A FIRST PRINCIPLES BASED METHOD FOR THE PREDICTION OF LOADING OVER FIXED AND ROTARY WING GEOMETRIES

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First-principles based techniques for the prediction of fixed and rotary wing wake geometry are described. It is demonstrated that fifth order accuracy schemes do substantially better than third order spatial accuracy schemes in capturing the details of the vortex core structure. It is demonstrated that the use of embedded grids can further enhance the resolution of the tip vortex, particularly if the boundary conditions and the order of interpolation accuracy are carefully maintained to be fifth order. A hybrid approach where the costly Navier-Stokes analysis is confined to small viscous regions near the blade surface is also described. Sample applications of this method to the vortex wake behind a fixed wing, and the surface pressure distribution over a rotor are presented.

Introduction

The earliest methods for modeling rotors were based on an extension of Prandtl's lifting line theory for wings. In these techniques, the individual blades were modeled as line vortices, and the wake was modeled as a deformed helix.

During 1970s and 1980's, these methods were augmented by modern CFD techniques. Caradonna and Isom applied the transonic small disturbance theory to lifting rotors [1]. Chang[2] modified the full potential flow solver FLO22 for isolated wings to model rotors. Egolf and Sparks[3] modified Chang's work by embedding the vortex element associated with the tip vortex with the potential flow field. Their approaches solved either the steady or quasi steady form of the potential flow equation. Sankar et al [4,5], Strawn[6], Bridgeman et al. [7], Strawn and Caradonna[8] developed unsteady full potential flow based rotor solvers. Ramachandran et al.[9,10] solved the full potential equation and included the rotor wake effects using a Lagrangean based approach for tracking the vortex filaments.

During the late 1980's, Euler methods matured to a point where calculation of the rotor flow field in hover and forward flight was feasible. These methods solved the mass, momentum and energy conservation equations in a time dependent fashion using finite-difference or finite-volume methods. These solvers did not include viscous effects but could analyze the transonic flow with non-isentropic shocks. Sankar et al.[11], Agarwal and Deese [12], and Hassan et al. [13] developed Euler solvers for isolated rotors. Again, the wake effects were modeled as an inflow angle of attack table supplied from a separate comprehensive analysis. In Ref. 14, Wake and Sankar developed a Navier-Stokes code to analyze rotor flow fields in hover and forward flight.

During the 1980s, a new class of Euler/Navier-Stokes codes were developed in an effort to capture the rotor wake from first principles without any need for external wake models. Removing the need for external information that depends on rotor geometry is a big step in the true simulation of the rotor flow field. These first-principles based solvers are particularly useful in analyzing new or complex rotor blades where no experimental data are available. Strawn and Barth[15], Srinivasan and McCroskey[16], Srinivasan et al.[17-19], Duque[20-21] all solved the hovering rotor flow fields by capturing the rotor wake in an Eulerian fashion, and from first principles. Hariharan [22] developed high order accuracy schemes for capturing rotor wakes. Bangalore [23] studied the use of high lift devices such as slats to enhance the maneuverability of rotorcraft.

Recently, a new class of methods has become available, which combine the simplicity of Lagrangean wake methods for capturing trailing vortices, the efficiency of potential flow methods and the accuracy of Navier-Stokes methods. These methods are discussed in references 24-26.

Scope of the Present Work

The present work is organized as follows. A compressible Navier-Stokes solver that is second or third order accurate in time, and fifth order accurate in space is briefly described. An overset grid approach is next described, which allows sharp gradients in the flow field such as shocks and vortices to be captured on a locally embedded fine grid. Next, a hybrid formulation, where the time consuming calculations are confined only to small regions surrounding the rotor is discussed.

A number of results are presented for rotors in hover, and for a wing in forward flight. The surface pressure distributions, and the velocity field in and around the tip vortices are presented and compared with measurements.

Because the mathematical formulation behind this work is well developed, and has been extensively documented [22-23], the present formulation is very briefly discussed. The emphasis of this work is on the predictive capabilities of the approaches described here.

