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**Global Flowfield About the V-22 Tiltrotor Aircraft**

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## THE CHIMERA METHOD OF SIMULATION FOR UNSTEADY THREE-DIMENSIONAL VISCOUS FLOW

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**Abstract:** The Chimera overset grid method is reviewed and 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 discussed. A variety of recent applications of the method is presented. Current limitations of the approach are identified.

### 1 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[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[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[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[9-12].

The present paper is a review of 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. However, such applications are not the focus of the present review. The paper includes discussion on the state of maturity of the various pieces of support software required to use the approach, including grid, flow-solver, and post-process analysis related software issues. A variety of recent applications of the method are presented. Current limitations of the approach are identified and used to suggest needs for future developmental efforts.

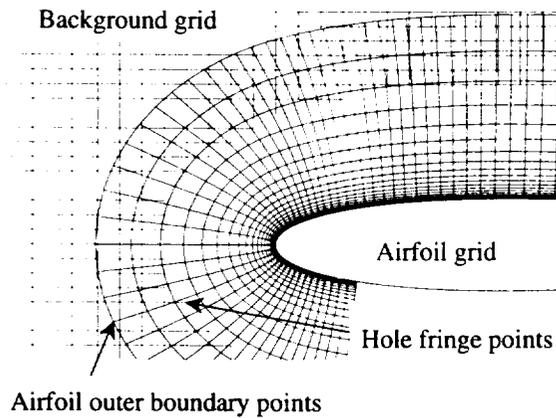
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## 2 OVERSET METHODS AND APPLICATIONS

### 2.1 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.



**Figure 1.** An example of Chimera intergrid boundary points.

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 solu-

tion. 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[13-19].

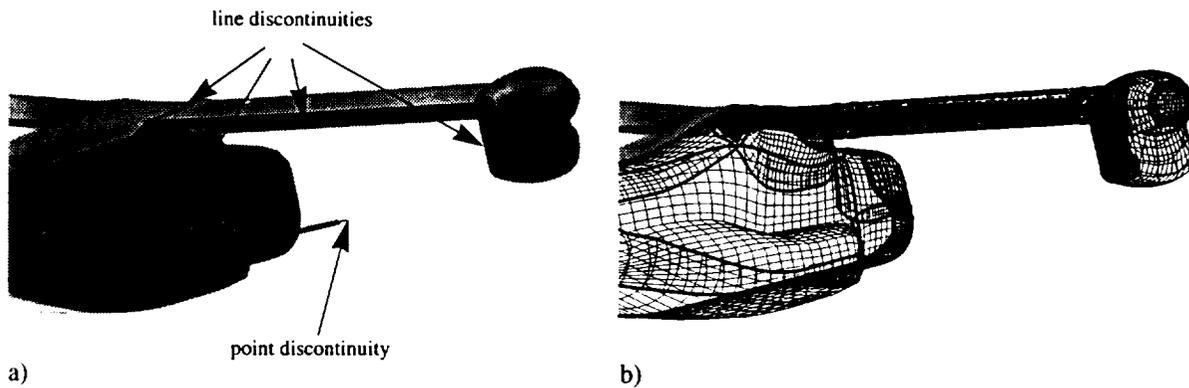
### 2.2 Grid Related Issues

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[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.

#### 2.2.1 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



**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.

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.

### 2.2.2 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[24]. The idea for hyperbolic surface grid generation was first put forward more recently[25], and has since been generalized[26].

### 2.2.3 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[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[29].

### 2.2.4 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 pur-

pose 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[17-19], donor search methods (including quality optimization)[14,17,19], automation[14,17-19], and parallelization[10].

The first general purpose domain connectivity algorithms that became widely available are the PEGSUS[13] and, later, CMPGRD[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[3] were carried out using a script controlled application of PEGSUS and the F3D thin-layer Navier-Stokes solver[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[15] and BEGGAR[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.

### 2.3 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)[31] for the thin-layer Navier-Stokes equations

$$\partial_{\zeta}\hat{Q} + \partial_{\xi}\hat{F} + \partial_{\eta}\hat{G} + \partial_{\zeta}\hat{H} = R_e^{-1}\partial_{\zeta}\hat{S} \quad (2.3.1)$$

is easily modified for Chimera-style overset grids as

$$\begin{aligned} & [I + i_b \Delta t \delta_{\xi} \hat{A}^n] [I + i_b \Delta t \delta_{\eta} \hat{B}^n] x \\ & [I + i_b \Delta t \delta_{\zeta} \hat{C}^n - i_b \Delta t R_e^{-1} \delta_{\zeta} \mathcal{J}^{-1} \hat{M}^n J] \Delta \hat{Q}^n = \\ & -i_b \Delta t (\delta_{\xi} \hat{E}^n + \delta_{\eta} \hat{F}^n + \delta_{\zeta} \hat{G}^n - R_e^{-1} \delta_{\zeta} \hat{S}^n) \end{aligned} \quad (2.3.2)$$

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.

#### 2.3.1 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 those listed in references [32-34]. In light of the significance typically placed on this subject, several points need to become generally recognized.

