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GRID RELATED ISSUES FOR STATIC AND DYNAMIC GEOMETRY PROBLEMS USING SYSTEMS OF OVERSET STRUCTURED GRIDS

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SUMMARY

Grid related issues of the Chimera overset grid method are discussed in the context of a method of solution and analysis of unsteady three-dimensional viscous flows. The state of maturity of the various pieces of support software required to use the approach is considered. Current limitations of the approach are identified.

INTRODUCTION

Unsteady three-dimensional viscous flow represents an important class of problems for which accurate methods of prediction are frequently required. Such applications are almost always complicated geometrically, may also involve relative motion between component parts, and exist in virtually all engineering disciplines. Experimental methods of analysis, including scale-model and full-scale prototype testing, are often not possible due to excessive cost, model limitations, human safety factors, and time-constraints associated with a commercially competitive environment. Mature computational methods are not always appropriate due to inherent method limitations. Unsteady viscous flowfields involving vortical wakes, interference effects, moving shocks, and body motion demand the most advanced computational means available.

Currently, the only viable high-order method of prediction for these problems is the so called Chimera (ref. 1) overset grid approach. The approach involves the decomposition of problem geometry into a number of geometrically simple overlapping component grids. Multiple-body applications, such as aircraft store-separation (refs. 2-7), are treated naturally in this way. Components of a particular configuration can be altered, or changed completely, without affecting the rest of the grid system (ref. 8). Grid components associated with moving bodies move with the bodies without stretching or distorting the grid system. The approach is applicable to both internal and external flow applications, though most of the Chimera-related algorithm development has thus far been motivated by external flow applications.

The computational incentives for employing an overset grid approach for unsteady three-dimensional viscous flows are multiple. The flow solution process is applied to topologically simple component grids. Body-fitted component grids are ideally suited to regions of thin shear flows such as viscous boundary-layers, wakes, etc. All the advantages associated with structured data are realizable in the approach, including highly efficient implicit flow solvers, memory requirements, vectorization, and fine-grained parallelism. Grid components can be arbitrarily split to optimize the use of available memory resources. Overset structured grid components provide a natural coarse-grained level of parallelism that can easily be exploited to facilitate simulations within distributed computing environments (refs. 9-12).

The present paper considers the current status of the Chimera-style overset grid method as it applies to unsteady three-dimensional viscous flow. Of course, much of what can be said of Chimera in this context is also true for steady-state (viscous and inviscid) applications. The paper includes discussion on the state of maturity of

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the various pieces of support software required to use the approach, including grid, and flow-solver related issues. Current limitations of the approach are identified and used to suggest needs for future developmental efforts.

THE CHIMERA OVERSET GRID APPROACH

Background

In a Chimera-style overset grid approach, domain connectivity is achieved through interpolation of necessary intergrid boundary information from solutions in the overlap region of neighboring grid systems. Consider, for example, the simple two grid discretization of the airfoil shown in figure 1.

The example problem domain is decomposed into a body-fitted grid system near the airfoil surface and a background Cartesian grid system which extends out to the far-field boundaries. The Cartesian grid completely overlaps the airfoil grid. Clearly, the airfoil grid outer boundary conditions can be interpolated from a solution in the off-body Cartesian grid, thereby providing the needed off-body to near-body connection for solution information transfer. It is also clear that a similar transfer of information from the near-body solution back to the off-body solution is required. However, the off-body Cartesian grid has no natural boundaries (physical or numerical) that overlap the near-body grid. The Chimera style of overset gridding makes it possible to create an artificial boundary (hole boundary) within the off-body grid system, and thereby establish the required near-body to off-body connectivity.

A hole boundary for this example is created by excluding the region of the off-body Cartesian grid that is overlapped by the airfoil. The resulting hole region is excluded from the remaining off-body solution. Conditions for the hole boundary are interpolated from the solution in the near-body airfoil grid. In general, one-way communication connections can be established between any set of component grids through hole and outer boundaries. Generalized algorithms for carrying out this task automatically have been developed (refs. 13-19).

Grid Related Issues

Surface decomposition and surface grid generation represent the primary impediments to the maturation of overset grid based methods. The amount of human resources, measured in time and expertise, currently required to generate suitable systems of overset grids for complex configurations lends validity to the notion that the approach is only an intermediate option, and that unstructured grid approaches will ultimately represent the method of choice for this class of problems. Even if this scenario becomes real, it is currently based on the false assumption that grid generation for structured overset grids is a mature discipline. It also greatly devalues the numerous computational advantages realizable through the use of structured data.

The current difficulties associated with surface decomposition and surface grid generation for overset grid systems exist for the simple reason that there has been virtually no research directed at this area. Available structured grid generation software has been developed almost exclusively for "patched," or "blocked" systems (refs. 20-23) which require neighboring grid components to share a common surface. Although differences between overset and blocked methods may appear slight (i.e., one requires neighboring grids to overlap and the other doesn't), the differences are in fact profound. An overset grid approach is really an unstructured collection of overlapping structured grid components. As such, the approach should enjoy most of the grid generation freedoms associated with unstructured grids, and retain, on a component-wise basis, all of the computational advantages inherent to structured data.

