ICAS-98-2,6,1

A98-31510

EROS: A EUROPEAN EULER CODE FOR HELICOPTER ROTOR FLOW SIMULATIONS

P. Renzoni and A. D'Alascio (CIRA), N. Kroll (DLR), D. Peshkin (DERA),
M.H.L. Hounjet (NLR), J.-C. Boniface (ONERA), L. Vigevano (Polit. Milano),
L. Morino (Univ. Roma Tre), C.B. Allen (Univ. Bristol), L. Dubuc (Univ. Glasgow),
M. Righi (Agusta), E. Schoell (ECD), A. Kokkalis (GKN-WHL)

Abstract

The helicopter rotor flowfield is one of the most complex and challenging problems in applied aerodynamics. Its accurate analysis is essential in the design of rotors with increased performance and in the development of rotors with reduced vibratory loads and with more environmentally-friendly acoustic signatures.

There is an industrial need in Europe for a rotor aerodynamic prediction tool able to capture rotational phenomena, such as blade tip and wake vortices, and to predict correctly the unsteady blade pressures over a range of different flight conditions. The EROS project addresses this need by developing a common European system capable of analysing the inviscid rotor flow environment by solving the 3D Euler equations. The method is based on a proven-technology time-accurate Euler formulation on overlapping structured grids (Chimera method). The grid generator provides an all-in-one capability for grid generation guiding the user from the generation of individual component grids to the Chimera domain decomposition through an interactive process which has embedded visualisation and animation capabilities. The cell-centred finite-volume solver adopts a dual-time implicit scheme on deforming grids. Nonconservative interpolation is used to transfer information across grid overlap regions. The current capabilities of the code are presented and future developments are described.

Nomenclature

CIRA	Centro Italiano Ricerche Aerospaziali
DERA	Defence Evaluation Research Agency
DLR	Deutsche Forschungsanstalt für Luft- und Raumfahrt
ECD	EUROCOPTER Deutschland
EROS	European Rotorcraft Software
GKN-WHL	GKN-Westland Helicopters
NLR	Stichting Nationaal Lucht- en Ruimtevaartlaboratorium
ONERA	Office National d'Études et de Recherches Aérospatiales

Introduction

Despite the great advances that have been made in Computational Fluid Dynamics (CFD) over the last decade, the accurate and efficient simulation of the helicopter rotor flowfield continues to be one of the most complex and challenging problems of applied aerodynamics. The flow around realistic rotor blades is unsteady and characterized by strong nonlinear and three-dimensional effects, transonic regions near the advancing tip blades and regions of shock induced separation and dynamic stall at retreating blades. Furthermore, the blades shed complex vortical wakes which strongly affect the operating characteristics of the rotor.

Considerable efforts have been devoted to the development and validation of advanced CFD methods based on the solution of the Euler and Navier-Stokes equations. Pioneering works on the solution of the Euler equations in the US(1, 2) and in Europe(3, 4) have spurred on developments in rotorcraft CFD. US research activities(5) have been directed towards the solution of the Navier-Stokes equations,(6) the use of the overlapping grid approach to treat complex configurations,(7, 8, 9) and the development of high-order schemes for convection problems.(10) Europe has a long tradition of research on Euler methods for rotorcraft CFD. DLR, ONERA and the Univ. of Stuttgart have implemented numerous algorithms over the past decade. Efforts have concentrated on the wake convection properties of various methods,(11, 12) on Chimera schemes(13, 14) and multi-block moving grid approach(15) for modelling complex multi-bladed rotors, on coupling with potential wake models(16) and on a Chimera scheme for rotor/fuselage

21st ICAS Congress
13-18 September 1998
Melbourne, Australia

configurations.(17) The key CFD technologies for rotors have been developed at the individual organisations and through Franco-German cooperation.(18) Development and validation activities have also been carried out through projects sponsored by the European Union. Simple rotors in hover were studied in the DACRO project(19, 20) while multi-bladed rotors in forward flight were studied in the ECARP project.(21) Complex multi-bladed rotors in hover were studied in the HELISHAPE project.(22)

The Euler codes that have been developed by the individual organizations are being applied to industrial applications and are available to some European rotorcraft manufacturers. Nevertheless there is a need for a common European rotorcraft aerodynamics simulation system which can build on the developments of the individual organizations and introduce:

- an efficient, dedicated grid generator for multi-bladed rotor applications (deforming meshes, Chimera, ...);
- software quality management from the very beginning;
- weak coupling with aeroelastic codes based on blade deformation;
- alternative schemes for both spatial (central and upwind schemes) and temporal (explicit and implicit scheme) discretization;
- inflow modelling with an embedded BEM module;
- dedicated I/O interfaces.

A common simulation code can be very advantageous in common development ventures between the rotorcraft manufacturers in the consortium by allowing the engineer to concentrate on the simulations rather than the simulation tools.

Objectives

The EROS project deals with the development and validation of a common European method capable of analysing the inviscid rotor flow environment by solving the 3D Euler equations. The aim is to develop a complete rotorcraft aerodynamics simulation system which will allow:

- multi-blade calculations in hover with wake capturing;
- multi-blade calculations in forward flight with wake modelling (grid generated around a single blade) and with wake capturing (grid generated around a full rotor);

with and without elastic deformations. The development is being carried out by rotorcraft manufacturers (Agusta, ECD, GKN-WHL), research centres (CIRA, DERA, DLR, NLR, ONERA), and Universities (Polit. Milano, Univ. Bristol, Univ. Glasgow, Univ. Rome 3) within the Brite/EuRam programme of the European Commission. The three-year project runs until the end of March 1999.

The research centres and the universities will have developed by the end of the project a unique platform on which to develop and test new algorithms. This will create a direct link between code developers and code users thus optimising the flow of state-of-the-art CFD technology to European rotorcraft manufacturers. At the end of this collaborative research, there will be a *significant improvement* in the rotor blade design and analysis tools available to the rotorcraft manufacturers in the consortium. In fact, the rotorcraft industries will significantly increase their design capability by the availability of such a code by being able to predict more accurately the aerodynamic load distribution along the blades. Knowledge of this would allow the designer to reduce pilot control-loads, to increase speed and to identify and quantify the aerodynamic noise sources. Furthermore, the Euler code is the stepping stone of the long term research goal of a general 3D unsteady Navier-Stokes solver for rotor aerodynamics computations.

In order to develop such an advanced aerodynamics simulation system (an Euler code with its own grid generator) for it to be used in an industrial context, software engineering standards must be adopted throughout the development of the system. The software life cycle is composed of various phases that lead from the user requirements to the user acceptance of the product, namely:

- definition of user and software requirements;
- detailed software development cycle;

  formulation
  ↪ precoding
  ↪ coding
  ↪ verification
- validation by the end-user;

with each phase having clearly defined objectives. The industrial partners are mainly responsible for defining the requirements and carrying out the validation of the developed software. The detailed software development is mainly carried out by the research centres and the universities, strictly adhering to the four-phase software development cycle. Such a structured software development cycle is further strengthened by the experience that a number of organizations bring from the development of a common European full potential rotor code.(23)

The EROS aerodynamics simulation system is currently undergoing the validation phase. This paper gives an overview of the general characteristics of the system and presents the simulations that have been performed two years into the project.