First, formal flow solver accuracy can be maintained using simple interpolation[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 (e.g., 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 consistent across the inter-

faces. 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[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 been suggested as a means for ensuring space-time conservation over the entire domain[37]. Perhaps the most general approach is that of introducing an unstructured grid in the vicinity of the intergrid boundaries[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.

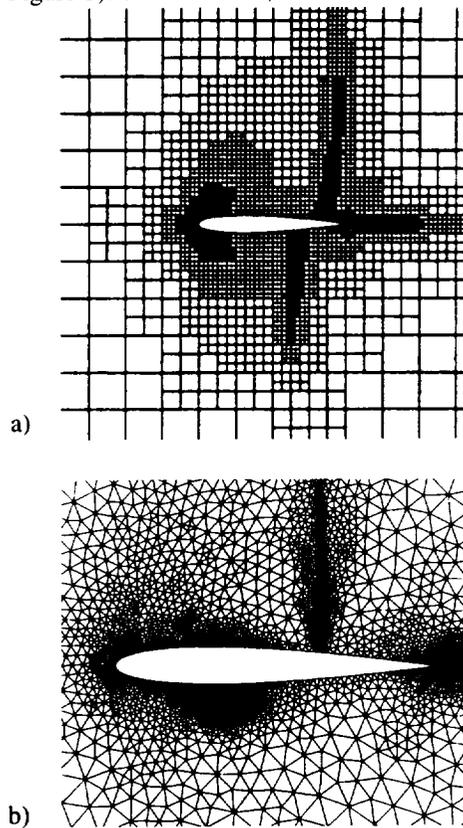
Somewhat less complicated schemes for ensuring conservation at grid interfaces are possible for incompressible flows. Non-conservative interpolation of intergrid boundary conditions can be made conservative by local redistribution of fluxes such that global conservation is ensured[39,40].

### 2.3.2 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[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.

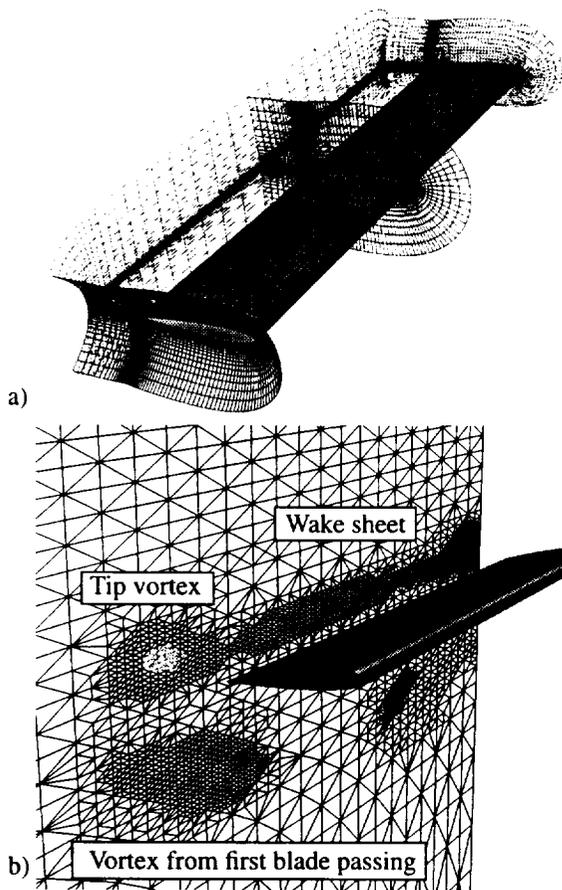
Currently, the most popular method of adaption appears to be unstructured cell subdivision. Indeed, the approach is very powerful and general. The

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.



**Figure 3.** Solution adaption via cell subdivision. a) Unstructured Cartesian cell subdivision[44]. b) Conventional unstructured cell subdivision[48].

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[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



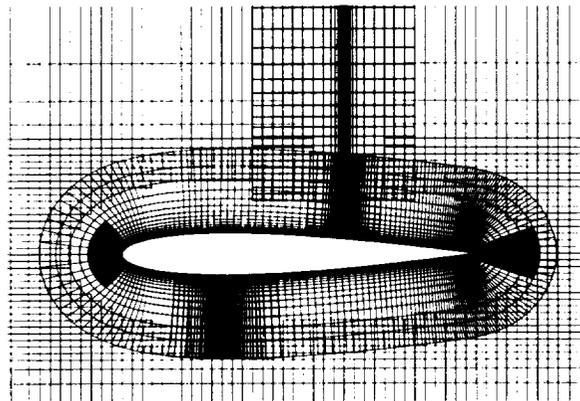
**Figure 4.** Hybrid structured Chimera overset/unstructured method of solution adaption. a) High-resolution body-fitted structured grid (viscous) for rotor blade. b) Unstructured background grid for solution adaption of off-blade vortex dynamics[49].

adaption algorithm[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 reference[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[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[51]. The basic approach is not limited to Cartesian grids, but can be applied in computational space as well for structured curvilinear grid systems[52].