Surface Geometry Decomposition. A good philosophy for a surface geometry decomposition software package might be to use the fact that all real objects can be viewed as composites of point and line discontinuities, and simple surfaces. For example, the sharp tip of a nose-cone would be a point. Likewise, sharp edges along a fuselage, the trailing edge of a wing, etc. are lines. All object areas that are not associated with points or lines are simple surfaces. Whether an object area corresponds to a point, line, or simple surface dictates the type of surface grid, and hence, volume grid topology that should be used for the overset grid discretization. A point suggests the need for a "nipple" topology for the object area in the vicinity of the point, and an axis topology for the resulting volume grid. A line suggests the need for grid clustering near the line to maintain the integrity of the line discontinuity in the overset grid component. Surface grids associated with line discontinuities lend themselves directly to hyperbolic surface grid generation techniques. Simple surfaces are amenable to either algebraic or elliptic surface grid generation methods. In an overset grid approach, surface grids associated with all object types (i.e., points, lines, and simple surfaces), are amenable to volume grid generation via hyperbolic methods.

Figure 2a illustrates a panel definition of a tiltrotor surface geometry. Object point and line discontinuities are indicated. A point discontinuity exists at the tip of the nose-mounted pitot tube. Line discontinuities exist at the wing/fuselage intersection, wing trailing edge, nacelle exhaust exit, and along the fuselage/sponson crease. One possible surface decomposition of this geometry definition is shown in figure 2b, where no point discontinuities were retained (pitot-tube and mount were neglected at the discretion of the analyst), but line discontinuities were resolved around the wing/fuselage intersection, wing trailing edge, and fuselage/sponson crease. The line discontinuity at the nacelle exhaust exit was smoothed over (at the discretion of the analyst) and treated as a simple surface. As illustrated by figure 2b, the surface grids that result from this method of surface geometry decomposition is a quilt of overlapping surface components.

Surface Grid Generation. Given a suitable surface geometry decomposition, generation of a corresponding set of overset surface grid components should be realizable in a highly automated way. Most of the basic algorithms needed to develop such software currently exist. Algebraic and elliptic surface grid generation techniques, appropriate for simple surfaces, have long been available (ref. 24). The idea for hyperbolic surface grid generation was first put forward more recently (ref. 25), and has since been generalized (ref. 26).

Volume Grid Generation. Generation of volume grids associated with body surfaces can easily be generated in an overset grid approach using hyperbolic grid generation techniques. Hyperbolic volume grid generators exist that are robust, highly efficient, and very easy to use (ref. 27,28). In an overset grid approach, generation of off-body volume grids is a trivial task. The near-body set of grid components must simply be overset onto a convenient background system of grids. While few software packages are currently available to perform the task of off-body grid generation automatically, the task is still trivial and some software is becoming available (ref. 29).

Domain Connectivity. A considerable amount of research and development in the area of domain connectivity among systems of overset grids has been carried out. Several general purpose algorithms for performing this task automatically are currently available. Although existing domain connectivity algorithms can still be improved in terms of efficiency and automation, this area of overset grid technology is maturing rapidly. Active areas of domain connectivity research include Chimera-style hole-cutting (refs. 17-19), donor search methods (including quality optimization) (refs. 14,17,19), automation (refs. 14,17-19), and parallelization (ref. 10).

The first general purpose domain connectivity algorithms that became widely available are the PEGSUS (ref. 13) and, later, CMPGRD (ref. 14) codes. Both codes enjoy substantial use among overset grid practitioners. Likewise, algorithm development associated with both codes is ongoing. In 1989 the first simulations of unsteady three dimensional viscous flow applications involving moving bodies (ref. 3) were carried out using a script controlled application of PEGSUS and the F3D thin-layer Navier-Stokes solver (ref. 30). The need for greater computational efficiency to carry out such applications, which require domain connectivity every time-step, spawned development of alternative domain connectivity algorithms. The DCF3D (ref. 15) and BEGGAR (ref. 17) codes were designed to accommodate moving body applications and are currently the only domain connectivity algorithms that are fully integrated with general purpose flow-solvers and body dynamics algorithms.

Flow Solver Related Issues

A major advantage of an overset grid approach for solving unsteady three-dimensional viscous flow problems is the fact that existing single grid (structured) flow solvers of documented accuracy and known efficiency can easily be adapted for application within overset grids. For example, the implicit approximately factored algorithm (i.e., block Beam-Warming, ref. 31) for the thin-layer Navier-Stokes equations

$$\partial_\tau \hat{Q} + \partial_\xi \hat{F} + \partial_\eta \hat{G} + \partial_\zeta \hat{H} = R_e^{-1} \partial_\zeta \hat{S} \qquad (1)$$

is easily modified for Chimera-style overset grids as

$$\left[I + i_b \Delta t \delta_\xi \hat{A}^n\right]\left[I + i_b \Delta t \delta_\eta \hat{B}^n\right] \times \qquad (2)$$

$$\left[I + i_b \Delta t \delta_\zeta \hat{C}^n - i_b \Delta t R_e^{-1} \delta_\zeta J^{-1} \hat{M}^n J\right] \Delta \hat{Q}^n =$$

$$- i_b \Delta t \left(\delta_\xi \hat{E}^n + \delta_\eta \hat{F}^n + \delta_\zeta \hat{G}^n - R_e^{-1} \delta_\zeta \hat{S}^n\right)$$

The single and overset grid versions of the algorithm are identical except for the variable i_b, which accommodates the possibility of having arbitrary holes in the grid. The array i_b has values of either 0 (for hole points), or 1 (for conventional field points). Accordingly, points inside a hole are not updated (i.e., $\Delta Q = 0$) and the intergrid boundary points are supplied via interpolation from corresponding solutions in the overlap region of neighboring grid systems. By using the i_b array, it is not necessary to provide special branching logic to avoid hole points, and all vector and parallel properties of the basic algorithm remain unchanged.

