the method so that it is applicable for a very broad class of configurations.[7,8] This method is accurate, inexpensive, simple, and insensitive to paneling considerations.

In this context, it is difficult to understand the utility of the filament formulation. Rusak et al. indicate that roughly 170 "vortex panels" are required to solve the subject (nonlinear) problem for one angle of attack with the noted numerical sensitivities. Accurate results for a comparable case with the vortex-lattice/suction-analogy method require roughly 60 panels to solve the complete problem (which is now linear) for an entire angle-of-attack range; this solution includes the nonlinear vortex lift effects without requiring the free vortex to be explicitly modeled.

The authors also point out in Ref. 1 that local solution details, such as load distributions, have a strong dependence on numerical modeling even when the overall force/moment coefficients converge to the same value. In general, other filament methods[9,10] have also yielded less than satisfactory estimates of surface load distributions, in spite of continuing development efforts beyond the cited literature. As was recently pointed out by Hoeijmakers,[11] estimation of surface load distributions apparently requires higher order formulations, examples of which include the free vortex sheet method[12] or the NLR VORSEP method.[13]

Therefore, the filament formulation seems to be caught in an unfortunate state for wing applications; it is unduly complicated and too numerically sensitive to yield reasonable estimates of force/moment properties and is also insufficiently accurate to yield reasonable estimates of detailed load distributions. These limitations have persisted despite extensive development efforts by a variety of qualified researchers. Perhaps, future efforts could be more profitably focused at finding other problems for which the free-filament technology could more suitably be applied.

References

[1]Rusak, Z., Seginer, A., and Wasserstrom, E., "Convergence Characteristics of a Vortex-Lattice Method for Nonlinear Configuration Aerodynamics," *Journal of Aircraft,* Vol. 22, Sept. 1985, pp. 743-749.

[2]Wentz, W. H. Jr., "Effect of Leading Edge Camber on Low-Speed Characteristics of Slender Delta Wings," NASA CR-2002, Oct. 1972.

[3]Polhamus, E. C., "Predictions of Vortex-Lift Characteristics by a Leading-Edge Suction Analogy," *Journal of Aircraft,* Vol. 8, April 1971, pp. 193-199.

[4]Wentz, W. H. Jr. and Kohlman, D. L., "Wind Tunnel Investigations of Vortex Breakdown on Slender Sharp-Edged Delta Wings," NASA CR-98737, Nov. 1968.

[5]Polhamus, E. C., "A Concept of the Vortex Lift of Sharp-Edge Delta Wings Based on a Leading-Edge Suction Analogy," NASA TN D-3767, Dec. 1966.

[6]Lamar, J. E. and Gloss, B. B., "Subsonic Aerodynamic Characteristics of Interacting Lifting Sufaces with Separated Flow Around Sharp Edges Predicted by a Vortex-Lattice Method," NASA TN D-7921, Sept. 1975.

[7]Lamar, J. E. and Luckring, J. M., "Recent Theoretical Developments and Experimental Studies Pertinent to Vortex Flow Aerodynamics—With a View Towards. Design," *High Angle of Attack Aerodynamics,* AGARD CP-247, Paper 24, Jan. 1979.

[8]Lamar, J. E. and Campbell, J. F., "Recent Studies at NASA-Langley of Vortical Flows Interacting with Neighboring Surfaces," *Aerodynamics of Vortical Type Flows in Three Dimensions,* AGARD CP-342, Paper 10, July 1983.

[9]Mook, D. T. and Maddox, S. A., "Extension to a Vortex-Lattice Method to Include the Effects of Leading-edge Separation" *Journal of Aircraft,* Vol. 11, Feb. 1974, pp. 127-128.

[10]Kandil, O. A., Mook, D. T., and Nayfeh, A. H., "Nonlinear Prediction of the Aerodynamic Loads of Lifting Surfaces," AIAA Paper 74-503, June 1974.

[11]Hoeijmakers, H. W. M., "Computation Vortex Flow Aerodynamics," *Aerodynamics of Vortical Type Flows in Three Dimensions,* AGARD CP-342, Paper 18, July 1983.

[12]Johnson, F. T., Lu, P., Tinoco, E. N., and Epton, M. A., "An Improved Panel Method for the Solution of Three-Dimensional Leading-Edge Vortex Flows. Volume 1.—Theory Document," NASA CR-3278, July 1980.

[13]Hoeijmakers, H. W. M., and Bennekers, B., "A Computational Model for the Calculation of the Flow about Wings with Leading-Edge Vortex Separation," *High Angle of Attack Aerodynamics,* AGARD CP-247, Jan. 1979.

Reply by Authors to J.M. Luckring

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THE authors of the subject paper[1] published an earlier paper[2] that described a combination of a so-called nonlinear vortex-lattice method (incorporating free vortex filaments to represent the leading-edge vortex separation), modeling all the lifting surfaces, and a linear source-panel method to represent the body. This method was shown to be a powerful tool for the evaluation of the nonlinear aerodynamic characteristics of complete aircraft and missile configurations that incorporate combinations of bodies and several lifting surfaces. Interactions of the bodies with the various lifting surfaces as well as the mutual interactions between the lifting surfaces themselves (canard-wing, wing-wing, wing-tail, etc.) and between their separated wakes were calculated with this method.

Working with their method, the authors have come across several of its numerical sensitivities and shortcomings and thought it was their duty to potential users to document them. This was done in Ref. 1. Luckring's Comment addresses two of these shortcomings and questions the utility of the whole formulation of the method.