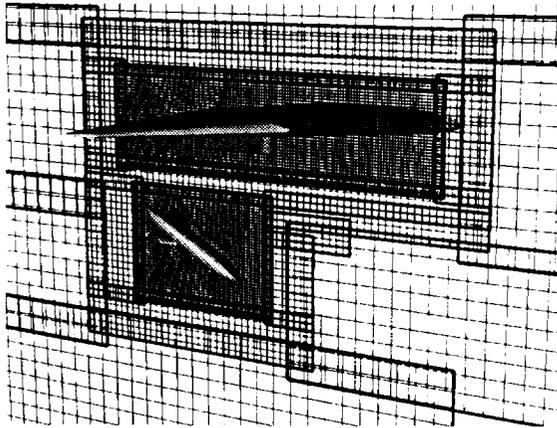
A pure Chimera approach to solution adaption has also been explored[34,53,54]. In this approach, structured fine grids are used to resolve flow features with coarse-to-fine and fine-to-coarse grid communication being accomplished via traditional Chimera domain connectivity methods (see Figure 5).



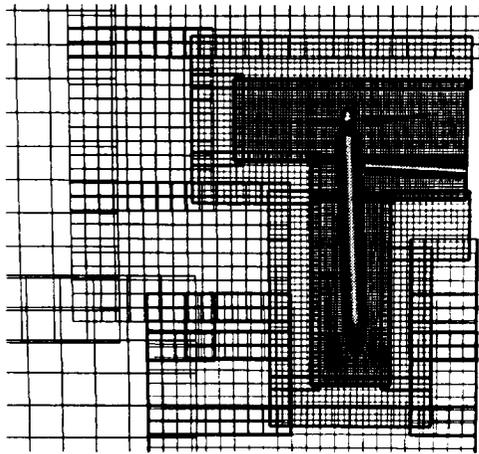
**Figure 5.** Solution adaption via overset structured fine grids. Base grid (medium resolution body-fitted airfoil grid and background Cartesian grid) plus 5 overset fine grid components[34].

Various alternatives to a pure Chimera approach to adaption have also been suggested[29,54]. The approach favored by the author is described in reference[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.



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



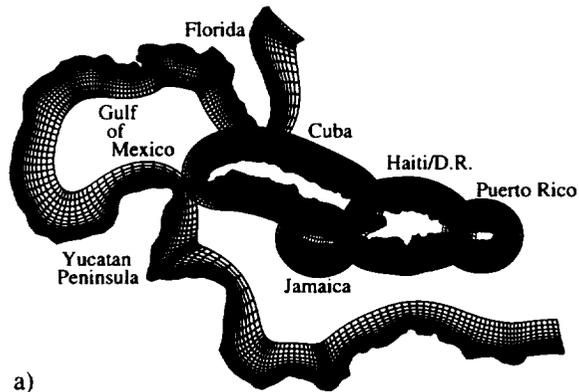
b) Tiltrotor downloads application (near-body viscous grid components not shown).

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

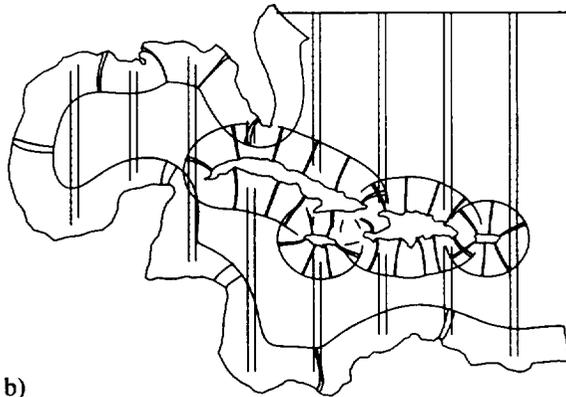
The obvious advantages of the overset structured methods of refinement noted above relate to the computational and memory incentives inherent with struc-

tured data. The Cartesian based methods noted in references [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. 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.

Solution adaption within overset systems of structured grids is an active area of research. General purpose solvers with adaption capability are not yet generally available.