Solution Accuracy and Conservation. A common criticism of overset grid approaches relates to the fact that simple interpolation is often used to establish needed domain connectivity. Of course, the use of simple interpolation implies that conservation is not strictly enforced. However, assuming the basic flow solver is conservative, conservation is maintained at all points in the domain except at a few intergrid boundary points. The subject of conservation on overlapping systems of grids has been studied by a number of researchers, including (refs. 32-34). In light of the significance typically placed on this subject, several points need to become generally recognized.

First, formal flow solver solution accuracy can be maintained using simple interpolation (refs. 33-35). For example, in a grid refinement study, if the position of component grid outer boundaries remains fixed with increasing resolution of the several grid components, the formal accuracy of a 2nd order flow solver will be maintained with an interpolation scheme that is 2nd order accurate (i.e., tri-linear interpolation of the dependent flow variables).

Second, the primary issue with interpolation of intergrid boundary information is not necessarily one of conservation, but one of grid resolution. If a flow solution is represented smoothly in both donor and recipient grids, simple interpolation is sufficient to carry out simulations that are accurate in all respects. In practical applications, given a fixed number of grid points, it is not possible to provide grid resolution of sufficient density to guarantee that flow features will always be smoothly represented in the grids. If a conservative interpolation scheme is used at intergrid boundaries, the speed and structure of flow features (i.e., shocks, vortices, etc.) may appear continuous across grid interfaces. However, lacking sufficient grid resolution, the accuracy of the solution can not be ensured in any case. Hence, grid resolution is the primary issue.

Third, the objective of adaptive grid techniques is to ensure smooth variation of flow variables throughout the computational domain. Accordingly, an effective adaptive grid technique appropriate for systems of overset grids should be viewed as the primary remedy for issues relating to conservation at grid interfaces.

Finally, methods are available for maintaining conservation at grid interfaces. Although complicated, special interpolation schemes that maintain conservation at grid interfaces have been developed (ref. 36). Interpolation of delta-quantities ($\hat{Q}^{n+1} - \hat{Q}^{n}$), rather than the dependent flow variables ($\hat{Q}^{n+1}$), at grid interfaces has also been suggested as a means for ensuring space-time conservation over the entire domain (ref. 37). Perhaps the most general approach is that of introducing an unstructured grid in the vicinity of the intergrid boundaries (ref. 38) and employing an appropriate solver on the unstructured grid interface. Such a hybrid approach would still have all the advantages of using structured data. Use of an unstructured solver would only be required for a small fraction of the overall domain.

Somewhat less complicated schemes for ensuring conservation at grid interfaces are possible for incompressible flows. Non-conservative interpolation of intergrid boundary conditions can be made conservative by local redistribution of fluxes such that global conservation is ensured (refs. 39,40).

Adaptive Grid Techniques. The subject of adaptive grids has a very large literature. It is clearly not the aim to review this subject here. However, some discussion on the various types of adaption and their respective strengths and weaknesses for application within overset systems of structured grids is provided. The broad class of adaption methods that redistribute a fixed number of points in response to evolving flow features (refs. 41-43) are not considered here. Although such an approach could be implemented within an overset system of grids, there are other methods of adaption that appear to be more general.

Currently, the most popular method of adaption appears to be unstructured cell subdivision. Indeed, the approach is very powerful and general. The approach has been exploited within Cartesian systems, as well as more traditional unstructured grid systems (see figure 3). In either case, the data is unstructured. In the approach, the geometric components of the problem and volume of the domain are discretized with a base grid system. Then, in response to evolving flow features, grid points are added to the base grid by local cell subdivision. Points added to the base grid can be later removed when no longer needed (refs. 44-47). The strength of the approach is that it efficiently allocates grid-points where they are required to maintain solution accuracy. There are several ways in which the approach could be implemented within systems of overset structured grids. The principal drawbacks to the approach are the memory and computational penalties associated with the requisite unstructured data. One possible implementation of this type of solution adaption within an overset structured approach is illustrated in figure 4. The implementation is a hybrid Chimera structured overset grid/unstructured solution adaption algorithm (ref. 49). In the approach, high resolution body-fitted structured grids are used near the bodies (which may move) and are overset onto an unstructured background grid. The bodies cut Chimera holes in the background unstructured grid. All off-body solution adaption is carried out in the unstructured grid using the approach described in (ref. 45).

Another class of solution adaption described in the literature utilizes systems of nested fine overset structured grids. The first such approach suggested the use of nested Cartesian grids (ref. 50) to align with flow features and maintain solution accuracy. Variations of the original approach have continued in the literature and have found application in Cartesian based solution procedures for geometrically complex applications (ref. 51). The basic approach is not limited to Cartesian grids, but can be applied in computational space as well for structured curvilinear grid systems (ref. 52).

A pure Chimera approach to solution adaption has also been explored (refs. 34,53,54). In this approach, structured fine grids are used to resolve flow features with coarse-to-fine and fine-to-coarse grid communication being accomplished via traditional Chimera domain connectivity methods (see figure 5).

Various alternatives to a pure Chimera approach to adaption have also been suggested (refs. 29,54). The approach favored by the author is described in (ref. 29) and divides the solution domain into near-body and off-body regions. Near-body regions of the domain are discretized with high-resolution body-fitted component grids that extend a relatively short distance from body surfaces. The method of adaptive refinement is designed to provide resolution of off-body dynamics subject to the motion of flow features and/or body components. The off-body portion of the domain is defined to encompass the near-body domain and extend out to the far-field boundaries of the problem. The off-body domain is filled with overlapping uniform Cartesian grids of variable levels of refinement. All adaptive refinement takes place within the off-body component grids. Initially, regions of the off-body field are marked for refinement level based on proximity to near-body boundaries. However, during the solution process, the off-body field is marked for refinement level based on proximity to near-body boundaries and estimates of solution error. Subsequent to refinement level marking, off-body regions of like resolution are coalesced into rectilinear blocks of space, each block becoming a uniform Cartesian grid. Accordingly, at any time during the simulation, the off-body field is discretized with a set of overlapping uniform Cartesian grid systems of varying levels of refinement. The approach is illustrated in figure 6.