Technical Content

Industrial Requirements

At the beginning of the project the three industrial partners laid down the basic requirements of the software to be produced within the project. The ESA software engineering standards(24) were used as a general guideline for the software life cycle to be used in the development of the EROS code.

The requirements have been subdivided into user and software requirements; the first dealing with the capabilities needed by the users and the constraints placed by the users, and the second dealing with *what* the product must do. The software requirements are also the reference against which both the design and the product will be verified.

In order to achieve the common goal of minimizing efforts in porting and in maintaining software onto various platforms, software coding standards and software coding style guidelines have been introduced. The latter is strongly motivated by the fact that once used and accepted in an industrial environment, the software may reach a lifetime an order of magnitude larger than the current span of the project. The code is being written in FORTRAN 77 (allowing some FORTRAN 90 extensions) and the message passing software library MPI, which is an industrial standard and in the public domain, will be used for the parallelisation. Critical aspects of software quality assurance and software configuration management have also been addressed.

Numerous test cases have been chosen in order to verify and validate the code over the entire operating regime of the rotor and include both 2D and 3D steady and unsteady flow cases. Specific reference is made to the user and software requirements that will be verified by each test case.

Grid Generation

Grid generation has a fundamental importance in all aerodynamics simulations and even more so in rotorcraft aerodynamics. The complex flowfield and the multiple bodies in relative motion (fuselage, main and tail rotor blades, platform) pose specific requirements on the grids and on the grid generation procedures. Even isolated rotor calculations require grids with varying characteristics if one considers a single blade or multiple blades, in hover or forward flight, with wake capturing or wake modelling, in rigid-body motion or with elastic deformations. Grids are needed with characteristics to capture accurately the wakes, the shocks and to cluster the points along characteristic surfaces at an intermediate distance from the blade where adequate resolution is needed to obtain useful data for acoustic prediction codes. Unique to rotorcraft simulations is the requirement to maintain grid quality in the far field in order to capture adequately the helicoidal rotor wakes over large distances. Grid quality is also an important issue because it affects the accuracy and convergence rate of numerical solutions. Also, for hover simulations the front and aft boundaries are required to form a perfect match at the inter-blade distance so as to avoid interpolation errors.

The existing 'commercial' grid generation packages are not able to meet the unique requirements of rotorcraft simulations. No one package covers fully the dynamic geometrical problems that need to be adressed: surface grid generation, volume grid generation, volume grid adaption/ deformation/ rotation/ positioning, dynamic connectivity and animation/prototyping of the dynamic geometries. Single-block grids are limited to simple blade shapes and are inefficient for accurately capturing and adapting to the vorticity regions. Multi-block methods are too demanding for 'non-grid expert' users and have an unacceptable turnaround time. Unstructured methods are not considered to be mature enough for a complete rotor simulation in forward flight particularly in view of extensions to Navier-Stokes simulations.

The stringent requirements of rotorcraft simulations inevitably lead to choosing the Chimera (overlapping grid, overset grid) domain decomposition approach on structured grids. The Chimera approach is selected for its natural adaptation to flow and dynamic (static) geometry characteristics (complexities), reduced wall clock times by simplifying grid generation, better accuracy using shape conforming grids and short familiarisation times. The approach has already been applied effectively to rotorcraft.(7, 8, 9, 14, 17) It consists of generating independent body conforming grids around separate geometrical components or separate parts of each component. The partial domains covered by these individual grids do not match exactly but rather overlap each other. Generally, a series of these body conforming "child" grids are embedded in a background grid ("parent" grid) of simple structure covering the whole domain. The subdomains associated with the child grids are blanked out in the parent grid, forming "holes". The parent/child or child/child overlapping regions require information to be transferred between the different grids by interpolation for which the connectivity has to be derived. This methodology provides the user with great flexibility while assuring high quality grids on the various rotorcraft components and in *interesting* regions of the flowfield.

The GEROS grid generation code has been designed(25) to comply as much as possible with the industrial requirements of rotorcraft manufacturers. The most important requirements are:

- ease of use for 'non-expert' and 'black-box' users,
- hardly any restriction in topology:
  tailored to multi-blade advanced CFD applications in hover and forward flight from simple (rectangular) to advanced (BERP-type) rotor blade geometries,
- growth potential in dealing with more advanced CFD (Navier-Stokes) and geometrical complexities (full rotorcraft),
- grid adaption,
- spacing control to pre-adapt zones where large gradients might occur (blade surface, wake surface, tip vortex and shock locations),
- matching front and rear faces (periodicity) for hover simulations,
- acceptable quality with respect to: orthogonality; stretching and aspect ratio of cells;
- quality analysis which might provide the priority in defining the connectivity of the grids,
- grid dynamics (rigid DOFs + elastic motion),
- robust and fast.

The grid generator approaches an **ALL-in-ONE** capability for grid generation by providing the following features:(26, 27)

- surface grid generation
  - parent segments described by discrete data
  - bilinear and/or NURB interpolation
  - control of spacing at patch edges
- volume grid generation
  - algebraic generation
  - elliptic smoothing
  - a posteriori quality enhancement
- volume grid dynamics (deformation and motion)
  - algebraic deformation
- multicomponent (Chimera) tagging and interpolation
  - CPMGRD algorithm with improved dynamic tagging
  - trilinear interpolation, volume spline interpolation
- explicit adaption by special cartesian adaption grids within the Chimera scheme
- visual inspection and prototyping by VISUAL3 link
- interactive control with on-line help functionality
- script control
- script driven batch operations
- coded in FORTRAN 77 with FORTRAN 90 extensions.

The embedded script facility allows the gridding process to be repeatable and to be documented and creates considerable flexibility for the user. It is also helpful when adaptation is required for the surface grids in which case a new surface grid can be generated based on the original input data by a reversed call of the solver. The prototyping feature allows the inspection and animation of the location and other characteristics of the deforming grids and their connectivity in relative motion for all azimuthal angles and all blades prior to the CFD simulation.

At present the basic components of the method have been realized and research is being performed aimed at improving the critical components of the process cycle. The main structure of the GEROS code, which is divided into 6 subsystems to perform the aforementioned main tasks, is shown in figure 1. Typical capabilities of the code are shown in figures 2-6. Figure 2 shows the surface grid on a BERP-type (British Experimental Rotor Programme) rotor blade. An O section at the blade root is also shown. Figure 3 shows a periodic O-H volume grid about the blade together with two embedded H-H grids for capturing the tip vortices of the current blade and the preceding one. The blade tip region containing the grid on the rotor disc plane is shown in detail. The prototyping feature of the GEROS code is shown in figure 4. A 4-bladed rotor with the different characteristics of the individual grids is *flown* inside the background grid. The volume grids shown in figures 3 and 4 have been smoothed elliptically. Figure 5 illustrates the status of the Chimera tagging applied to a multi-component airfoil. The trivial tagging results in a maximum overlap while the CMPGRD type of tagging, in which the child grid has highest priority, results in minimum overlap. The *smart* tagging is being developed which gives the highest priority to the smallest volume in the two grids. It is expected that this last tagging algorithm will be a significant improvement over the first two. The capabilities of the algebraic deformation module may be seen in figure 6 where the blade undergoes large pitch motions and vertical elastic deformations at the tip while the outer boundaries of the O-H grid are maintained fixed.

