Convergence of Lift and Drag Predictions by a Morino Panel Method (VSAERO)

John S. Letcher Jr.*
AeroHydro, Inc., Southwest Harbor, Maine

Abstract

CONVERGENCE results from both two-dimensional and three-dimensional versions of a Morino-type panel code are presented an analyzed. In both two and three dimensions it is found that reasonably accurate lift and moment predictions are obtained using modest numbers of nominally uniform-sized panels, but induced drag predictions are seriously inaccurate and converge at best very slowly with increasing panel density. Two ways are found to improve accuracy and convergence of drag predictions: 1) use cosine spacing for chordwise distribution of panels on foil sections, or 2) deduce lift and drag from the far-field wake by a classical Trefftz-plane analysis. Of the two methods, the far-field analysis has superior accuracy and convergence properties and, indeed, produces highly accurate and stable drag predictions even from quite coarse panelizations. It is also shown that large benefits in accuracy and/or savings in computational effort are possible by use of Richardson extrapolation applied to results from two or more relatively coarse (but systematically related) panelizations.

Contents

Although panel methods have been extensively employed and validated for aerodynamic lift and moment calculations, they have a reputation for being inaccurate or unreliable with respect to drag. The work reported here was stimulated by attempts to apply the panel code VSAERO to calculate the lift and induced drag of complex wing-body configurations representing sailboat hull, keel, and rudder geometries,[1] for which induced drag (effective span) is the characteristic that most strongly impacts performance. (Note that there exist various versions of VSAERO. The three-dimensional code used in this study, a public-domain version obtained directly from NASA in 1984 and currently distributed by COSMIC, may differ from commercial versions.) Conventional VSAERO drag predictions were found to be highly sensitive to details and density of panelization and in poor agreement with experiments. These studies, undertaken to discover the sources and magnitude of the errors, led eventually to usably accurate drag predictions by two methods that are believed to be applicable to most three-dimensional panel codes.

Any panel code is a discrete approximation to a continuous flow: a mostly smooth body surface is approximated by an assemblage of triangular or quadrilateral panels, and continuous flow quantities (e.g., singularity strengths and pressure) are approximated by simple distributions over each panel. As the subdivision of the body is made successively finer, the discretized model approximates the true body geometry and the continuous flow more closely and so, presumably, computed flow quantities such as lift and drag will converge toward the exact continuous solution.

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*President. Member AIAA.

The rate of convergence is of considerable practical interest because the computational effort of a panel method solution increases rapidly with the number N of panels. Using a finer panelization than necessary is, therefore, very expensive in terms of time and computer resources. Also, if reliable rates of convergence can be established for some systematic way of subdividing the panels, a projection to infinite panel density is possible from two or more relatively coarse panelizations using Richardson extrapolation.

VSAERO[2,3] is a "low-order" three-dimensional subsonic panel code for general configurations. In common with many current production panel codes, for its potential-flow calculations it adopts the Morino formulation[4] with constant known source and unknown doublet panels. In the "solution" phase, a Morino panel code sets up and solves a large system of linear equations for the unknown doublet densities on the panels. In the "analysis" phase, surface velocities, hence pressures, are obtained by local differencing of the doublet densities; these pressures are multiplied by panel areas and normals and summed to obtain total forces. This near-field force calculation is referred to in the sequel as "panel pressure analysis" (PPA).

A principal tool for investigating the sources of drag error was VSA2D, a two-dimensional incompressible panel code based on the same singularity model, the same integral equation, and the same pressure, force, and moment calculations as VSAERO. VSA2D alternatively evaluates lift and drag from a far-field analysis (FFA), which is extremely simple in two dimensions. Numerical results are given for two airfoils for which exact analytic results are available for comparison: a biconvex section and a Joukowsky section. Some lift and drag results are plotted in Fig.1 against $1/N$, for both uniform and cosine panel spacings on the 10% biconvex section, with N ranging from 6 to 80.

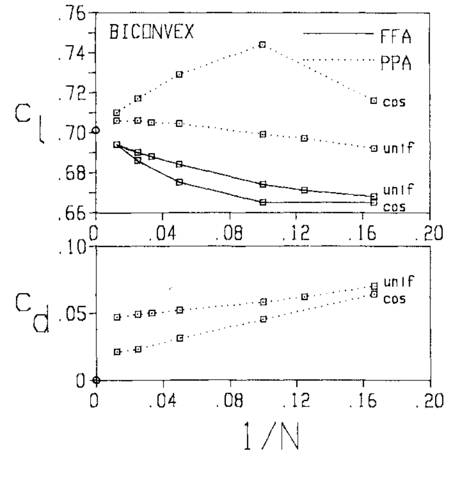

Fig. 1 Convergence of lift and drag vs panel count for the biconvex section (VSA2D results). Circle symbol on vertical axis shows the exact result from conformal mapping.