The obvious advantages of the overset structured methods of refinement noted above relate to the computational and memory incentives inherent with structured data. The Cartesian based methods noted in (refs. 29,51) offer additional advantages derivable from multiple characteristics of Cartesian systems. For example, no memory is required for grid related data for uniform Cartesian grid components except for the two points that define the diagonal of a box which bounds the grid component and the grid spacing constant. Domain connectivity among systems of uniform Cartesian grids is trivial. Also, highly efficient flow solvers for Navier-Stokes equations on uniform Cartesian grids can be employed.

CONCLUDING REMARKS

A review of even a small sample of recent applications of overset methods for unsteady three-dimensional viscous flow situations will clearly demonstrate the power and generality of the overall approach. Highly complex geometric configurations can be accurately simulated, including cases involving relative motion between component parts.

All the advantages associated with structured data are realizable in the approach, including highly efficient implicit flow solvers, memory requirements, vectorization, and fine-grained parallelism. Grid components can be arbitrarily split to optimize the use of available memory resources. Decomposition of problem domains into a number of overlapping components creates a coarse-grained level of parallelism that can easily be exploited to facilitate simulations within distributed computing environments.

The subject of surface geometry decomposition for overlapping systems has been heretofore ignored and currently represents the largest impediment to the maturation of Chimera-style overset grid methods. Existing surface grid generation software for blocked, or patched, grid systems do not allow full exploitation of the inherent advantages of overlapping grid systems. Research in this area is badly needed. Other aspects of the Chimera-style overset grid approach are maturing more rapidly. These include algorithm development and generalization for domain connectivity, volume grid generation, surface grid generation, parallel computing, and solution adaptive grid techniques.

REFERENCES

1. Steger, J.; Dougherty, F. C.; and Benek, J.: A Chimera Grid Scheme, Advances in Grid Generation, K. N. Ghia and U. Ghia, eds., ASME FED-Vol 5., 1983, pp. 59-69.

2. Dougherty, F. C.; Benek, J.; and Steger, J.: On Applications of Chimera Grid Schemes to Store Separation, NASA TM-88193, 1985.

3. Meakin, R. and Suhs, N.: Unsteady Aerodynamic Simulation of Multiple Bodies in Relative Motion, AIAA Paper 89-1996-CP, 9th CFD Conf., 1989, pp. 643-657.

4. Meakin, R.: Computations of the Unsteady Flow About a Generic Wing/Pylon/Finned-Store Configuration, AIAA Paper 92-4568-CP, AFM Conf., 1992, pp. 564-580.

5. Lijewski, L. and Suhs, N.: Time-Accurate Computational Fluid Dynamics Approach to Transonic Store-Separation Trajectory Prediction, AIAA J. Aircraft, vol. 31, no. 4, 1994, pp. 886-891.

6. Atwood, C.: Computation of a Controlled Store Separation from a Cavity, AIAA Paper 94-0031, 32rd ASM&E, 1994, Reno, NV.

7. Sahu, J. and Nietubicz, C.: Application of Chimera Technique to Projectiles in Relative Motion, AIAA Paper 93-3632-CP, AFM Conf., 1994, pp. 167-176.

8. Gea, L., Halsey; N, Intemann, G.; and Buning, P.: Applications of the 3-D Navier-Stokes Code OVERFLOW for Analyzing Propulsion-Airframe Integration Related Issues on Subsonic Transports, ICAS-94-3.7.4, Proc. 19th Congress Intnl. Council Aero. Sci., 1994, pp. 2420-2435.

9. Smith, M. and Pallis, J.: MEDUSA - An Overset Grid Flow Solver for Network-Based Parallel Computer Systems, AIAA Paper 93-3312-CP, 11th CFD Conf., 1993, pp. 167-175.

10. Barszcz, E.; Weeratunga, S.; and Meakin, R.: Dynamic Overset Grid Communication on Distributed Memory Parallel Processors, AIAA Paper 93-3311-CP, 11th CFD Conf., 1993, pp. 155-166.

11. Atwood, C. and Smith, M.: Nonlinear Fluid Computations in a Distributed Environment, AIAA Paper 95-0224, 33rd ASM&E, 1995, Reno, NV.

12. Weeratunga, S. and Chawla, K.: Overset Grid Applications on Distributed Memory MIMD Computers, AIAA Paper 95-0573, 33rd ASM&E, 1995, Reno, NV.

13. Benek, J.; Steger, J.; Dougherty, F.; and Buning, P.: Chimera: A Grid-Embedding Technique, AEDC-TR-85-64, 1986.

14. Brown, D.; Chesshire, G.; Henshaw, W.; and Kreiss, O.: On Composite Overlapping Grids, 7th Intnl. Conf. Finite Element Methods in Flow Probs., 1989, Huntsville, AL.

15. Meakin, R.: A New Method for Establishing Intergrid Communication Among Systems of Overset Grids, AIAA Paper 91-1586-CP, 10th CFD Conf., 1991, pp. 662-671.