Euler Solver

The organizations in the consortium have a wide experience in developing time-accurate Euler codes, both for fixed wing(28, 29, 30, 31) and rotary wing(32, 19, 18) applications, and have carefully evaluated the formulations that could best satisfy the industrial requirements. A formulation had to be chosen that would guarantee:

- multi-blade calculations with geometrically complex blades;
- wake-capturing capabilities for a large portion of the wake near the rotor;
- accurate solutions within the time limits dictated by an industrial environment.

The industrial requirements have stressed the need for a robust and well established formulation that could be used with confidence in an industrial context. Nevertheless, the research centres have also answered to their mission of promoting state-of-the-art algorithms that would ensure Europe's competitiveness in the years to come. The EROS code is based on a proven-technology unsteady Euler formulation on overlapping structured grids.(33) Its main elements are:

- Euler equations in relative frame using absolute velocities;
- Chimera domain decomposition of structured grids;
- cell-centred finite-volume formulation;
- central discretisation with scalar dissipation or Roe flux difference splitting with MUSCL approach;
- dual-time implicit scheme with explicit Runge-Kutta or factored-unfactored implicit methods in pseudo time;
- boundary element method (BEM) inflow modelling;
- weak coupling to aeroelastic codes through a deforming grid approach.

The decision to adopt a Chimera domain decomposition of structured grids is fundamental in providing the user with wide flexibility and simplifies the inputs needed from an industrial user when performing domain decomposition of complex rotor configurations. The Chimera method is based on the decomposition of a complex geometry into a number of geometrically simple component grids. Trilinear interpolation is used to transfer information across the grid overlap regions. The Chimera method may also be useful as a tool for domain partitioning and inter-domain communications in view of implementations on parallel architectures.

A cell-centred finite volume formulation has been chosen for the Euler equations written in the relative frame. The choice of the Chimera algorithm was the motivating factor behind the choice of formulating the momentum conservation law in the non-inertial frame linked to each blade. The conservative variables are written using absolute velocities in order for the numerical scheme to have good free stream conservation properties. Two spatial discretisation schemes have been implemented. They are the classical central scheme with a scalar artificial dissipation according to Jameson and the flux difference splitting of Roe with a MUSCL variable extrapolation to achieve second order accuracy.

An implicit dual-time method has been chosen for the time discretisation scheme and allows an implicit discretisation to be used in real time, but at each time step marches the solution in pseudo time to steady state. This permits the acceleration techniques of steady flow, such as local time stepping, residual smoothing, multigrid or implicit methods to be used in pseudo time since real time is fixed. This also allows the real time step to be chosen based on accuracy requirements alone and not on stability restrictions. Two methods may be used to solve the steady state problem in pseudo time: a multistage Runge-Kutta explicit time stepping scheme and an implicit factored-unfactored (FUN) method where the two-dimensional unfactored term is solved with a Conjugate Gradient type method with preconditioning. Convergence acceleration in pseudo time is performed through local time stepping and implicit residual smoothing for the Runge-Kutta scheme.

Four distinct types of boundary conditions occur when simulating inviscid rotor flows. On a solid body the physical condition of no-normal flow is imposed through the concept of ghost cells. Boundary conditions at the inboard cylinder are needed only when performing single blade simulations, in hover and forward flight conditions. Since the proper handling of these boundary conditions is still an open problem, different formulations have been implemented: zero normal flow condition, characteristic type condition, and extrapolation type condition. The flow field around a multibladed hovering rotor may be subdivided into subdomains in which the flow is periodic. The grid generator allows the generation of grids with an exact match of the inflow and outflow planes thus allowing the simple definition of symmetry conditions on these two planes. A characteristic type boundary condition is applied at the far field based on freestream conditions if the far field is placed relatively far from the body. When the far field boundary is placed relatively close to the body, the characteristic type boundary condition uses conditions calculated through a boundary element method.

This leads to a feature in the EROS code which is not common in Euler codes. Although Euler codes naturally capture the wake (within the limits imposed by numerical diffusion), full Euler multibladed calculations are computationally very intensive and it is likely that in an industrial context a lot of analysis will be performed on single bladed configuration with wake modelling. Wake modelling(16, 34) is a means by which the influence of the far wake and of the *other* blades are modelled by a boundary element method and felt by the single blade as an inflow through its boundary conditions. Two types of coupling have been implemented between the boundary element method and the Euler solver:

- wake-induced flow prescribed at the blade surface (lifting-line and lifting-surface approach),
- improvement of the far-field boundary conditions.

Another feature which is fundamental to the industrial use of the code is the weak coupling to comprehensive aeroelastic codes. Modern rotor blades are extremely flexible (especially in torsion) and it is imperative that any CFD simulation be able to take into account blade elastic deformations. A deforming grid approach is implemented in the EROS code in order to account for the deformations computed by an external comprehensive aeroelastic code.

The above formulation has been implemented into a software package with numerous features intended to assist the user during the simulation:(35)

- interactive input with on-line help functionality
- script control
- script driven batch operations
- visual inspection by VISUAL3 link.

The interactive input with the on-line help functionality is essential in guaranteeing that the various numerical schemes are properly used even by a non-CFD expert. The embedded script facility allows the simulation process to be repeatable and to be documented. The main structure of the EROS code is shown in Fig. 7.

Applications

Two years into the project only a limited number of test cases have been performed with respect to the large number of applications that are planned by the end of the project. The main focus at this stage is to verify the various numerical algorithms on increasingly complex applications (2D/3D steady fixed wing ⇒ rotors) and check the links between the solver and the grid generator.

The first test case is the steady flow over a NACA0012 airfoil at $M_\infty = 0.8$ and $\alpha = 1.25°$. Figure 8 shows the computed pressure coefficient over the airfoil using a 128x32 C grid. The EROS solution compares well with the AGARD-AR-211 reference solution obtained on a much finer grid. The solution technique consists of an explicit starting procedure followed by the implicit FUN scheme with a *2nd* order Roe upwind scheme. The convergence behavior of such a technique is shown in figure 9.

The second steady test case considered is the ONERA M6 wing at $M_\infty = 0.84, \alpha = 3.06°$ which represents attached flow conditions. Figure 10 shows the computed pressure coefficient at several spanwise locations. The present method is compared to experimental data and to another Euler method.(30) The agreement is fairly good with discrepancies limited to the tip region. Figure 11 shows the isobar contours on the upper surface of the wing and the agreement of the two numerical methods is relatively good. The present method uses a 128x32x32 C-H grid with 96 points along the chord and 20 points along the span. The same solution technique as in the steady airfoil case is used. The convergence behaviour for this steady wing case is shown in figure 12.