Mathematical and Numerical Formulation

<u>Navier-Stokes Analysis:</u>

The three-dimensional compressible Navier-Stokes equations are solved in an integral form in the present study. These equations may be formally written as:

$$\frac{\partial}{\partial t}\iiint_V q \cdot dV + \oiint_S \left[\overline{F} - q \cdot \overline{V}_G\right] \bullet \overline{n} dS = \iint_S \overline{R} \bullet \overline{n} dS$$

(1)

Here, the symbol V refers to the control volume on which the governing equations are applied in the above integral form. The symbol τ represents time; The quantities F and G are inviscid and viscous fluxes evaluated at the boundaries S of the control volume. Finally, V_G is the velocity of the grid surfaces in an inertial coordinate system. All the motions of the blade such as pitching, flapping and the rotations about the rotor shaft enter the calculations through this term. This is in contrast to calculations in a rotational frame, where the centrifugal, angular acceleration and Coriolis terms are explicitly represented.

A fifth order accurate essentially non-oscillatory (ENO) scheme is used in the present work to compute the flow properties q to the left and right side of each of the six cell face S. An adaptive stencil is used, which uses only the smoothest part of the flow properties information in the cell, and its neighbors.

The semi-discrete form of the equations may be written as:

$$\frac{d(qV)}{dt} = R \tag{2}$$

Here the symbol V represents the cell volume. At any time step 'n+1', this equation is solved using an implicit iterative scheme of the form:

$$\left[\frac{1}{\Delta t} - \frac{\partial R}{\partial (qV)}\right]\Delta(qV) = \left[R - \frac{\partial(qV)}{\partial t}\right]^{n+1} \tag{3}$$

where the objective of the iteration is to drive Δ(qV) to zero, thereby satisfying equation (2). The left side matrix is approximately factored into several smaller tridiagonal factors facilitating the inversion. Of course, when the iterations converge, the factorization errors disappear. If only a single iteration is done, then the present scheme reduces to a classical non-iterative ADI scheme.

It may also be noted that matrix equation (3) may be solved using multigrid techniques. The left side operator as well as the right side "Residual" may be injected onto coarser grids and then inverted. This multigrid approach has been used in some wing-alone calculations, but were not used in this study.

<u>Hybrid Navier-Stokes/Full Potential Approach:</u>

In this approach, the above Navier-Stokes calculations are done only in a small region surrounding the rotor blade. At node points away from the viscous region, the following simplified form of the governing equations is used:

$$\frac{\partial \rho}{\partial t} + \nabla \bullet \left(\rho \nabla \phi\right) = -\nabla \bullet \left(\rho\, \overline{q}_V\right) \tag{4}$$

Here, the quantity $\nabla\phi$ represents the irrotational portion of the velocity field. For a lifting rotor, the presence of the rotor wake leads to pockets of rotational flow in the vicinity of the tip vortices trailing from the rotor. In the present work, these rotational effects are modeled by tracking the vortical elements leaving the Navier-Stokes zone with markers, and applying the Biot-Savart law to find the induced velocity field q_v associated with these vortical elements. Finally, the isentropic energy equation is used to compute the density ρ in terms of the velocity potential, and the rotational component.

<u>Overset Grid Scheme:</u>

In rotary wing in forward flight applications, it is difficult to know the vortex trajectory a priori. As a result, the grid in the vicinity of the vortices is not likely to be adequately clustered. In other instances, for example in rotor airframe interaction applications, a single body-fitted grid around the rotor and the airframe can not be generated. For these reasons, an overset capability has been implemented in the present method. In this approach, independent curvilinear refined grids are placed on top of existing grids. The base grid and the overset grid will not coincide as in conventional patched grids. Thus, information between the base grid and the overset grid must be exchanged by three-dimensional interpolation. Efficient 3-D interpolation techniques and search procedures that identify holes and fringe points have been developed.

Results and Discussion

In this section, a number of results are presented to demonstrate the capabilities of the present approach.