16. Suhs, N. and Tramel, R.: PEGSUS 4.0 User's Manual; AEDC-TR-91-8, 1991.

17. Maple, R. and Belk, D.: Automated Set Up of Blocked, Patched, and Embedded Grids in the Beggar Flow Solver, Numerical Grid Generation in Computational Fluid Dynamics and Related Fields, ed. N.P. Weatherill et al., 1994, Pine Ridge Press, pp. 305-314.

18. Wey, T.: Development of A Mesh Interface Generator for Overlapped Structured Grids, AIAA Paper 94-1924, 12th AA Conf., 1994.

19. Chiu, I. and Meakin, R.: On Automating Domain Connectivity for Overset Grids, AIAA Paper 95-0854, 33rd ASM&E, 1995, Reno, NV.

20. Steinbrenner, J.; Chawner, J.; and Fouts, C.: A Structured Approach to Interactive Multiple Block Grid Generation, AGARD FDP Specialists Mtg. on Mesh for Complex Three-Dimensional Configurations, 1989, Leon, Norway.

21. Thompson, J.: Composite Grid Generation Code for General 3-D Regions - the EAGLE Code, AIAA Journal, vol. 26, no. 3, 1988, pp. 271-272.

22. Soni, B., et al.: GENIE++, EAGLEView and TIGER: General and Special Purpose Graphically Interactive Grid Systems,

AIAA Paper 92-0071, 30th ASM&E, 1992, Reno, NV.

23. Akdag, V. and Wulf, A.: Integrated Geometry and Grid Generation System for Complex Configurations, Software Systems for Surface Modeling and Grid Generation, NASA CP 3143, 1992, pp. 161-171.

24. Thompson, J., Warsi, Z., and Mastin, C.: Boundary-Fitted Coordinate Systems for Numerical Solution of Partial Differential Equations - A Review, J. Comput. Phys., vol. 47, no. 1, 1982, pp. 1-108.

25. Steger, J.: Notes on Surface Grid Generation using Hyperbolic Partial Differential Equations, unpublished report, TM CFD/UCD 91-101, Dept. Mech., Aero. & Mat. Eng., 1989, Univ. Cal., Davis.

26. Chan, W. and Buning, P.: A Hyperbolic Surface Grid Generation Scheme and its Applications, AIAA Paper 94-2208, 25th FD Conf., 1994, Colorado Springs, CO.

27. Chan, W. and Steger, J.: A Generalized Scheme for Three-Dimensional Hyperbolic Grid Generation, AIAA Paper 91-1588-CP, 10th CFD Conf., 1991, pp. 683-695.

28. Chan, W., Chiu, I., and Buning, P.: User's Manual for the HYPGEN Hyperbolic Grid Generator and the HGUI Graphical User Interface, NASA TM 108791, 1993.

29. Meakin, R.: An Efficient Means of Adaptive Refinement Within Systems of Overset Grids, AIAA Paper 95-1722-CP, 12th CFD Conf., 1995, San Diego, CA.

30. Steger, J.; Ying, S.; and Schiff, L.: Partially Flux-Split Algorithm for Numerical Simulation of Compressible Inviscid and Viscous Flow, Workshop CFD, Inst. Non-Linear Sci., 1986, Univ. of Cal., Davis.

31. Warming, R. and Beam, R.: On the Construction and Application of Implicit Factored Schemes for Conservation Laws, SIAM-AMS Proc., vol. 11, 1978, pp. 85-129.

32. Berger, M.: On Conservation at Grid Interfaces, SIAM J. Numer. Anal., vol. 24, no. 5, 1987, pp. 967-984.

33. Chesshire, G. and Henshaw, W.: Conservation on Composite Overlapping Grids, IBM Research Report, RC 16531, IBM Res. Div., T. J. Watson Res. Ctr., 1991, Yorktown Hts., NY.

34. Meakin, R.: On the Spatial and Temporal Accuracy of Overset Grid Methods for Moving Body Problems, AIAA Paper 94-1925-CP, 12th AA Conf., 1994, pp. 858-871.

35. Henshaw, W.: Part I: The Numerical Solution of Hyperbolic Systems of Conservation Laws. Part II: Composite Overlapping Grid Techniques, Ph. D. Diss., Cal. Inst. of Tech., 1985, Pasadena, CA.

36. Moon, Y. and Liou, M.: Conservative Treatment of Boundary Interfaces for Overlaid Grids and Muli-level Grid Adaptations, AIAA Paper 89-1980-CP, 9th CFD Conf., 1989, pp. 480-487.

37. Steger, J.: Studies of the Chimera Method of Flow Simulation (unpublished notes), 1991.

38. Wang, Z.: A Fully Conservative Structured/Unstructured Chimera Grid Schem, AIAA Paper 95-0671, 33rd ASM&E, 1995, Reno, NV.

39. Meakin, R.: Application of Boundary Conforming Coordinate and Domain Decomposition Principles to Environmental Flows, Ph. D. Diss., Stanford Univ., 1986, Stanford, CA.

40. Saltzman, J.: Conservation and Linear System Issues on Overset Composite Grids, Proc. 2nd Overset Composite Grid Sol. Tech. Symp., 1994, Fort Walton Beach, FL.

41. Brackbill, J. and Saltzman, J.: Adaptive Zoning for Singular Problems in Two Dimensions, J. Comput. Phys., vol. 46,

1982, pp. 342-368.

42. Eiseman, P.: Adaptive Grid Generation, Comput. Meth. Appl. Mech. Eng., vol. 64, nos. 1-3, 1987, pp. 321-376.

43. Davies, C. and Venkatapathy, E.: Application of a Solution Adaptive Grid Scheme, SAGE, to Complex Three-Dimensional Flows, AIAA Paper 91-1594-CP, 10th CFD Conf., 1991, pp. 756-779.