An unsteady test case is presented in order to show the time-accurate nature of the method. The standard AGARD CT5 test case is chosen consisting of a NACA0012 airfoil pitching about its quarter chord at transonic conditions ($M_\infty = 0.755$, mean angle of attack $\alpha_m = 0.016°$, amplitude $\Delta\alpha = 2.51°$ and reduced frequency based on semichord $k = 0.0814$). Figure 13 shows the instantaneous pressure distributions and Mach contours as the airfoil undergoes a complete oscillation. The present method compares well with the experimental data except in the upstroke region (figures 13a and 13b) where the uncertaincies in the measured phase angle seem most relevant. This behaviour has also been observed in other Euler methods.(14, 29) The results of the present method are shown on two different C grids of nearly the same dimensions, 128×29 and 128×32, produced independently by two partners. Both runs were performed using an explicit starting procedure followed by the implicit FUN scheme with a *2nd* order Roe upwind scheme. No significant differences may be observed in the two solutions. Figures 14 and 15 show the evolution of the normal force and moment coefficients through 3 cycles after which the solution is periodic. The comparison with the experimental data is reasonable and similar to other Euler methods.(14, 29)

A single blade case in non-lifting forward flight is considered. It consists of a rectangular NACA0012 blade of aspect ratio 6 in high speed flight. The code was run in steady mode at three azimuthal stations. Figure 16 shows the relative Mach number distribution on the blade and in the rotor disk plane at $\Psi = 60°, 90°, 120°$. The influence of the varying freestream may be seen as the blade advances from 60° to 120° and the direction of the spanwise component of velocity changes sign.

Conclusions and Future Prospects

The EROS rotorcraft aerodynamics simulation system is under development in Europe. It will be the answer to the rotorcraft manufaturers' need for a prediction tool able to capture rotational phenomena, such as blade tip and wake vortices, and to predict correctly the unsteady blade pressures over a range of different flight conditions. The system is composed of the GEROS grid generator and Chimera domain modeller and the EROS Euler code. It is being developed through a structured software life cycle which guarantees the conformity of the software to the industrial requirements.

The baseline version of the code is presently undergoing verification and the preliminary results are encouraging. The verification activities are to cover all operational conditions of the code from steady two-dimensional conditions to multi-bladed forward flight conditions and aim to test all aspects of the code so as to detect any weak areas that need to be addressed in order to meet fully the industrial requirements. The recommendations from the validation phase will be the input to the last phase of the project in which the developing partners will improve the efficiency of the code (*e.g.* parallel implementation on a system of distributed workstations, faster tagging algorithms) and will extend its capabilities (*e.g.* improved surface grid generation).

The project is forging together an experienced research group combining the experience of industry, research centres and academia to develop a methodology for common code development in Europe. This experience is not only crucial in future extensions of the system to Navier-Stokes but also lays down the foundation for common European efforts addressing the multidisciplinary rotorcraft problem.

Acknowledgements

This work is partly supported by the European Union under the Brite-EuRam Contract No. BRPR-CT96-0162 (EROS project).

References

[1] L.N. Sankar, B.E. Wake, and S.G. Lekoudis. Solution of the Unsteady Euler Equations for Fixed and Rotor Wing Configurations. *AIAA Journal of Aircraft*, 23(4):283–289, April 1986.

[2] R.K. Agarwal and J.E. Deese. Euler Calculations for Flowfield of a Helicopter Rotor in Hover. In *Proceedings of the AIAA 4th Applied Aerodynamics Conference*, AIAA-86-1782, June 1986.

[3] N. Kroll. Computation of the Flow Fields of Propellers and Hovering Rotors Using the Euler Equations. In *Proceedings of the 12th European Rotorcraft Forum*, Garmish-Partenkirchen, Germany, September 1986.

[4] E. Krämer, J. Hertel, and S. Wagner. Computation of Subsonic and Transonic Helicopter Rotor Flow Using Euler Equations. In *Proceedings of the 13th European Rotorcraft Forum*, Arles, France, 1987.

[5] A.J. Landgrebe. New Direction in Rotorcraft Computational Aerodynamics Research in the U.S. In *Proceedings of the AGARD FDP Aerodynamics and Aeroacustics of Rotorcraft Symposium*, AGARD-CP-552, Berlin, Germany, August 1994.

[6] G.R. Srinivasan and W.J. McCroskey. Navier-Stokes Calculation of Hovering Rotor Flowfields. *AIAA Journal of Aircraft*, 25(10):865–874, October 1988.

[7] E.P.N. Duque and G.R. Srinivasan. Numerical Simulation of a Hovering Rotor Using Embedded Grids. In *Proceedings of the 48th Annual American Helicopter Society Forum*, Washington, D.C., June 1992.

[8] R.L. Meakin. Moving Body Overset Grid Methods for Complete Aircraft Tiltrotor Simulations. In *Proceedings of the AIAA 11th Computational Fluid Dynamics Conf.*, AIAA-93-3350-CP, pages 576–588, Orlando, FL, July 1993.

[9] J. Ahmad and E.P.N. Duque. Helicopter Rotor Blade Computation in Unsteady Flows Using Moving Overset Grids. In *Proceedings of the AIAA 12th Applied Aerodynamics Conference*, Colorado Springs, CO, June 1994.

[10] N. Hariharan and L.N. Sankar. High Order Numerical Simulation of Rotor Flow Field. In *Proceedings of the 50th Annual American Helicopter Society Forum*, Washington, D.C., May 1994.

[11] E. Krämer, J. Hertel, and S. Wagner. Euler Procedure for Calculation of the Steady Rotor Flow with Emphasis on Wake Evolution. In *Proceedings of the AIAA 8th Applied Aerodynamics Conference*, AIAA-90-3007-CP, Portland, Oregon, August 1990.

[12] J. Raddatz and K. Pahlke. 3D Euler Calculations for Multibladed Rotors in Hover: Investigation of the Wake Capturing Properties. In *Proceedings of the AGARD Aerodynamics and Aeroacoustics of Rotorcraft Symposium*, AGARD-13, Berlin, Germany, October 1994.

[13] R. Stangl and S. Wagner. Calculation of the Steady Rotor Flow Using an Overlapping Embedded Grid Technique. In *Proceedings of the 18th European Rotorcraft Forum*, Avignon, France, September 1992.

[14] K. Pahlke and J. Raddatz. Flexibility Enhancement of Euler Codes for Rotor Flows by Chimera Techniques. In *Proceedings of the 20th European Rotorcraft Forum*, Amsterdam, NL, October 1994.

[15] J.-C. Boniface, B. Mialon, and J. Sidès. Numerical Simulation of Unsteady Euler Flow around Multibladed Rotors in Forward Flight using a Moving Grid Approach. In *Proceedings of the 51st Annual American Helicopter Society Forum and Display*, Fort Worth, TX, USA, May 1995.

[16] D. Wehr, L. Zerle, and S. Wagner. Coupling Euler and Potential Methods for the Calculation of Helicopter Rotors in Unsteady Forward Flight. In *Proceedings of the 22nd European Rotorcraft Forum*, Brighton, (UK), September 1996.