Fixed Wing Tip Vortex Generation Process:

A NACA0015 wing tested by McAlister et al. [27], has been studied. This experimental data is quite extensive including velocity profiles across the cross-section of the tip vortex at various stations downstream of the wing. A C-grid consisting of 121 points in the streamwise direction, 25 points in the spanwise direction and 31 points in the normal direction was constructed. The angle of attack of the wing was set at 12 degrees and the free stream Mach number was 0.18.

Figure 1 presents the surface pressure distribution comparison between the two schemes, at two spanwise stations. The solution computed by the fifth order scheme is found to be superior at all the stations, comparing better with the experimental values. At the inboard stations the suction peak is picked up better by the fifth order scheme, and the overall agreement with experiment is better. Very close to the tip (97% semi-span), the difference between the third and the fifth order scheme is even more marked. The fifth order scheme correctly predicts the rear bump in the suction side, caused by the formation of the tip vortex and the subsequent roll-up over the wing upper surface.

To study of tip vortex evolution in detail, the inviscid calculations were repeated with 40 points in the spanwise direction, retaining the same number of points in the other two directions. Figure 2 shows the velocity (V_Z) profile normal to the wing plane across the tip vortex core at two streamwise locations behind the trailing edge. The fifth order solution is again found to be superior to the third order solution. Immediately behind the trailing edge (x/c =0.1, 0.2, 1.0) the fifth order solution agrees very well with the experiments.

Around x/c > 2 the velocity peaks captured by the fifth order scheme starts to diminish when compared to experiments. The grid stretching in the streamwise direction becomes too large to produce the exact peak.

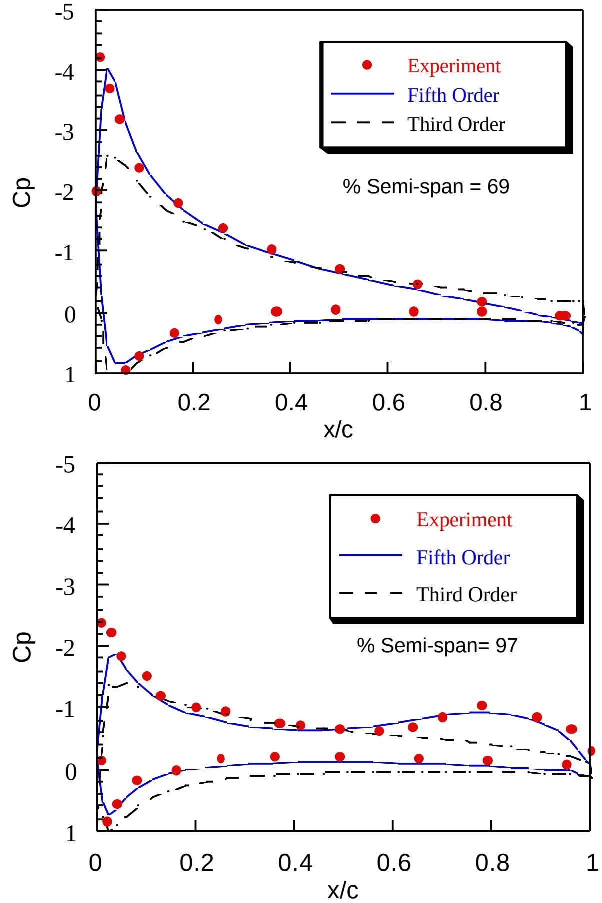

Figure 1. Surface Pressures over a Rectangular Wing Tested by McAlister, α=12°, M∞= 0.18.

An embedded grid shown on Figure 3 removes this difficulty. The normal velocity field was accurately computed up to six chords away from the rotor as shown in Figure 4. The fifth order scheme with an embedded grid was also able to capture the axial component of velocity inside the vortex core, as shown in Figure 5.