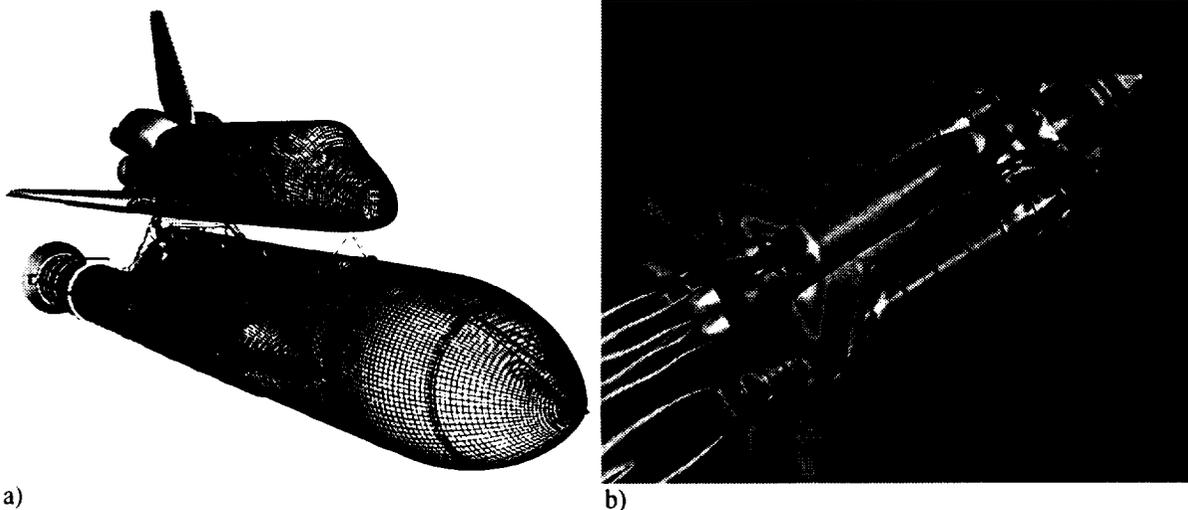


a)



b)

**Figure 7.** Overset grids for unsteady simulation of basin-scale oceanic flows. a) Grids for the Gulf of Mexico and the Greater Antilles islands. b) Grid decomposition for solution in a distributed computing environment [58].



**Figure 8.** Three-dimensional viscous flow simulations about the integrated space shuttle vehicle in ascent[60]. a) selected surface components from the overset grid discretization of the integrated shuttle configuration. b) Surface pressure coefficient and off-body Mach contours ( $M_\infty = 1.25$ ,  $\alpha = -3.3^\circ$ , and  $R_e = 283 \times 10^6$ ).

## 2.4 Applications

Although development of Chimera-style overset grid methods have been largely motivated by aeronautics applications, the approach is being applied with increasing frequency in other disciplines of science and engineering. Some recent examples include particle flow simulation[55], submarine hydrodynamics[56], and non-Newtonian fluid flow simulation of a paper coating process[57]. Figure 7 illustrates an overset grid discretization of the Gulf of Mexico and the Greater Antilles islands for unsteady basin-scale simulation of oceanic flows[58].

The present section highlights four recent aerodynamics applications. Overset structured grid methods have been used to carry out three-dimensional viscous flow simulations (steady and unsteady) for many applications. The four cases highlighted here were chosen in part because of the author's familiarity with the results, but primarily because they are illustrative of the advantages and generality of the approach. Also, the examples identify some of the data management requirements of large-scale unsteady applications and post-process analysis.

### 2.4.1 The Space Shuttle Launch Vehicle in Ascent

It is appropriate that the first example highlighted in this section corresponds to the space shuttle. Applica-

tion of three-dimensional Navier-Stokes CFD methods to improve understanding of the space shuttle aerodynamics in ascent was initiated in the mid-1980's[59] and has been continued to the present[60, 61]. These CFD investigations have covered a range of integrated vehicle ascent conditions and various abort maneuvers. They have been used advantageously in reconciling vast amounts of wind-tunnel and flight data, carrying out debris studies, and evaluating proposed design modifications to components of the integrated launch vehicle.

The shuttle aerodynamics research and analysis has stimulated many aspects of overset grid technology development including flow solver[62], domain connectivity[15,19], grid generation[26,27,63], and unsteady moving-body algorithm development[3,64]