44. Zeeuw, D. and Powell, K.: An Adaptively-Refined Cartesian Mesh Solver for the Euler Equations, AIAA Paper 91-1542-CP, 10th CFD Conf., 1991, pp. 166-180.

45. Biswas, R. and Strawn, R.: A New Procedure for Dynamic Adaption of Three-Dimensional Unstructured Grids, AIAA Paper 93-0672, 31st ASM&E, 1993, Reno, NV.

46. Aftosmis, M.: Upwind Method for Simulation of Viscous Flow on Adaptively Refined Meshes, AIAA J., vol. 32, no. 2, 1994, pp. 268-277.

47. Baum, J. Luo, H. and Lohner, R.: A New ALE Adaptive Unstructured Methodology for the Simulation of Moving Bodies, AIAA Paper 94-0414, 32nd ASM&E, 1994, Reno, NV.

48. Barth, T.: Aspects of Unstructured Grids and Finite-Volume Solvers for the Euler and Navier-Stokes Equations, AGARD-R-787, 1992, pp. 6.1-6.61.

49. Duque, E.: A Structured/Unstructured Embedded Grid Solver for Helicopter Rotor Flows, AHS 50th Ann. Forum Proc., vol. II, 1994, pp. 1249-1258.

50. Berger, M. and Oliger, J.: Adaptive Mesh Refinement for Hyperbolic Partial Differential Equations, J. Comput. Phys., vol. 53, 1984, pp. 484-512.

51. Berger, M. and LeVeque, R.: A Rotated Difference Scheme for Cartesian Grids in Complex Geometries, AIAA Paper 91-1602, 10th CFD Conf., 1991, Honolulu, HI.

52. Berger, M. and Jameson, A.: Automatic Adaptive Grid Refinement for the Euler Equations, AIAA J., vol. 23, no. 4, 1985, pp. 561-568.

53. Chawla, K. and Banks, D.: Tracking Flow Features Using Overset Grids, AIAA Paper 93-0197, 31st ASM&E, 1993, Reno, NV.

54. Rogers, S. and Pulliam, T.: Accuracy Enhancements for Overset Grids Using a Defect Correction Approach, AIAA Paper 94-0523, 32nd ASM&E, 1994, Reno, NV.

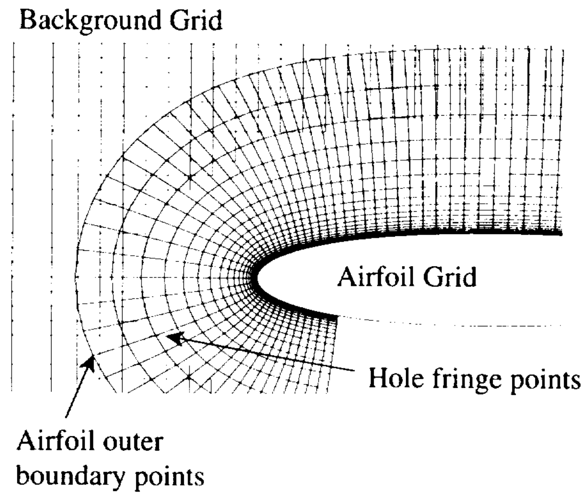
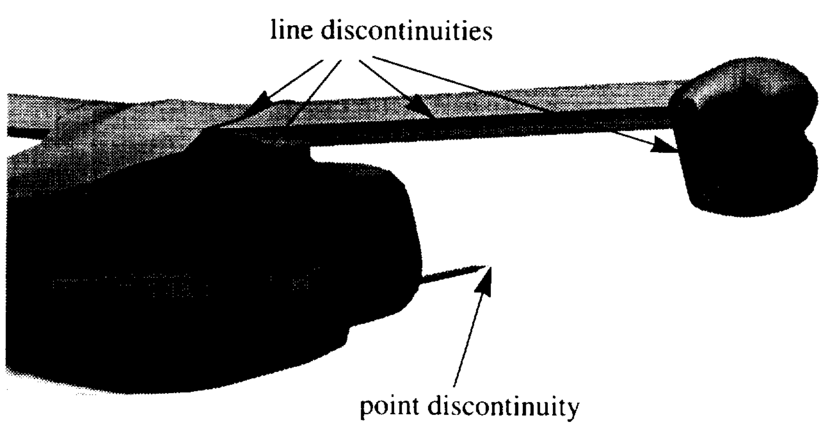
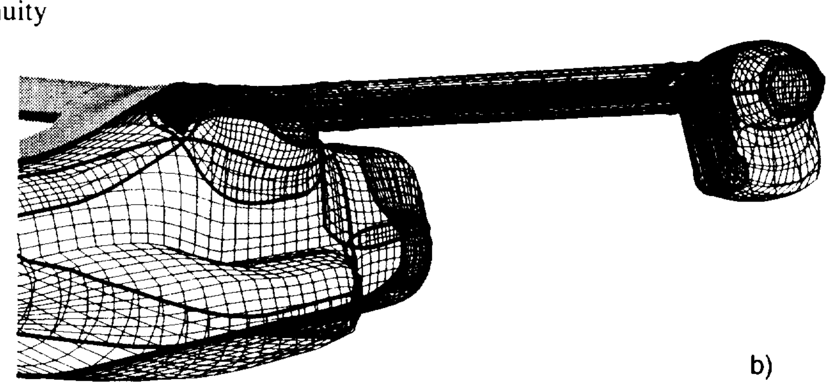


