Engineering Notes

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Evaluation of a Stalled Airfoil Analysis Program

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Introduction

OVER the last decade, several iterative, coupled, viscous-inviscid interaction programs have been developed for predicting the aerodynamic performance of airfoils with massive turbulent separation. A recently developed Stalled Airfoil Analysis Program[1] (SAAP) has been evaluated by a systematic comparison with experimental data. Comparisons have also been made with the methods developed by Maskew and Dvorak (called CLMAX),[2] and Barnwell,[3] which were recently assessed as the two most accurate production codes in a comparative study of five such programs.[4] A summary of results is presented in this Note.

Although Barnwell's method is designed to treat airfoils with substantial compressibility effects, SAAP and CLMAX are strictly valid for airfoils in incompressible, steady flow. Therefore, all comparisons presented in this Note are made at low Mach numbers where the compressibility effects are assumed to be negligible.

Method

A brief summary of the computational methods used to determine the stalled airfoil performance is given in this section; details of the computational methods discussed can be found in their respective references. SAAP couples an inviscid panel method and a viscous boundary-layer method numerically and solves iteratively for an "effective" inviscid streamline shape until the lift converges to within a specified tolerance. In regions where the flow is attached, the effective streamline corresponds to the contour displaced from the airfoil by the boundary-layer displacement thickness. The separation model is similar to that used in Refs. 2 and 3. The major assumption is that the pressure on the airfoil is constant downstream of the separation point. In the separated region, the effective streamline corresponds to the separated wake boundary, which is determined iteratively to satisfy the constant-pressure assumption. The separation point is taken as the streamwise location where the boundary-layer shape factor first exceeds an empirically determined critical value.

The inviscid and viscous solution methods in SAAP are represented by the MCAIR two-dimensional panel method and the Truckenbrodt integral boundary-layer method, respectively. The coupling procedure involves a simultaneous matching of the inviscid and viscous solutions. At the beginning of each iteration cycle, first-order relationships are developed between perturbations to the unknowns (which represent the effective inviscid streamline geometry) and the resulting changes in inviscid and viscous quantities. A set of linear algebraic equations results, the solution of which establishes corrections to the original unknowns. Generally, the program solves for increasing angles of attack, with the converged inviscid streamline shape from the lower angles being used as initial data for the higher ones. Three iterations per angle of attack are usually sufficient for convergence.

In contrast, CLMAX and Barnwell's method employ separate viscous and inviscid calculations which are coupled by an iterative relaxation procedure. CLMAX uses two iteration loops—a wake shape iteration loop nested within another viscous/potential iteration loop. After the boundary-layer analysis has determined the separation points, the wake shape is iterated upon separately. This new wake shape is then used in the next viscous/potential iteration step. Barnwell's scheme evaluates the exact boundary condition slope at the chord line of the airfoil, so no wake shape is directly involved in the solution process.

All three schemes require relatively little computer time to give results over the entire angle-of-attack range of a wing section. For example, SAAP typically requires 25-30 s of CP per iteration on the MDC Cyber 750 computer.

Results

SAAP was evaluated for the airfoils and conditions given in Table 1 over the angle-of-attack range from zero lift through stall. These airfoils provide a wide range of leading-edge radii, maximum thickness, and camber line variations. SAAP was implemented with the transition fixed, although the results were generally independent of whether transition was specified or unspecified. Results from CLMAX with the transition unspecified were significantly different from those with it specified and usually were more representative of the experimental data, so the former are used for comparison in this Note. The results from Barnwell's code were obtained with fixed transition in all cases.

In general, SAAP predicted lift coefficients in good agreement with experimental data at low angles of attack, as expected. At higher angles of attack (up to and beyond stall), SAAP tended in most cases to slightly overpredict the maximum lift coefficient, with an average absolute error of

Table 1 Airfoils and conditions evaluated

Airfoil	Mach No.	Reynolds No., $\times 10^6$
GA(W)-1	0.15	6.3
	0.15	2.1
GA(W)-2	0.15	4.3
	0.15	2.1
NACA 4412	0.15	6.3
NACA 65-213	0.10	5.9
NACA A-1	0.20	1.9
	0.30	2.5
NACA 0012	0.15	6.0
	0.15	2.0