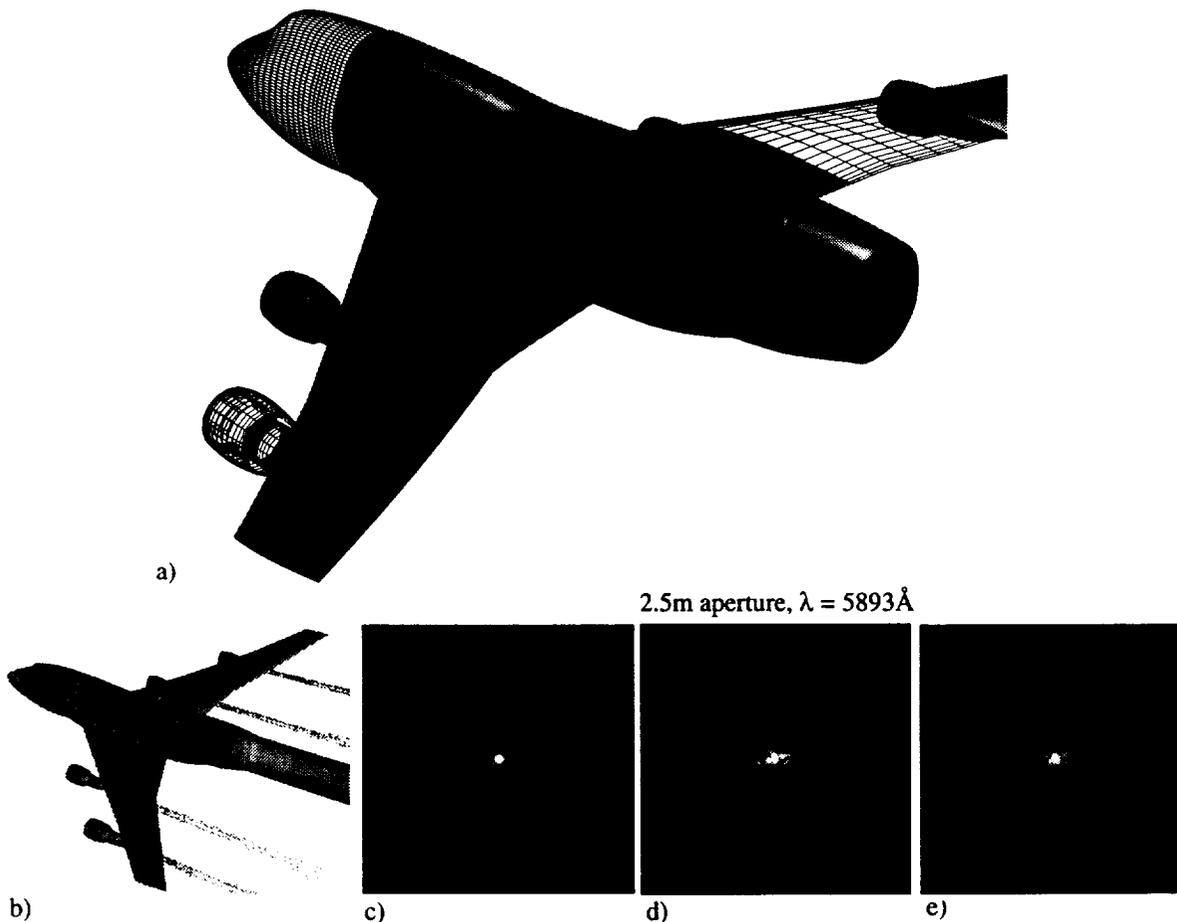
Early CFD representations of the integrated space shuttle vehicle were relatively simple, and included grids for the orbiter, external-tank, and solid-rocket boosters[59]. The tail-section was ignored, as was the attach hardware and virtually all other geometric protuberances that exist on the actual vehicle. However, these early CFD configurations provided valuable information. The geometric fidelity of the CFD model of the vehicle has since been improved (incrementally) by adding grid-points and grid components corresponding to vehicle components and protuberances that were previously ignored. Resolution and geomet-

ric completeness requirements of the grid system have been driven by the need to predict aerodynamic wing loads on the integrated launch vehicle during ascent to within 5 percent of the maximum structural load of the orbiter wing. The current space shuttle grid system is illustrated in Figure 8 and facilitates shuttle aerodynamic performance predictions to the required level of accuracy[60].

The current system of grids employs 113 components and approximately 16 million points, including grids for resolution of the main-engine and solid-rocket booster plumes. Simulations involving flight conditions with plumes have been consistently turned around in 3 to 10 days on a Cray Y-MP/4 (see [60] for

details). A single solution file (5 dependent flow variables and one turbulence quantity) requires more than 900 megabytes of disk storage (64-bit words). Simulations which include engine plumes and variable gamma require nearly 1.4 gigabytes per restart file.

The present shuttle grid system is illustrative of the degree of geometric complexity that can be treated with an overset grid approach. The ability to replace vehicle parts without the need for regeneration of other grid components illustrates a very appealing aspect of the approach from a design analysis standpoint (e.g., alternative solid-rocket booster designs have been evaluated).



**Figure 9.** Flowfield simulation about the SOFIA airborne observatory[66]. a) Selected surface components from the overset grid discretization of the SOFIA configuration. b) Surface pressure coefficient and engine plume temperature contours. c), d), and e) are far-field diffraction patterns based on phase distortion levels (from CFD predicted SOFIA aerodynamic field) and a 64 x 64 array of rays normal to the telescope aperture initialized immediately above the secondary mirror. c) Airy (no distortion), d) instantaneous exposure, e) 28ms exposure (SR=0.34).

The magnitude of data generated from the shuttle simulations poses a formidable problem in terms of data management, mass storage, and post-process solution analysis. The present shuttle grids are certainly extreme by current standards. However, as computational resources continue to increase in performance capacity, the frequency of massive data sets will also increase. Worse, even relatively modest grid systems in frequent use today (1 to 4 million points) for unsteady three-dimensional viscous flow simulations easily dwarf the data requirements of the high-fidelity space shuttle grids.

#### 2.4.2 The SOFIA Airborne Observatory

Simulations of the Stratospheric Observatory For Infrared Astronomy (SOFIA) represent a multi-disciplinary application of the overset grid approach[65, 66]. The SOFIA airborne observatory is a 2.5 meter Cassegrain telescope mounted in an open cavity in the fuselage of a Boeing 747SP (see Figure 9a). One objective of the SOFIA simulations deal with light propagation through an unsteady aerodynamic field (transonic aero-windows). However, the application has broader relevance in the context of the present review. Aero-windows have important applications ranging from laser weaponry to astronomy platforms. The SOFIA configuration is relevant to cavity flows in general, is geometrically complex, and is an unsteady three-dimensional viscous flow application.

The overset grid system used to discretize the SOFIA configuration indicated in Figure 9a involves 35 grid components and approximately 3 million grid points. Unsteady flow simulations were carried out for specified SOFIA configurations and then used in a post-process to predict the optical performance of the telescope.