Figure 1. —An example of Chimera intergrid boundary points

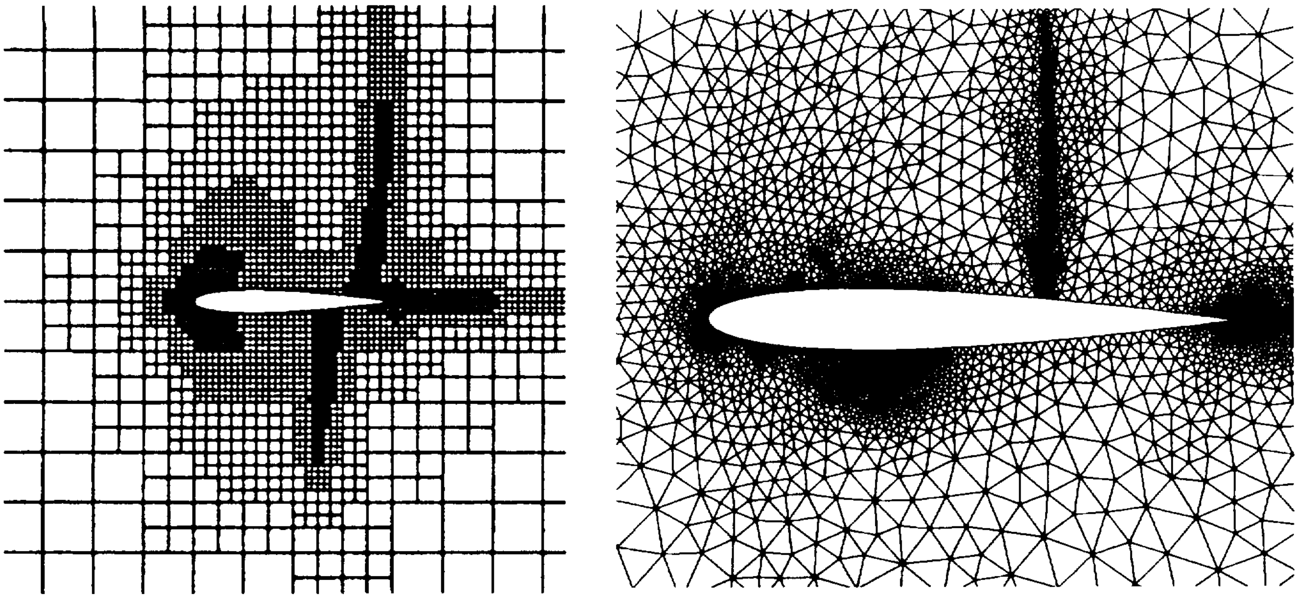


a)

Figure 2. — Surface geometry of a tiltrotor aircraft. a) Panel definition (note indicated point and line discontinuities). b) Quilt of overlapping surface grid components. Component grids retain the line discontinuities indicated in the original panel definition of the geometry.

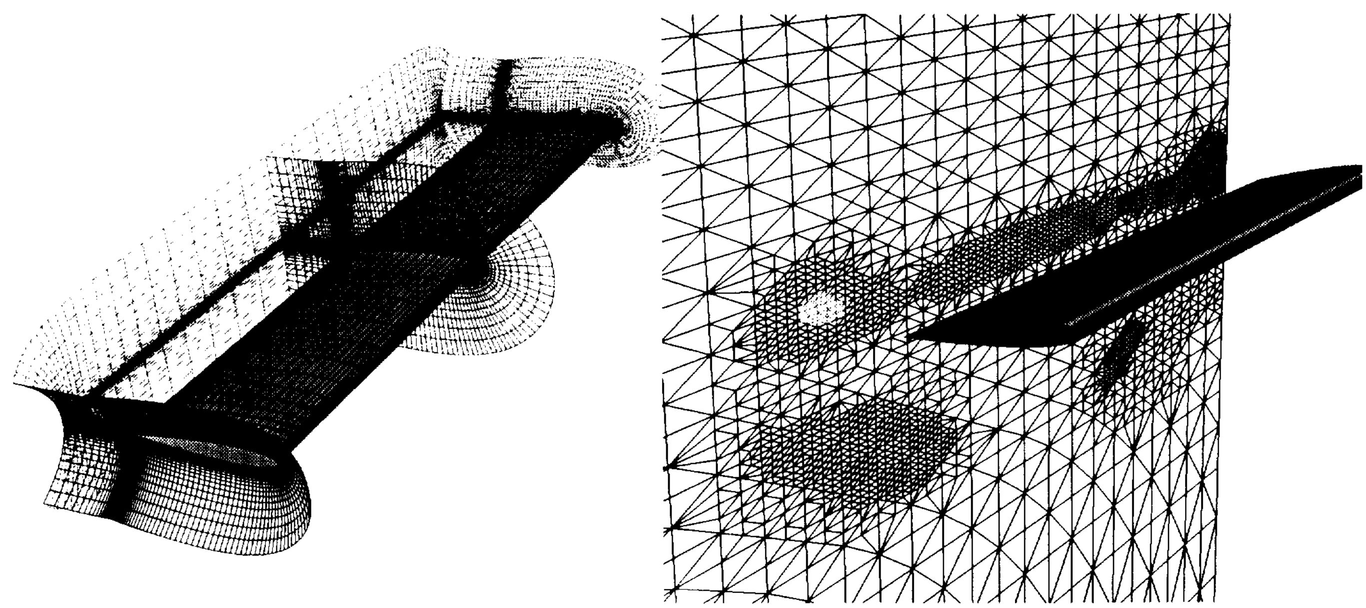


b)



a) b)

Figure 3. — Solution adaption via cell subdivision. a) Unstructured Cartesian cell subdivision (ref. 44). b) Conventional unstructured cell subdivision (ref. 48).



a) b)

Figure 4. — Hybrid structured Chimera overset/unstructured solution adaption. a) High-resolution body-fitted structured grid (viscous) for rotor blade. b) Unstructured background grid for solution adaption of off-blade vortex dynamics (ref. 49).