[17] R. Stangl and S. Wagner. Euler Simulations of a Helicopter Configuration in Forward Flight Using a Chimera Technique. In *Proceedings of the 52nd Annual American Helicopter Society Forum*, Washington, D.C., June 1996.

[18] J.-C. Boniface and K. Pahlke. Calculations of Multibladed Rotors in Forward Flight using 3D Euler Methods at DLR and ONERA. In *Proceedings of the 22nd European Rotorcraft Forum*, Brighton, UK, September 1996.

[19] J.-C. Boniface and J. Sidès. Numerical Simulation of Steady and Unsteady Euler Flows Around Multibladed Helicopter Rotors. In *Proceedings of the 19th European Rotorcraft Forum*, C10, Cernobbio (Como), Italy, September 1993.

[20] P. Renzoni. European Calculations of the Flowfield of Helicopter Rotors in Hover using the Euler Equations. In *AERODAYS 93, Second Community Aeronautics RTD Conference*, Naples, Italy, October 1993.

[21] K. Pahlke, J. Sidès, and D. Wehr. Two- and Three-Bladed ONERA Model Rotor. In W. Haase, E. Chaput, E. Elsholz, M.A. Leschziner, and U.R. Müller, editors, *ECARP - European Computational Aerodynamics Research Project: Validation of CFD Codes and Assessment of Turbulence Models*, volume 58 of *Notes on Numerical Fluid Mechanics*. Vieweg, 1997.

[22] J. Raddatz and O. Rouzaud. Calculations of Multibladed Rotors in Hover Using 3D Euler Methods of DLR and ONERA. In *Proceedings of the 21st European Rotorcraft Forum*, Saint Petersburg, (Russia), September 1995.

[23] M. Costes, J.C. Le Balleur, L. Gasparini, L. Vigevano, M.H.L. Hounjet, A. Kokkalis, J.V. Miller, M. Spruce, A. Pagano, P. Renzoni, A. Rocchetto, and F. Toulmay. Development of a Common European Unsteady Full Potential CFD Code for Helicopter Rotors in Hover and Forward Flight. In *Proceedings of the 53rd Annual Forum of the American Helicopter Society*, Virginia Beach, VA, April 1997.

[24] *ESA Software Engineering Standards*. ESA PSS-05- Issue 2, February 1991.

[25] M.H.L. Hounjet , A. D'Alascio, P. Renzoni, K. Pahlke, J. Westland, L. Gasparini, L. Vigevano, C.B. Allen, S.P. Fiddes, L. Dubuc, and A. Kokkalis. A Formulation of a Grid Generator for a Rotorcraft Simulation. NLR TR 97024 L, January 1997.

[26] M.H.L. Hounjet, A. Pagano, A. D'Alascio, L. Gasparini, L. Vigevano, C.B. Allen, and S.P. Fiddes. Precoding of a Grid Generator for a Rotorcraft Simulation Method. Volume 1: Predesign and Reference Manual, Volume 2: Appendices. NLR TR 98049 VOL-1,VOL-2, January 1998.

[27] M.H.L. Hounjet, C.B. Allen, L. Gasparini, L. Vigevano, and A. Pagano. GEROS: A European Grid Generator for Rotorcraft Simulation Methods. In *Proceedings of the 6th International Conference on Numerical Grid Generation in Computational Field Simulation*, London, UK, July 1998.

[28] D. Ambrosi, L. Gasparini, and L. Vigevano. Full Potential and Euler Solutions for Transonic Unsteady Flow. *Aeronautical Journal*, 98:340–348, 1994.

[29] C.B. Allen. Adaption by Grid Motion for Unsteady Euler Aerofoil Flows. In *Progress and Challenges in CFD Methods and Algorithms*, AGARD-CP-578, Seville, Spain, October 1995.

[30] B. Prananta and M.H.L. Hounjet. Aeroelastic Simulation with Advanced CFD Methods in 2D and 3D Transonic Flow. In *Proceedings Conference on Unsteady Aerodynamics*, RAeS, London, July 1996.

[31] R. Heinrich, K. Pahlke, and H. Bleecke. A Three-Dimensional Dual-Time Stepping Method for the Solution of the Unsteady Navier-Stokes Equations. In *Proceedings Conference on Unsteady Aerodynamics*, RAeS, London, July 1996.

[32] K. Pahlke and Raddatz J. 3D Euler Methods for Multibladed Rotors in Hover and Forward Flight. In *Proceedings of the 19th European Rotorcraft Forum*, C20, Cernobbio (Como), Italy, September 1993.

[33] A. D'Alascio, P. Renzoni, N. Kroll, M.H.L. Hounjet, J.J.W. van der Vegt, J.-C. Boniface, J. Sidès, L. Gasparini, L. Vigevano, C.B. Allen, L. Dubuc, F. Salvatore, L. Morino, and E. Schöll. Formulation of an Euler Rotorcraft Simulation Method. CIRA-TR-97-044, March 1997.

[34] H. Khanna and J.D. Baeder. Free-Wake/CFD Coupled Solutions for Hovering Rotors Using a Field Velocity Approach. In *Proceedings of the 52nd Annual American Helicopter Society Forum*, Washington, D.C., June 1996.

[35] A. D'Alascio, D. Peshkin, N. Kroll, M.H.L. Hounjet, J.J.W. van der Vegt, J.-C. Boniface, L. Gasparini, L. Vigevano, C.B. Allen, L. Dubuc, F. Salvatore, L. Morino, and E. Schöll. Software Design and Reference Report of the EROS Rotorcraft Simulation Method. CIRA-TR-97-141, November 1997.

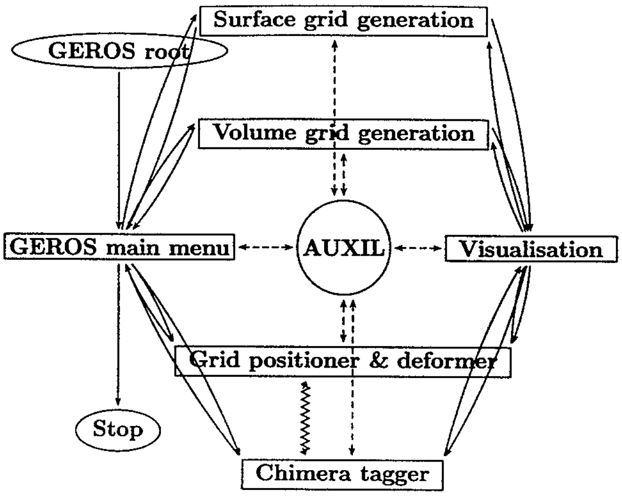

FIGURE 1 - GEROS structure.

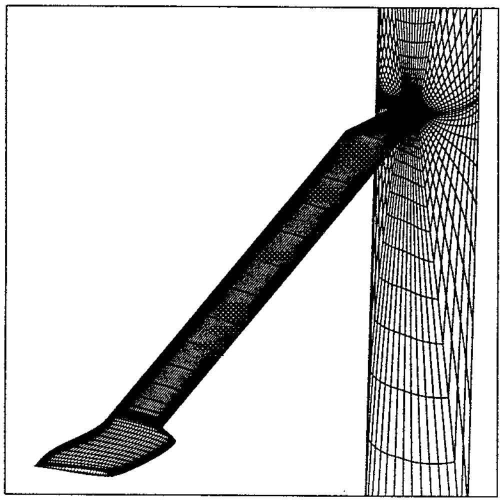

FIGURE 2 - Surface grid on BERP-type blade.