A broad question analyzed by the simulations concerned the placement of the telescope and cavity along the fuselage of the 747. Placement of the telescope in a favorable pressure gradient region (forward of the wing) has optical advantages (i.e., thin boundary layer), but poses considerable manufacturing difficulties. An alternative site for the telescope aft of the wing (shown in Figure 9a) mitigates these concerns and permits the use of a larger cavity volume, but poses several possible problems from an optical standpoint.

An overset grid discretization of the problem geome-

try allows repositioning of the telescope and cavity with minimal impact to the overall grid system. Only the grids directly associated with the cavity need to be regenerated. The telescope grids and all airframe grids are reusable without modification.

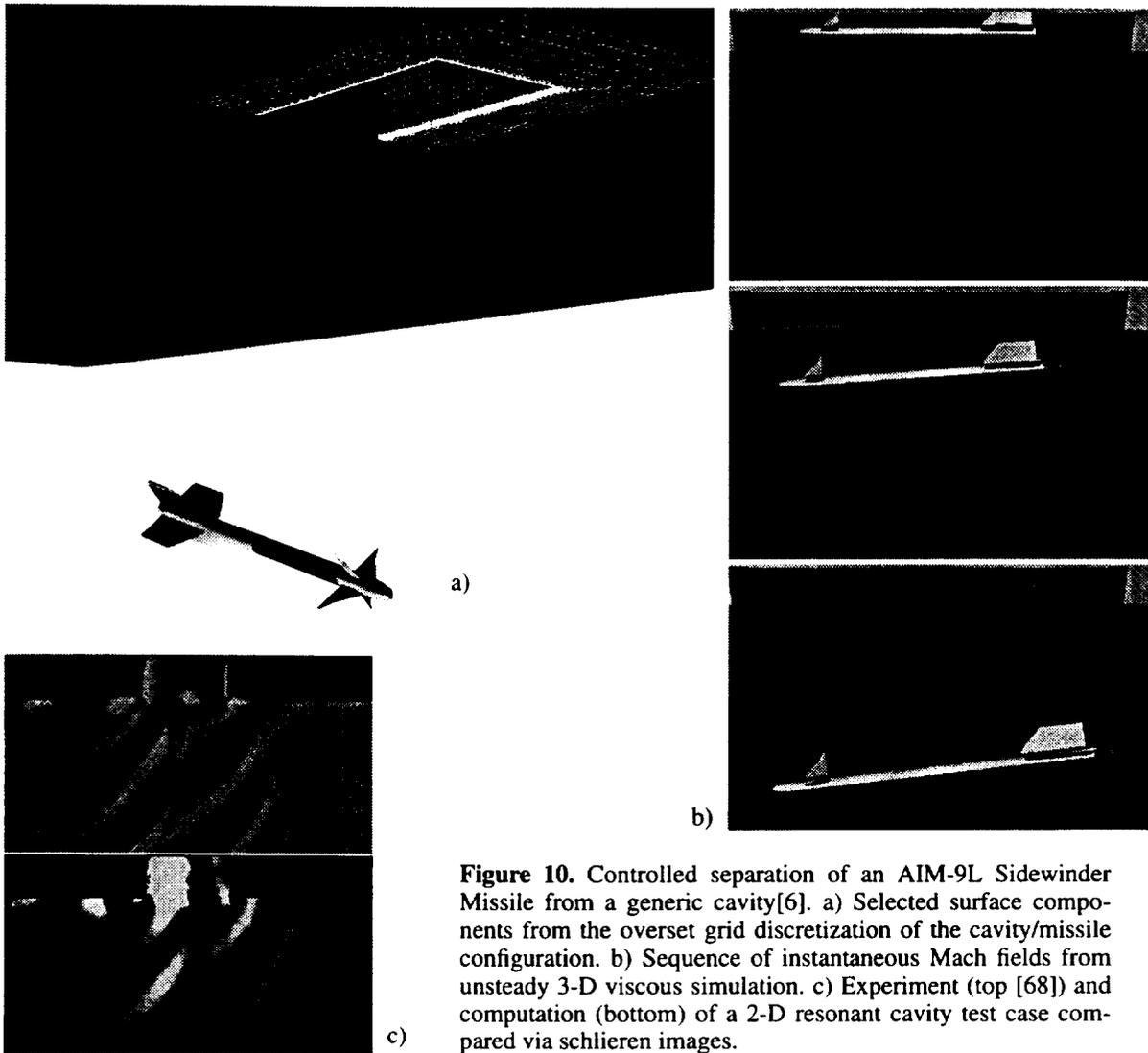
Solution restart files for this case were approximately 160 megabytes (64-bit words). Although the simulations were unsteady, restart files were only saved periodically for restart purposes. That is, restart files were overwritten and not used to construct a time-history data base. The simulations correspond to wind-tunnel tests where experimental data measuring locations were known a-priori to the CFD simulations. Hence, collection of unsteady data from the simulations was done selectively. Computed pressure data was saved as a function of time to provide comparison with experimental data. Similarly, flow variables from limited sections of the domain needed for carrying out post-process optics computations and unsteady telescope aerodynamic loads analyses were also saved.