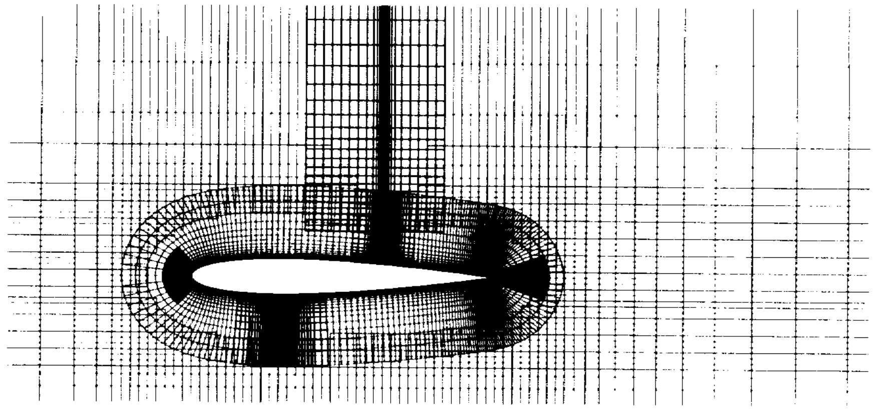
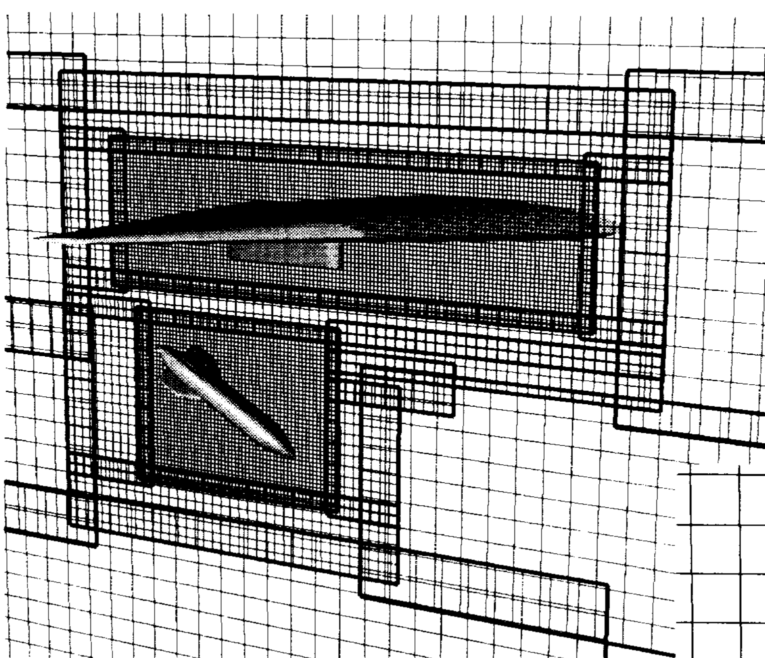
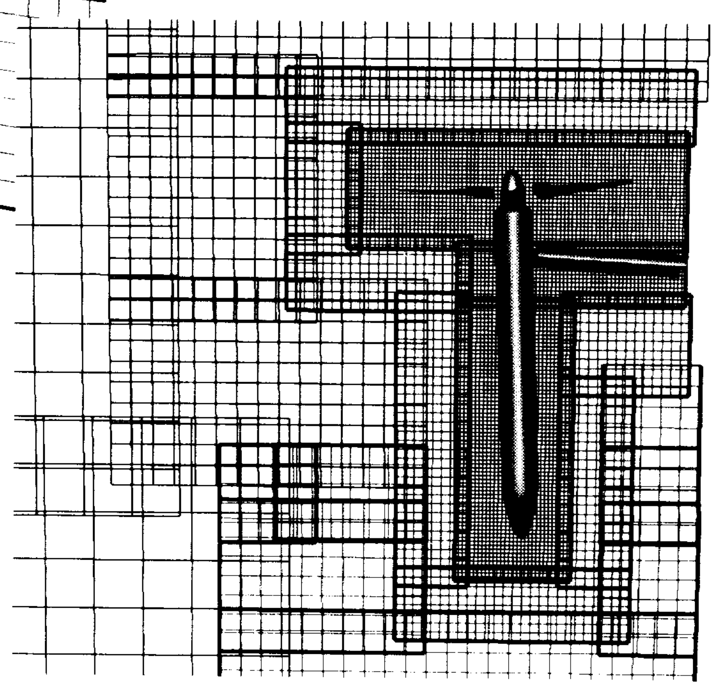


Figure 5. — Solution adaption via overset structured fine grids. Base grid (medium resolution body-fitted airfoil grid and background Cartesian grid) plus 5 overset fine grid components (ref. 34).

Figure 6. — Solution adaption via off-body uniform Cartesian structured grids (high-resolution body-fitted grids are used to discretize space near physical boundaries) (ref. 29).



a) Store separation application (near-body viscous grid components not shown).



b) Tiltrotor downloads application (near-body viscous grid components not shown).