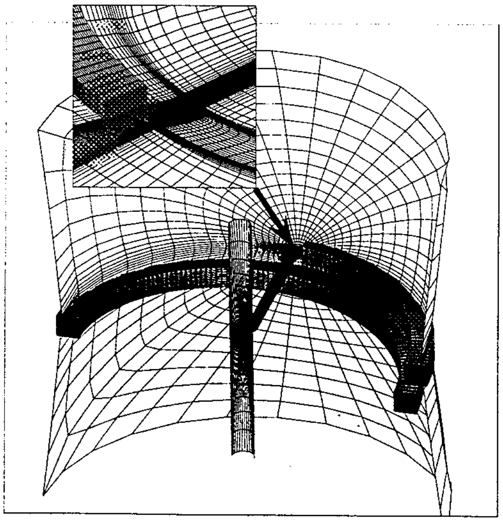

FIGURE 3 - Periodic O-H grid about BERP-type blade with 2 embedded H-H tip vortex grids.

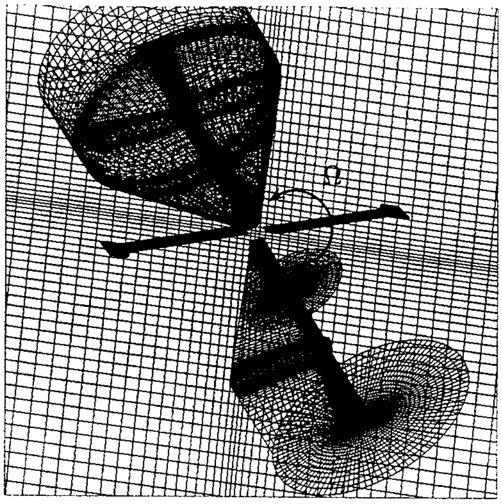

FIGURE 4 - Animation of grids about a 4-bladed rotor.

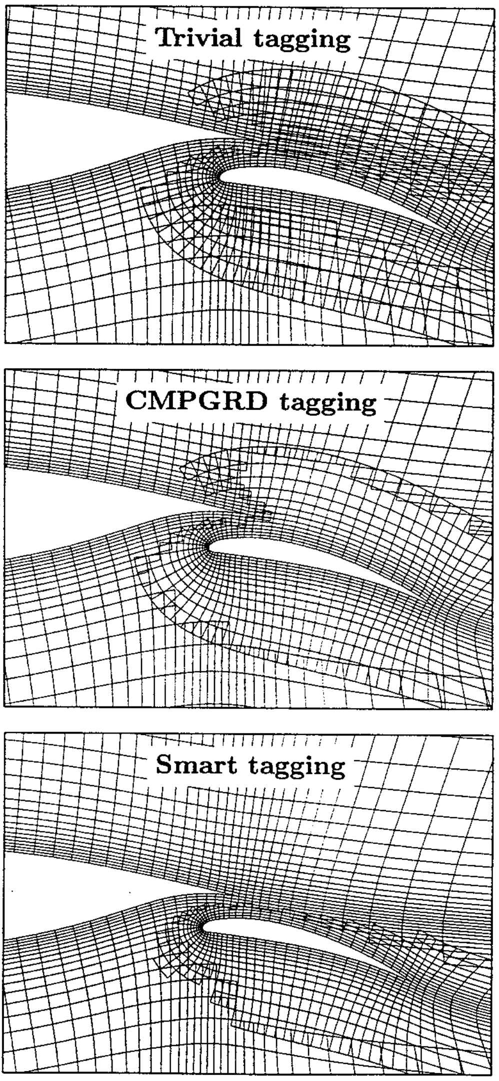

FIGURE 5 - Different tagging algorithms on a multi-component airfoil.

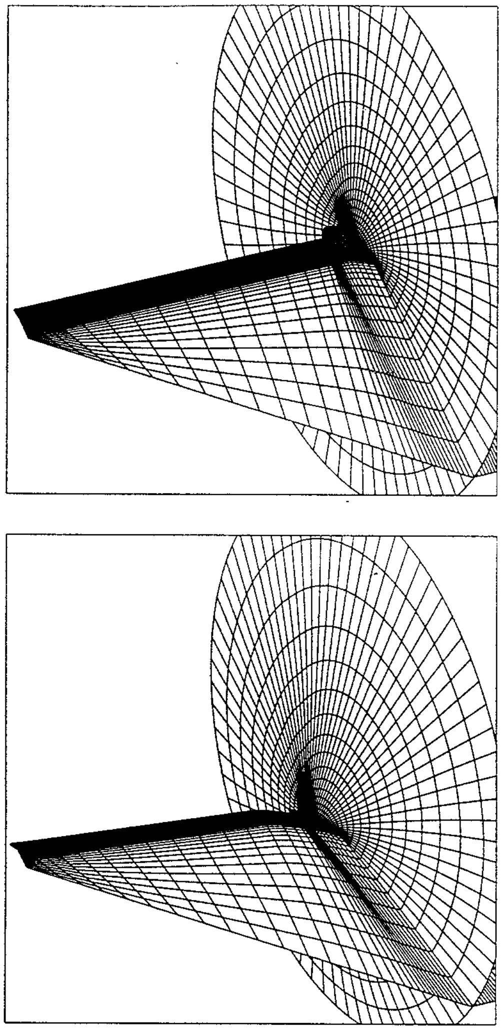

FIGURE 6 - Deformation of an O section due to large pitch and vertical elastic blade deformations.

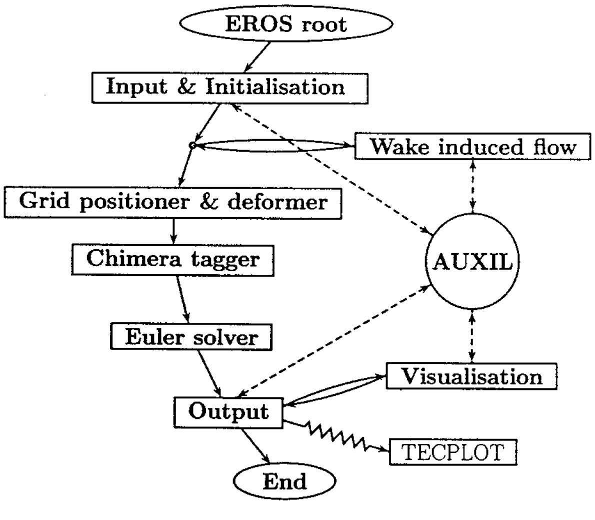

FIGURE 7 - EROS structure.