#### 2.4.3 Controlled Store Separation from a Cavity

Aircraft store separation is the primary application that has driven unsteady moving-body algorithm development. A host of studies focused on advanced CFD methods and applications for aircraft store separation exist in the literature (see, for example, references [3-7]). The case highlighted here corresponds to the controlled separation of an AIM-9L Sidewinder missile from a cavity carriage position[6].

Although the case highlighted here is not representative of the degree of geometric complexity that is regularly treated with overset grid methods, it is noteworthy for several other reasons. First, the case is unsteady, three-dimensional, viscous, and involves relative motion between component parts of the configuration. Second, the case involves *controlled separation*, which requires computation of the integrated effects of ejector forces, aerodynamic loads, and a pitch-attitude control law in order to predict the store trajectory and attitude during separation. Finally, the carriage position of the store is inside a cavity, which significantly increases the complexity of the aerodynamic field in which separation occurs.

Validation of the basic flow solver applied to cavity flows has been carried out for 2-D and 3-D applications[65,67]. Figure 10c includes an illustration of a comparison between 2-D computational results and



**Figure 10.** Controlled separation of an AIM-9L Sidewinder Missile from a generic cavity[6]. a) Selected surface components from the overset grid discretization of the cavity/missile configuration. b) Sequence of instantaneous Mach fields from unsteady 3-D viscous simulation. c) Experiment (top [68]) and computation (bottom) of a 2-D resonant cavity test case compared via schlieren images.

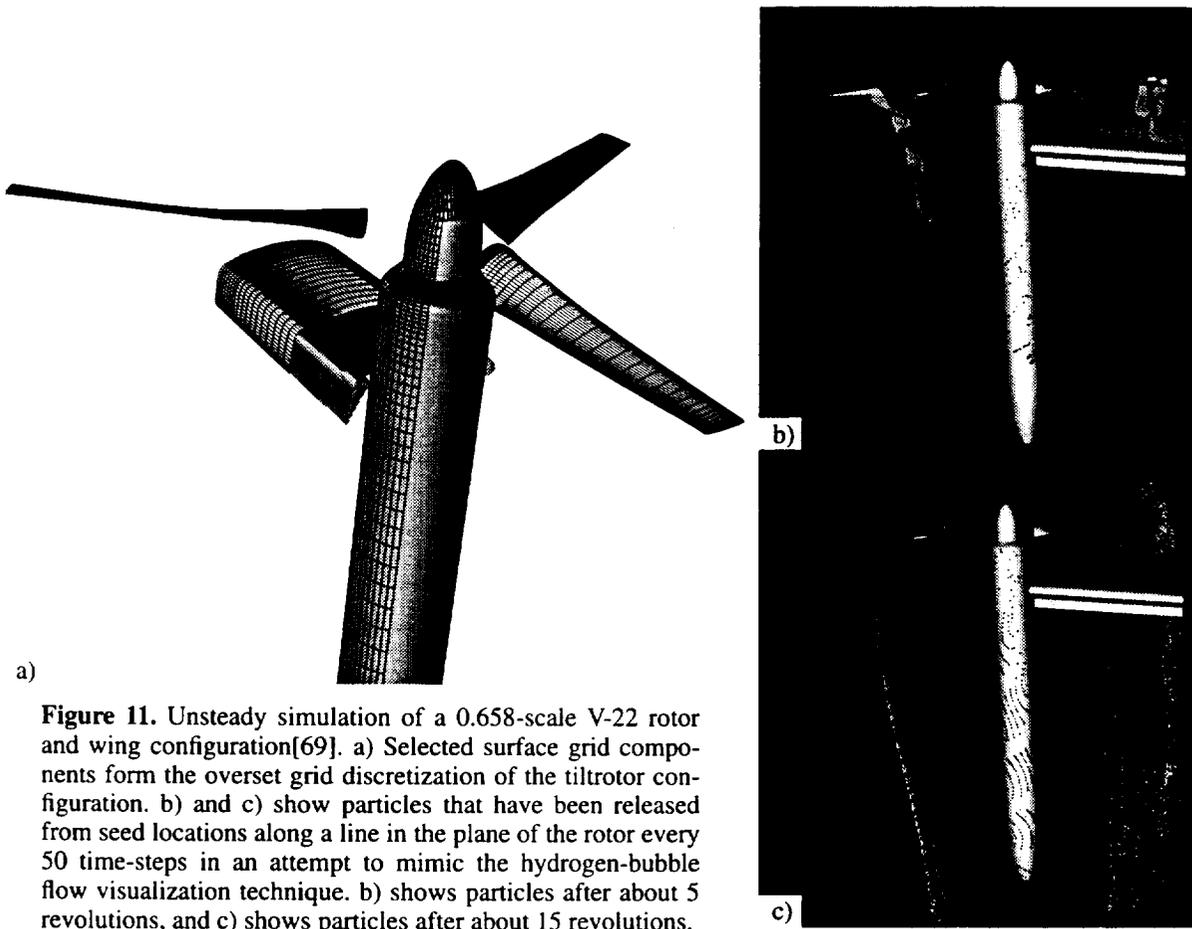
data from a self-excited resonant cavity experiment. Results of the unsteady three-dimensional viscous flow simulation (viz., controlled store separation sequence) compares well with wind-tunnel data.