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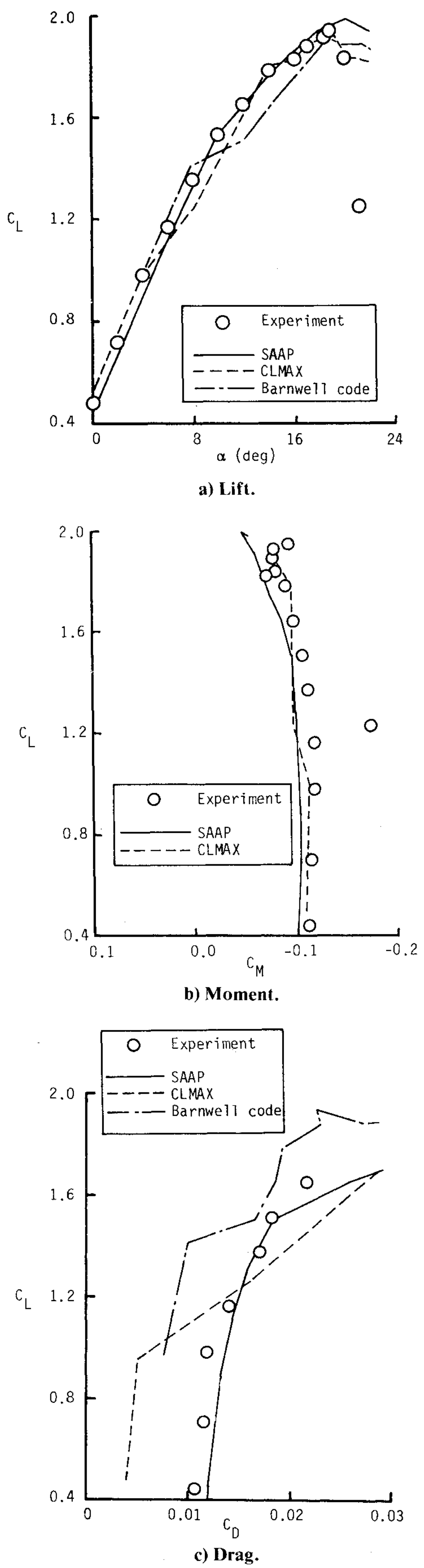

Fig. 1 Comparison of theory and experiment for the GA(W)−1 airfoil (Re = 6.3 × 10^6; M = 0.15).

about 5%. SAAP gave an adequate prediction of the angle of attack for maximum lift within an average of 0.8 deg. In comparison to the results given in Ref. 4, SAAP performed about as well as CLMAX at high angles of attack near stall. While SAAP usually overpredicted the maximum lift, CLMAX usually underpredicted with the same average percent error. CLMAX was more accurate in determining the angle of attack at stall, giving an average error of about 0.4 deg. Barnwell's code produced an average absolute error in $C_{L\max}$ of about 7% and predicted the angle of attack for $C_{L\max}$ to within 1.3 deg on average.

At the lower angles of attack, both CLMAX and Barnwell's code exhibited oscillations in the lift curve slope. The lift curve slope changed, often dramatically, from one angle of attack to the next, as can be seen in Fig. 1a for the GA(W)-1 case. Other cases (not shown) demonstrated similar oscillations. In constrast, SAAP yielded a smooth lift variation with angle of attack for all cases. The lift curve slope always remained constant or decreased as the angle of attack increased, which is more representative of the airfoil data considered. One possible explanation for the more accurate modeling of the lift curve is the simultaneous treatment of the viscous/inviscid coupling equations in the SAAP. The method of obtaining a linear perturbation array and solving simultaneous equations gives very reliable, rapid solution convergence, while using separate viscous and inviscid calculation steps leads to the oscillating solution behavior noted above.

The moment coefficient was predicted accurately by both SAAP and CLMAX, as shown in Fig. 1b, whereas no moment results were available from Barnwell's code. However, the drag coefficient as a function of lift was predicted more consistently and accurately by SAAP than by either of the other two codes. The results in Fig. 1c for the GA(W)-1 present the typical behaviors of the three methods. The SAAP solution follows the data fairly closely and does not show the oscillations evident in the solutions from CLMAX and the code developed by Barnwell.

Conclusions

SAAP, a computer code designed to predict the aerodynamic characteristics of an airfoil up to and beyond stall, has been evaluated through comparison with experiment and two other theoretical methods. The comparisons were made over an extensive range of airfoils and Reynolds number conditions for which significant trailing-edge separation exists at maximum lift. SAAP predicted maximum lift to within 5% of experiment on average and determined the angle of attack at $C_{L\max}$ to within 0.8 deg on average. The predictions of $C_{L\max}$ and the angle of attack for $C_{L\max}$ by SAAP were comparable to the results from the method of Maskew and Dvorak.[2] SAAP modeled the drag more accurately than either of the other methods and, at angles of attack below stall, produced a smoother lift variation with angle of attack.

References

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