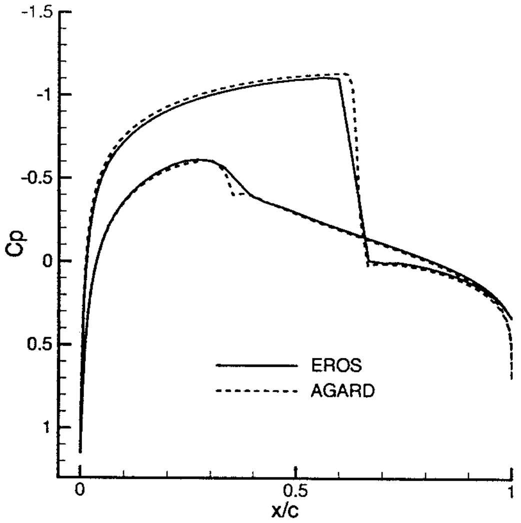

FIGURE 8 - Pressure distribution on NACA0012 airfoil ($M_\infty = 0.8, \alpha = 1.25°$).

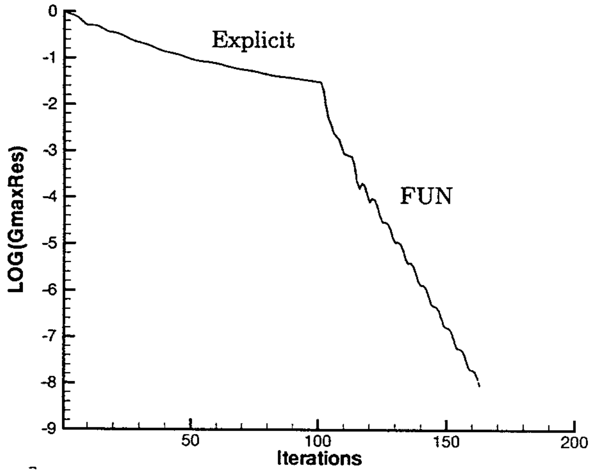

FIGURE 9 - Convergence history of steady NACA0012 airfoil case.

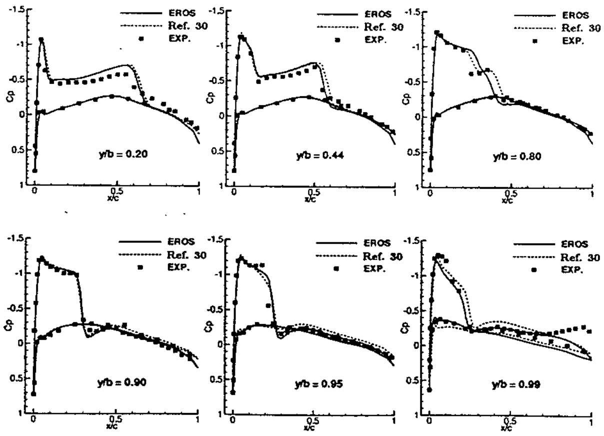

FIGURE 10 - Pressure distributions on ONERA M6 wing ($M_\infty = 0.84, \alpha = 3.06°$).

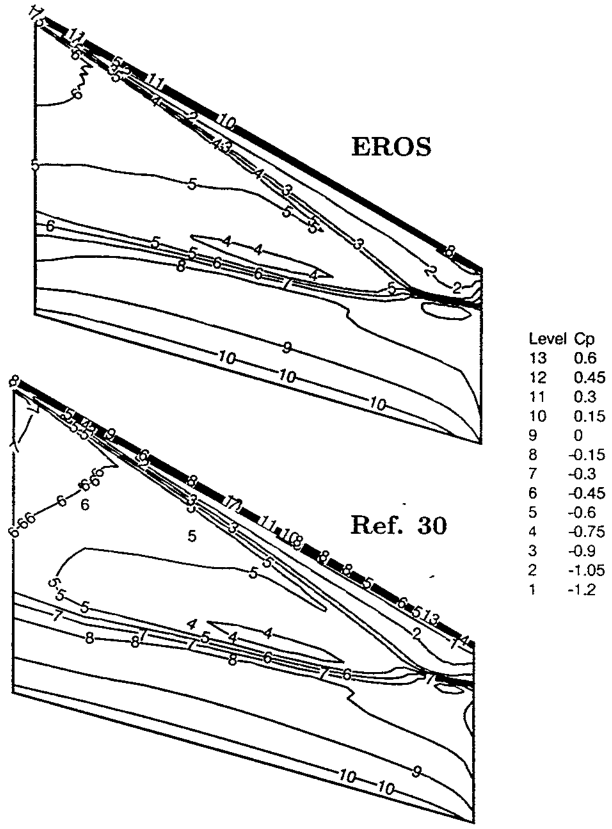

FIGURE 11 - Comparison of EROS and Ref. 30 calculated isobar contours for the M6 wing.

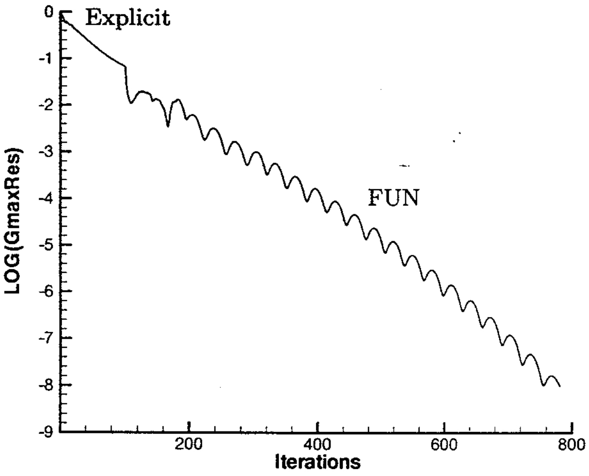

FIGURE 12 - Convergence history of steady M6 wing case.