Rotary Wing Analysis- Forward Flight

The full Navier-Stokes analysis has been applied to wings in hover and forward flight. Sample results from the Ph. D. Dissertation of Bangalore [23] for a UH-60A rotor in forward flight is given in Figure 6. These calculations involving four blades required 1.2 Million grid points, and were done using a distributed computing strategy. Although the surface pressure distribution over most of the rotor is in good agreement, the integrated loads shown in Figure 7 do not agree with the measurements well. Considerable additional work is needed in the areas of tip vortex modeling and 3-D dynamic stall modeling to improve agreement between the analyses and the measurements.

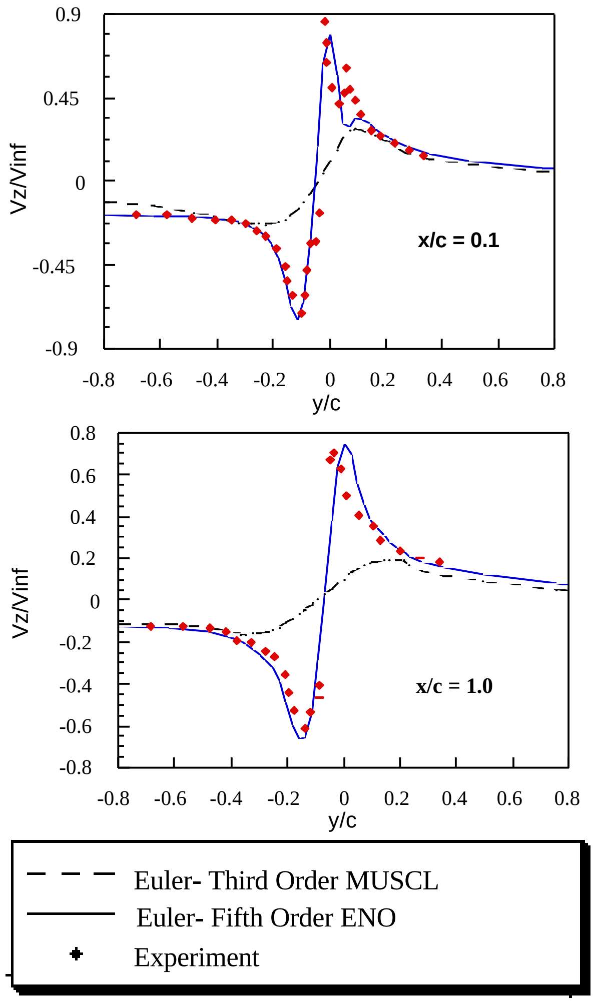

Figure 2. Variation of the Component of Velocity normal to the Wing Planform across the Vortex Core

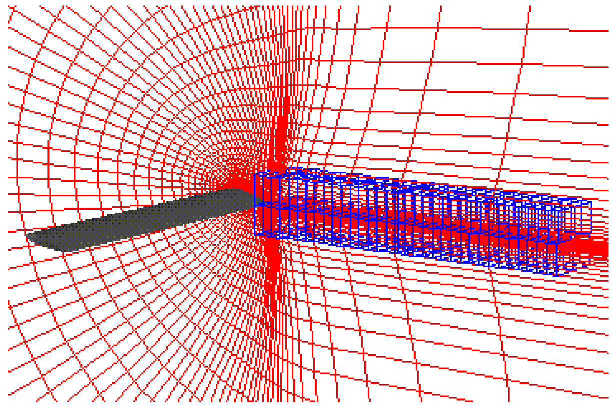

Figure 3. Embedded grid for Improved Resolution of the Tip Vortex

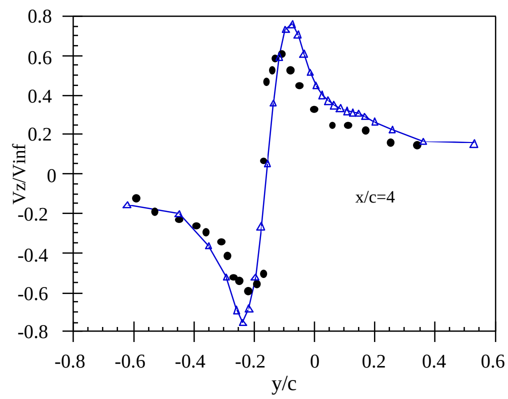

Figure 4. Variation of Normal Component of Velocity inside the Vortex Core with the Embedded Grid