The geometric configuration of the controlled store-separation problem is shown in Figure 10a. The physical domain was discretized using 21 overlapping component grids and approximately 2.2 million grid points. An unsteady simulation was carried out with the store fixed in carriage position. The final unsteady store-in-carriage solution was used as the initial solution for the controlled separation case. Approximately 20% of the computational expense of the controlled separation case was due to domain connectivity, which was required every time-step due to the motion

of the store.

In addition to store position and attitude parameters that were saved every time-step of the simulation, complete grid and solution files were saved every 20 time-steps (out of 8,000). Data storage requirements of the store position data is minimal. However, the grid and solution files require a total of approximately 98 megabytes (32-bit words) for each time-step saved. Accordingly, approximately 40 gigabytes of disk space was required for the 400 time-steps saved.

**2.4.4 Prediction of Tiltrotor Downloads in Hover**  
Rotorcraft applications represent a formidable challenge for any Navier-Stokes simulation method. Accurate simulation of the off-body aerodynamics of a



**Figure 11.** Unsteady simulation of a 0.658-scale V-22 rotor and wing configuration[69]. a) Selected surface grid components form the overset grid discretization of the tiltrotor configuration. b) and c) show particles that have been released from seed locations along a line in the plane of the rotor every 50 time-steps in an attempt to mimic the hydrogen-bubble flow visualization technique. b) shows particles after about 5 revolutions, and c) shows particles after about 15 revolutions.

rotorcraft configuration is very important since such aircraft fly in their own wake. The geometric complexities of rotorcraft applications are greatly complicated by the fact of relative motion between rotor-blades and the rest of the airframe. Aeroelastic effects of the rotor-blades are important, as well as aeroacoustic effects in terminal operation. An understanding of hover aerodynamics is very important to the design of efficient and environmentally acceptable tiltrotor aircraft.

The application highlighted here corresponds to a tiltrotor aircraft in hover[69]. Such a flowfield is very complex. The flowfield includes blade-tip vortices, which are relatively high frequency flow structures that convect down and impinge on the wings. The rotor wakes interact with the wings to form a lower frequency recirculating flow condition over the fuselage/wing junction known as the tiltrotor "fountain." The rotor downwash over the wings results in massive regions of separated flow on and below the wing.

Blade interaction with tip-vortices and the fountain are primary sources of acoustic noise.

An unsteady Navier-Stokes simulation of a 0.658-scale V-22 rotor and flapped-wing configuration was carried out to study the aerodynamics of a tiltrotor in hover. Of particular importance to the study is the mechanism of formation and dynamics of the tiltrotor fountain. The simulation conditions were derived from an experimental investigation[70] carried out in the NASA Ames 40x80 foot wind tunnel. The simulation includes accurate modeling of all geometric components of the flapped-wing and rotor test rig, including rotor blades. Accordingly, rotor-blade motion and rotor/airframe interference effects are directly simulated. The computed rotor thrust and power, and wing surface pressures are in very good agreement with experimentally measured values. The predicted wing download is within 7% of the measured value, the difference between computation and experiment being less than 1% of the rotor thrust.

The grid system employed in the study is indicated in Figure 11a and consists of 26 overlapping component grids and approximately 2.5 million grid points. In the simulation, the rotor-blades were started impulsively from quiescent flow conditions and run time-accurately for 17 revolutions. Approximately 3,600 time-steps were used to resolve each revolution of the blades (~0.1 deg/time-step).

Rotor thrust and shaft-torque, and wing-down loads, were saved every time-step. Solution and grid files were saved every 50 time-steps for post-process analysis and visualization of the off-body aerodynamic field. The entire solution and grid files were saved for a total of 1,224 steps (i.e., once every 50-steps for 17revs x 3,600 steps/rev). Data storage requirements for each set of solution and grid files required approximately 110 megabytes (32-bit words). Accordingly, a total of approximately 135 gigabytes of disk space was required to save the entire data set.

### 3 SUMMARY AND FUTURE DIRECTIONS

A review of even a small sample of recent applications of overset methods for unsteady three-dimensional viscous flow situations clearly demonstrates 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.

As computational capacity continues to grow, and the possibility of carrying out unsteady three-dimensional viscous flow simulations becomes more practical, the issue of data management will become critical. Mass-storage systems, data transfer hardware/networks, software for post-process analysis and visualization of unsteady data sets all represent areas in which research and development is needed. These needs will exist regardless of simulation approach.

It can rightly be argued that for validation studies, simulation data can be saved on a very selective basis in order to make judicious use of available data storage devices. However, as use of computational methods as predictive tools increases, the need to save more data will increase dramatically. The geometry of the controlled store-separation case highlighted in the previous section is not very complex. However, disk storage requirements of the corresponding unsteady data is 30 times that required to store grid and restart files for the very high-resolution space shuttle configuration (16 million points, steady-state case). The tiltrotor in hover case required more than 100 times the disk storage of the space shuttle case.

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