One of the shortcomings documented in Ref. 1 and commented on by Luckring is the sensitivity of the lift coefficient to the ratio of the length scale of the wake vortices (Δx_W) to that of the wing vortices (Δx_p). In a later paper,[3] the authors demonstrated that this sensitivity was an inherent feature of the numerical formulation of the method. In Ref. 1 an approximate formula for the choice of the "best" value of the ratio ($\Delta x_W/\Delta x_p$) was also proposed for a delta wing of a given aspect ratio that would closely predict the experimental results for the same wing. In his Comment, Luckring correctly points out that this formula is nothing more than a narrowly applicable curve fit. It was proposed by the authors not as a major achievement but rather as an afterthought, to aid the future user of the method. There is, however, little doubt that for a fixed length-scale ratio the relation between the predicted lift coefficient and the experimentally determined value depends on the aspect ratio of the wing. For low aspect-ratio delta wings, the method tends to underpredict the lift coefficient and a high length-scale ratio seems to be best. For higher aspect-ratio delta wings, the method tends to overpredict the lift and a low length-scale ratio performs better. This is true also for angles of attack and aspect ratios other than those presented in Ref. 1.

From Luckring's second point, one has to conclude that the authors did not make their point sufficiently clear. Certainly a

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wing with full leading-edge separation can only support a normal force. If the normal force coefficient in this case is C_N, then the lift coefficient must be $C_L = C_N \cos\alpha$ and the induced drag coefficient $C_{Di} = C_N \sin\alpha$; therefore, $C_{Di} = C_L \tan\alpha$. However, as Hunt[4] already pointed out, the modeling of a lifting surface by a discretized vortex lattice permits "leaks" through the surface, so the flow parallels the surface at the collocation points only. The flow over the bound vortices themselves (where the lift and induced drag were computed) does not parallel the surface. The induced drag must, therefore, differ from $C_L \tan\alpha$ even in the converged solution. Luckring erroneously attributed this result to lack of convergence. The result is fully converged, as can be seen in Fig. 1 of his Comment, but C_{Di} can never converge (in this method) to $C_L \tan\alpha$. Reference 1 points this out as a shortcoming of the method, suggesting the use of $C_L \tan\alpha$ as a better approximation.

Finally, Luckring's questioning the general utility of the free vortex filament formulation is completely out of place. Luckring is certainly right when he says that for wing applications the linear vortex-lattice method coupled with Polhamus' leading-edge suction analogy (his Ref. 6) is faster, simpler, and less expensive. This method is, however, applicable to wings only, accounting for leading-edge and trailing-edge separation. It was extended, with great difficulties, to wings with strakes (Luckring's Refs. 7 and 8), but it still cannot handle interactions between separate lifting surfaces (canard-wing, wing-tail, etc.) and between bodies and wings. Even the simple problem of a single vortex filament (such as a tip vortex or one filament out of the trailing-edge vortices of a leading wing or of a canard) passing close above another trailing wing is insurmountable for this method. However, the filament formulation of Ref. 2, which is criticized by Luckring, was developed for just such cases, which it handles with great success. Even the higher order formulations cited by Luckring (his Refs. 12 and 13) are still unable to cope with the complex problems that were solved in Ref. 2.

The authors wish to emphasize again that their free vortex filament formulation was developed for the prediction of the overall nonlinear aerodynamic coefficients of complete vehicle configurations. The surface load distributions, although "less than satisfactory" and not accurate, were more than what the vortex-lattice/leading-edge suction analogy could do. (It cannot estimate the surface load distribution even for a wing, and for a complex configuration it cannot estimate even the integral coefficients.) The higher order formulations can do better for the surface load distribution but are limited to simpler configurations.

In conclusion, the free vortex filament formulation of Refs. 1 and 2 is currently the only method that can predict the nonlinear aerodynamic coefficients of complete complex configurations. The authors are now in the process of developing a new idea that seems to promise also a correct or, at least, a better estimate of the surface load distributions over such configurations.

References

[1]Rusak, Z., Seginer, A., and Wasserstrom, E., "Convergence Characteristics of a Vortex-Lattice Method for Nonlinear Configuration Aerodynamics," *Journal of Aircraft,* Vol. 22, Sept. 1985, pp. 743-749.

[2]Rusak, Z., Wasserstrom, E., and Seginer, A., "Numerical Calculations of Nonlinear Aerodynamics of Wing-Body Configurations," *AIAA Journal,* Vol. 21, July 1983, pp. 929-936.

[3]Rusak, Z. and Seginer, A., "An Analytical Parametric Investigation of Numerical Nonlinear Vortex-Lattice Methods," *Proceedings 27th Israel Annual Conference on Aviation and Astronautics,* Tel-Aviv and Haifa, Israel, Feb. 1985, pp. 13-22.

[4]Hunt, B., "The Mathematical Basis and Numerical Principles of the Boundary Integral Method for Incompressible Potential Flow over 3-D Aerodynamic Configurations," *Numerical Methods in Applied Fluid Dynamics,* Academic Press, London, 1980, pp. 49-135.

ERRATA

•"Is Any Free Flight/Wind Tunnel Equivalence Concept Valid for Unsteady Viscous Flow?," Vol. 22, No. 9, 1985, pp. 915-919. The title of the article should have read: "Is Any Inviscid Free Flight/Wind Tunnel Equivalence Concept Valid for Unsteady Viscous Flow?" Also, on page 917, the figures quoted under the heading "Free Flight/Wind Tunnel Equivalence" should be Figs. 1-6, not Figs. 7-9.