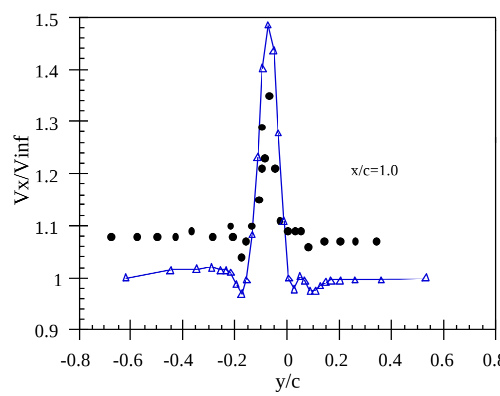

Figure 5. Variation of Axial Velocity within the Vortex Core with the Embedded Grid.

Hybrid Analysis:

As discussed earlier, the CPU time for first principles based analysis can be reduced by a factor of 2 or more if most of the flow field is modeled using potential flow techniques. The resulting hybrid solver has been validated for a typical current generation rotor, the four bladed UH-60A rotor. The Blade planform has an aspect ratio of 15.3 and a maximum twist of 13°. The blade has a rearward sweep of 20° starting from a rotor radius of 93%. The blade is made up of two airfoil sections, SC1095 as the main airfoil and SC1095R8 section in the midspan [28].

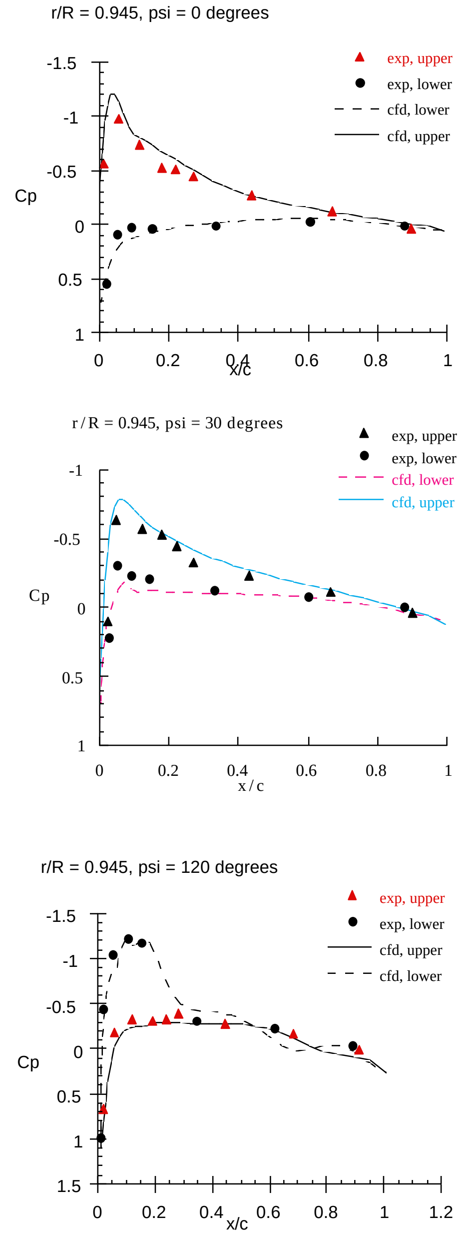

Figure 6: Surface pressure distribution, 95 % radial station at selected azimuthal locations, M_{tip} = 0.628, advance ratio = 0.3, UH-60A Rotor

Figure 8 shows the surface pressures at two radial stations. The results are in agreement with the experimental measurements. In these studies, the wake marker locations were iteratively adjusted until the wake filaments were force free, as in conventional free wake analyses. These calculations required only 50% of CPU time required by a full blown Navier-Stokes analysis.

