member AIAA.

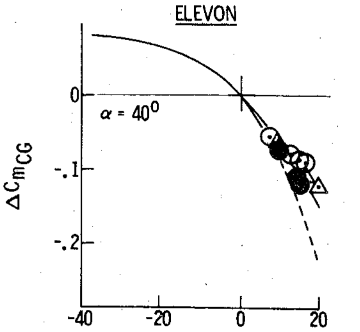

Fig. 1 Shuttle orbiter incremental pitching moment comparison.

predicted by the QTDM) in their comparison. If these predicted data points are incorporated in Fig. 2 of Ref. 1, the data agreement of the test and prediction will be significantly improved (Fig. 1 of this paper). The influence of wall cooling effects on the flow separation mechanism, for high-aspect-ratio unswept elevon configurations, is substantially greater than that due to flow spillage effects. Significant qualitative and quantitative improvements in the prediction was achieved by inclusion of wall cooling in the analysis, supporting the aforementioned contention.

Conclusion

The validity of the quasi-three-dimensional methodology is substantiated by Whitehead and Keyes experiments[5] and by the SSO wind tunnel test data when they are properly interpreted. It is well known that inviscid flow produces the most effective control surfaces predictions. Under these conditions, the control effectiveness can be easily predicted by any junior engineer with knowledge of compressible gasdynamics. The control surface becomes most ineffective when laminar viscous interaction produces flow separation. Prediction are most difficult under this condition and its uncertainty is of primary concern to designers. Therefore, both extreme points must be known during vehicle design to avoid embarrasing situations which may arise during flight.

Predictions of unsteady control hysteresis effects, leeside flow separation phenomena, and the OMS pod's flow interference effects, which may produce control problems, are not in the context of the present study. These phenomena are important enough to warrant separate investigations.

References

[1] Ericsson, L. E. and Reding, J. P., "Comment on a Re-Entry Control Effectiveness Methodology for the Space Shuttle Orbiter," *Journal of Spacecraft and Rockets*, Vol. 15, May-June 1978, pp.

[2] Ikawa, H., "A Re-Entry Control Effectiveness Methodology for the Space Shuttle Orbiter," *Journal of Spacecraft and Rockets*, Vol. 14, Nov. 1977, pp. 669-675.

[3] Reding, H. P., Guenther, R. A., and Ericsson, L. E., "Nonexistence of Axisymmetric Separated Flow," *AIAA Journal*, Vol. 7, July 1969, pp. 1374-1375.

[4] Marvin, J. G., Seegmiller, H. G., Lockman, W. K., Matear, G. G., Pappas, C. C., and DeRose, C. E., "Surface Flow Patterns and Aerodynamic Heating on Space Shuttle Vehicles," *Journal of Spacecraft and Rockets*, Vol. 9, Aug. 1972, pp. 573-579.

[5] Whitehead, A. H. Jr. and Keyes, J. W., "Flow Phenomena and Separation Over Delta Wings with Trailing Edge Flaps at Mach 6," *AIAA Journal*, Vol. 6, Dec. 1968, pp. 2380-2387.