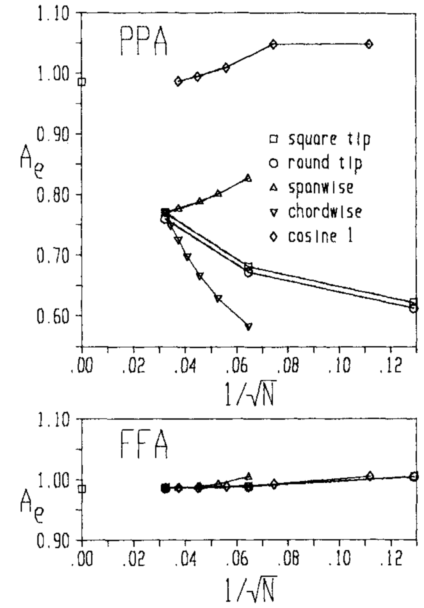

Fig. 2 Convergence of effective aspect ratio vs panel count for the square wing by panel pressure analysis (upper) and far-field analysis (lower).

For α up to 12 deg, lift and moment are impressively accurate using PPA and uniform spacing, even with as few as six panels. However, with increasing N the PPA lift does not converge to the correct value. Lift by FFA is slightly less accurate for small N, but it becomes more accurate at about $N = 40$ and does converge to the exact value like $N^{-1/2}$.

PPA predicts significant drag (either positive or negative) in all of these cases, whereas the correct two-dimensional potential-flow result is zero drag. With cosine panel spacing, the drag is somewhat less than with the same number of uniform panels. On the biconvex section, the drag does not converge to zero for either uniform or cosine spacing.

Convergence is much better for the Joukowsky section; both lift and drag do converge to their exact values with rates of $N^{-1/2}$ or better.

Up to $\alpha = 12$ deg, the PPA drag varies quadratically with lift to within a few percent, behaving just like induced drag. Its magnitude can be appreciated by expressing it as an "effective aspect ratio" $c_\ell^2/[\pi(c_d - c_{d_0})]$. For uniform panels, this falls in the range of only 2 to 4. It also can be compared with the nose suction that would occur on a flat plate, with magnitude on the order of $c_\ell\alpha$; this would be about 0.073 at $\alpha = 6$ deg. Results obtained with the biconvex section suggest that PPA misses about 60% of the nose suction on this sharp edge even with N approaching infinity; with $N = 6$, it misses about 80%.

The main conclusions from the two-dimensional calculations are that 1) PPA produces reliable lift and moment with as few as six panels for moderate α, 2) PPA is not a reliable way to calculate drag with any reasonable number of uniform panels, 3) cosine spacing significantly improves the accuracy of the drag calculated by PPA, and 4) FFA provides a more robust analysis of lift and a more accurate (in fact exact) analysis of drag.

The outline for a far-field analysis (FFA) for lift and drag in three dimensions, including nonplanar wakes and wing-body interference, is given in Ref. 1. It is specialized in the present paper to planar wakes with bilateral symmetry and without thickness effects. The VSAERO wake is composed of constant-strength doublet panels. The FFA lift and drag are obtained from the wake doublet densities by discrete forms of classical lifting-line integral formulas.

The three-dimensional test body is a wing having square planform and a constant NACA 0010 section. The wingtips are square and are paneled in coordination with the wing surface. To investigate whether slow convergence of PPA lift and drag might be associated with the sharp lateral edges, one panel series uses rounded wingtips (semicircular section). The wake lines lie in the plane of the wing and are straight and parallel (i.e., thickness effects, which would produce a small lateral contraction of the wake, are neglected). The angle of attack is 6 deg for all lifting cases; however, each case had to be run at zero angle of attack as well to determine the PPA "tare" drag C_{D_0}.

The panel arrangements and essential results from seven systematic panelization series are presented in the full paper. The spanwise panel spacing is uniform in all cases; the chordwise spacing is uniform except for two cosine series. Convergence of effective aspect ratio $A_e = C_L^2/[\pi(C_D - C_{D_0})]$ is shown in Fig. 2 for N ranging from 60 to 960 panels (on each half-wing). Except for the cosine series, the PPA results vary over a wide range and are all grossly in error. In contrast, all FFA results are within 2% of the converged value; most are much more accurate, and all show strong convergence.

The striking similarity between results obtained from two-dimensional and three-dimensional codes indicates that the poor drag predictions obtained from the three-dimensional code do not trace to any coding error peculiar to VSAERO or to the doublet solution stage of the Morino formulation in general but, instead, derive from inaccuracies inherent in the panel pressure (PPA) method of force and moment analysis.

The first general conclusion is an indictment of PPA drag calculations when practiced with uniform panel size. Within the range of panel densities in this study, PPA drag results from systematic increases of panel density converge, if at all, to incorrect values that depend strongly on the system of panelization and subdivision.

The robust and rapidly convergent lift and drag values obtained by the present alternative far-field analysis (FFA) demonstrate that the VSAERO singularity solution is correctly formulated and contains drag information that is far more accurate than PPA is able to resolve. Indeed, this information is quite easy to extract for a simple wing.

Richardson extrapolation is shown to hold considerable promise for improving accuracy and efficiency in application of panel methods. An essential element in this strategy is the planning of truly systematic panelization series in which the panel density is increased in the same proportion in both spanwise and chordwise directions. Two successive quadruplings of N, resulting from doublings in both directions, are always feasible (and easy to implement in VSAERO, as panel densities are specified separately from the underlying geometry) and produced the best extrapolation series in this study.

Acknowledgments

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