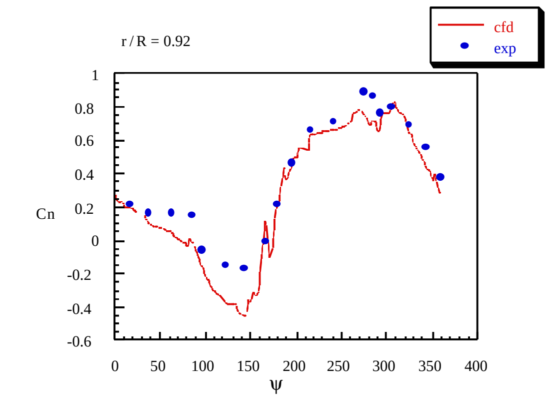

Figure 7. Variation of Normal Forces at 92% for the UH-60A Rotor

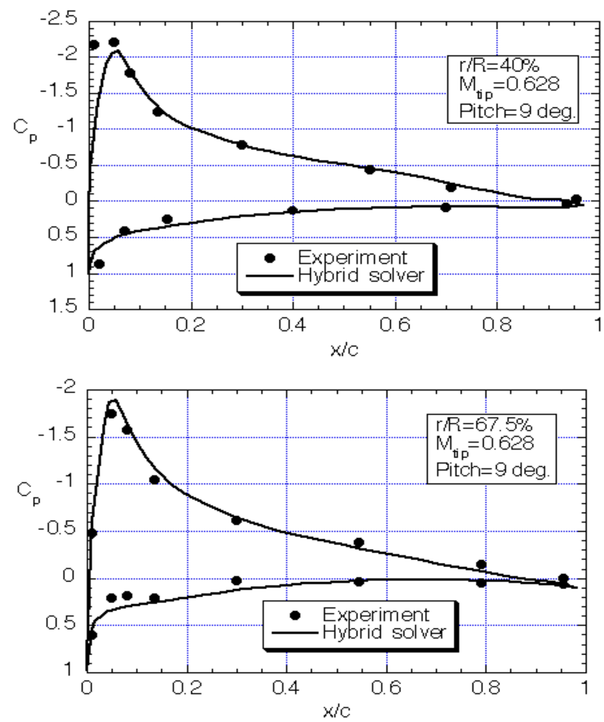

Fig 8. Surface Cp over UH-60A Rotor; Hybrid Method

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References

1. Caradonna, F. X. and Isom, M. P., "Subsonic and Transonic Potential Flow over Helicopter Rotor

Blades, AIAA Journal, No. 12, Dec 1972, pp. 1606-1612.
2. Chang, I. C., " Transonic Flow Analysis for Rotors, " NASA TP 2375, July 1984.
3. Egolf, T. A. and Sparks, S. P., " A Full Potential Rotor Analysis with Wake Influence using an Inner-Outer Domain Technique, " 42nd Annual AHS Forum, June 1986.
4. Sankar, L. N. and Prichard, D., " Solution of Transonic Flow past rotor blades using the Conservative Full Potential Equation, " AIAA Paper 85-5012, October 1985.
5. Sankar, L. N., Malone, J. B. and Tassa, Y., " A Strongly Implicit Procedure for Steady Three-dimensional Transonic Potential Flow, " AIAA Journal, Vol. 20, No. 5, 1982.
6. Strawn, R.C., " Numerical Modeling of Rotor Flows with a Conservative form of the Full Potential Equation, " AIAA Paper 86-0079, July 1986.
7. Bridgeman, J. O., Strawn, R. C. and Caradonna, F. X., " An Entropy and Viscosity Corrected Potential Method for Rotor Performance prediction, " 44th Annual AHS Forum, June 1988.
8. Strawn, R. C. and Caradonna, F. X., "Conservative full potential model for unsteady transonic rotor flows, " AIAA Journal, Vol. 25, February 1987, pp. 193-198.
9. Ramachandran, K., Tung, C. and Caradonna, F. X., "Rotor hover performance prediction using a free-wake computational fluid dynamics method, " Journal of Aircraft, Vol. 26, December 1989, pp. 1105-1110.
10. Ramachandran, K., Moffitt, R. C., Owen, S. J. and Caradonna, F. X., " Hover Performance Prediction using CFD, " 50th Annual AHS Forum, June 1994.
11. Sankar, L.N., Wake, B.E. and Lekoudis, S.G., "Solution of the Unsteady Euler equations for fixed and rotor wing configurations," Journal of Aircraft, Vol 23, No.4, April 1986, pp283-289.
12. Agarwal, R. K. and Deese, J. E., " An Euler solver for calculating the flow field of a Helicopter Rotor in Hover and Forward Flight, " AIAA 19th Fluid Dynamics, Plasma Dynamics and Laser Conference, June 1987.
13. Hassan, A. A., Tung, C. and Sankar, L. N., " An Assessment of Full Potential and Euler Solutions for Self generated Blade-Vortex Interactions, " 46th Annual AHS Forum, May 1990.
14. Wake, B.E. and Sankar, L.N., "Solution of Navier-Stokes equations for the flow over a rotor blade", AHS Journal, April 1989.