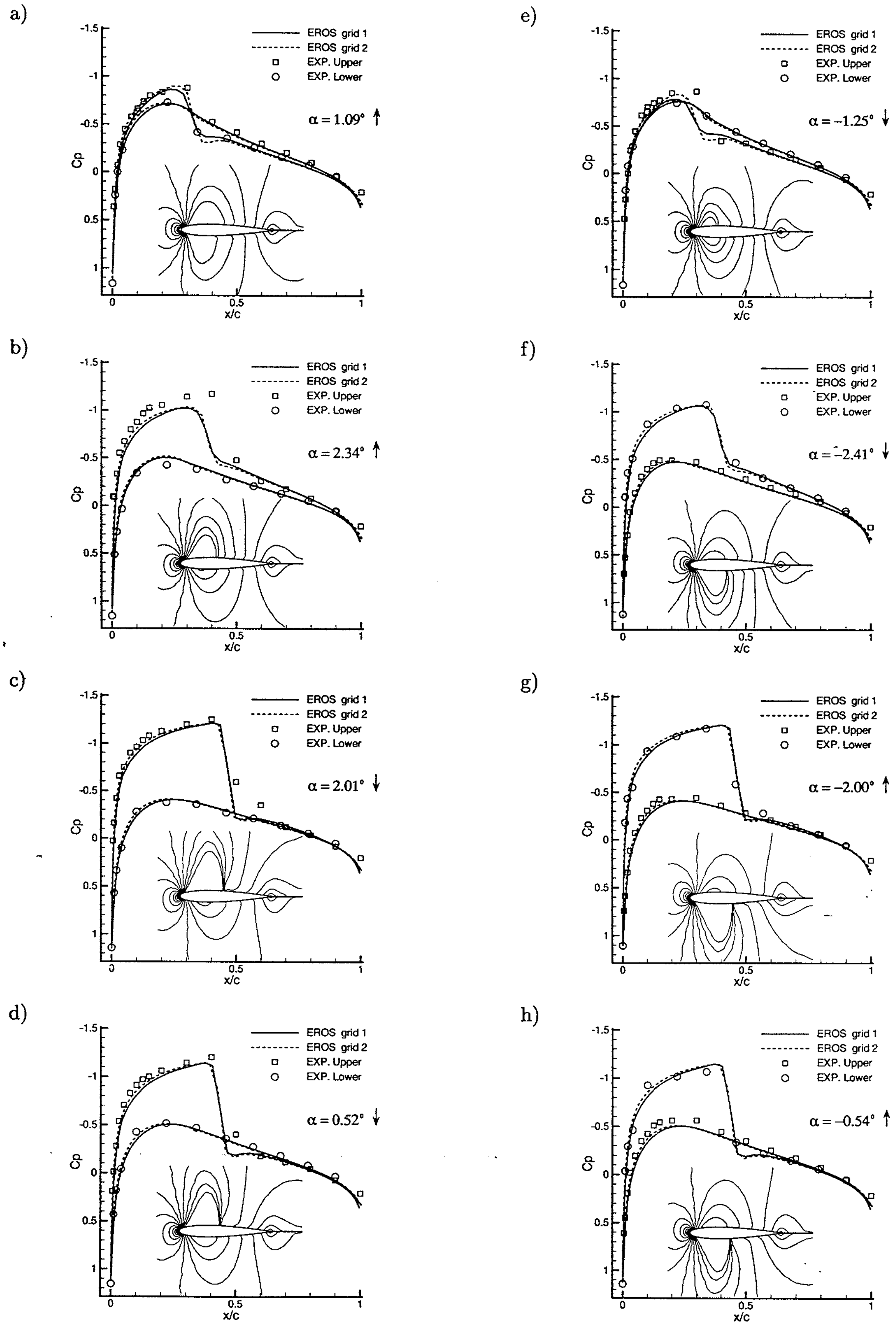

FIGURE 13 - Instantaneous pressure distributions and Mach contours on a NACA0012 airfoil oscillating about its quarter chord - $M_\infty = 0.755, k = 0.0814, \alpha = 0.016^\circ + 2.51^\circ sin(\omega t)$.

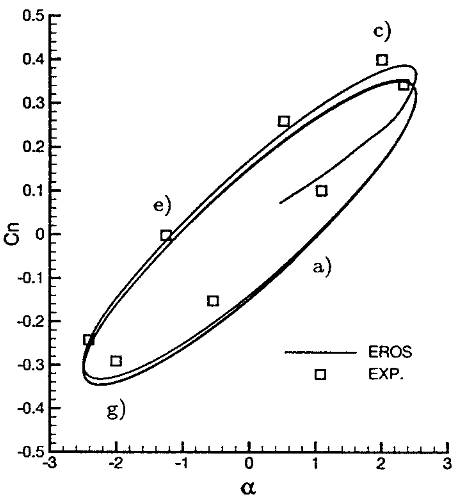

FIGURE 14 - Normal force coefficient distribution on an oscillating NACA0012 airfoil.

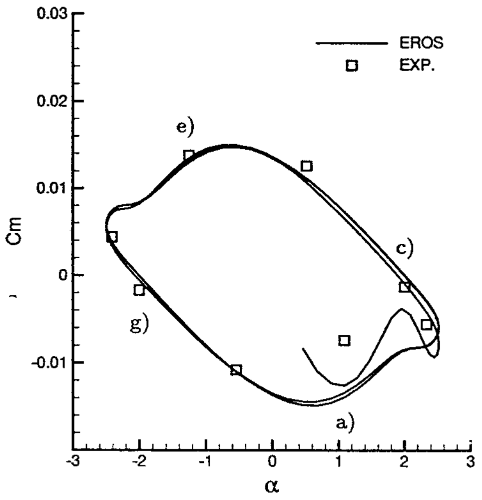

FIGURE 15 - Moment coefficient distribution on an oscillating NACA0012 airfoil.

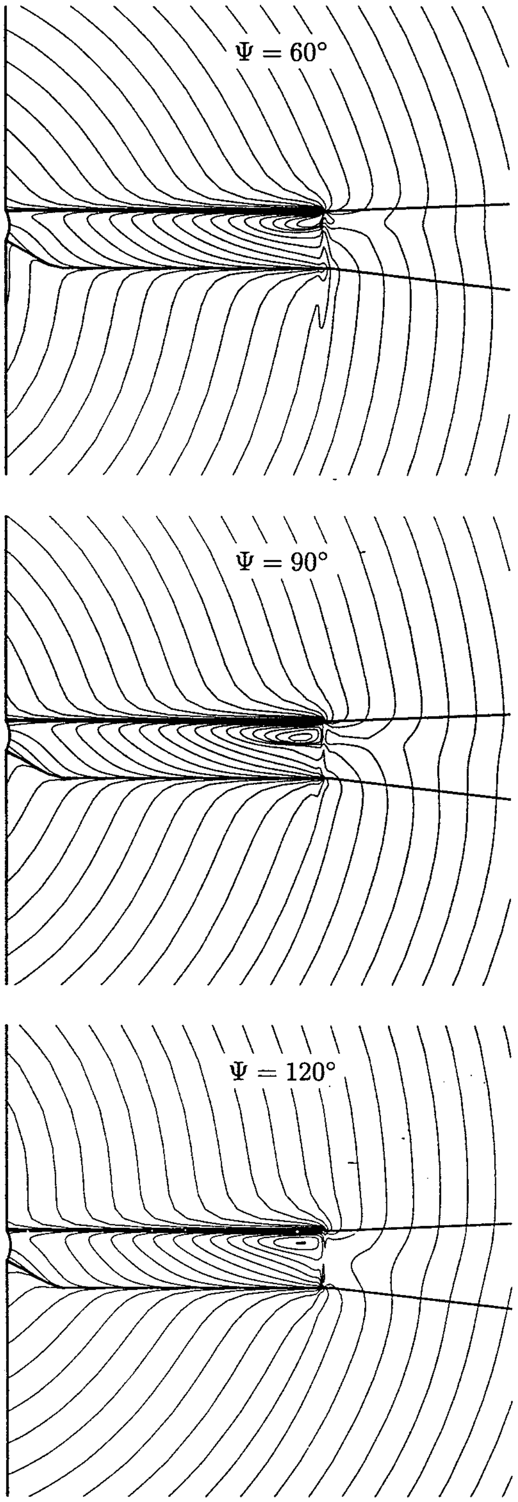

FIGURE 16 - Relative Mach number at $\Psi = 60°, 90°$ and 120° on the blade surface and in the rotor disk ($M_{\omega R} = 0.624$, $\mu = 0.4$, $M_\infty = 0.25$)