15. Strawn, R.J and Barth, J.T "A finite-volume Euler solver for computing rotary-wing aerodynamics on unstructured meshes", presented at the 48th Annual AHS Forum, Washington D.C, June 1992.
16. Srinivasan, G. R. and McCroskey, W. J., "Navier-Stokes Calculations of Hovering Rotor Flow fields, " Journal of Aircraft, Vol. 25, No. 10, October 1988, pp. 865-874.
17. Srinivasan, G.R., Baeder, J. D., Obayashi, S. and McCroskey, W. J., "Flow field of a Lifting Rotor in Hover : A Navier-Stokes Simulation, " AIAA Journal, Vol. 30, No. 10, October 1992.
18. Srinivasan, G.R and Baeder, J.D "TURNS: A free wake Euler/Navier-Stokes numerical method for helicopter rotors", AIAA Journal, Volume 31, Number 5 May 1993.
19. Srinivasan, G.R, Raghavan, V., Duque, E.P.N and McCroskey, W.J "Flow field analysis of modern helicopter rotors in hover by Navier-Stokes method", presented at the AHS International Technical Specialists meeting on Rotorcraft Acoustics and Rotor Fluid dynamics, Oct 1991, Philadelphia, PA.
20. Duque, E. P. N., " A Numerical Analysis of the British Experimental Rotor Program Blade, " 45th Annual AHS Forum, Boston, MA, May 1989.
21. Duque, E. P. N. and Srinivasan, G. R.,"Numerical Simulation of a Hovering Rotor using Embedded Grids, " 48th Annual AHS Forum, Washington D.C., June 1992.
22. Hariharan, N., Sankar, L. N., "Higher Order Numerical Simulation of Rotor Flow Field," AHS Forum and Technology Display, Washington, DC., May 1994.
23. Bangalore, A., Computational Fluid Dynamic Studies of High Lift Rotor Systems Using Distributed Computing, " Ph. D Thesis, Georgia Institute of Technology, Atlanta, GA, May 1994.
24. Mello, O. A. F., "An Improved Hybrid Navier-Stokes/Full Potential Method for Computation of Unsteady Compressible Flows, " Ph. D Thesis, Georgia Institute of Technology, Atlanta, GA, November 1994.
25. Berezin, C. R. and Sankar, L. N., "An Improved Navier-Stokes/Full Potential Coupled Analysis for Rotors, " Mathematical Computational Modeling, Vol. 19, No. 3/4, 1994, pp. 125-133.
26. Moulton, M. A., Hafez, M. M. and Caradonna, F. X., "Zonal procedure for predicting the hovering performance of a helicopter, " ASME Journal, Vol. 184, 1984.
27. McAlister, K. W., Takahashi, R. K., "NACA 0015 Wing Pressure and Trailing Vortex Measurements," USAAVSCOM TR-91-A-003, 1991.
28. Lorber, P. F., Statuter, R. C., Landgrebe, A. J. “A Comprehensive Hover Test of the Airloads and airflow of an Extensively Instrumented Model Helicopter Rotor,” Proceedings of 45th Annual Forum of the AHS, MA, May 1989.