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AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
GRANT F49620 (97-1-0059 to 99-1-0007)
Final Report - November 1999

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SUMMARY

This is a four-part final report on the research supported by the Air Force Office of Scientific Research Center under Grant F49620 (97-1-0059 to 99-1-0007), entitled **Numerical Simulation of Three-Dimensional High-G Dynamic Maneuvers of a Complete and Flexible Aircraft Configuration**.

~~1. Motivations and research plan~~

Our long-term objective is the development of a fast and sound methodology for simulating the dynamic aeroelastic response of an aircraft during three-dimensional high-G maneuvers in transonic and supersonic airstreams. Our focus is on AIR FORCE relevant problems exemplified by a transonic/supersonic lifting body geometry performing complex multi-G maneuvers at a free-stream Mach number M_∞ ranging between 0.7 and 3 ($0.7 \leq M_\infty \leq 3$).

In order to achieve this long term-objective, we have defined the following milestones that constitute our short-term objectives, all of which initially assume inviscid Euler flows.

- Improve the fidelity, robustness, and computational speed of the basic aeroelastic simulation technology developed at the University of Colorado, and demonstrate it on a detailed structural model relevant to an aircraft where the spars, ribs, skin, fuselage, hinges, control surfaces, and discrete masses are modeled by suitable finite elements. Include composite materials where appropriate, as a first step towards the simulation

of the behavior of aeroelastically tailored materials. This in turn requires addressing the two following issues

Mesh motion. Most mesh motion schemes for flow problems with moving and deforming boundaries are based on particular instances of the concept of a virtual elastodynamic fluid grid. So far, the PI and his co-workers have used the network of springs variant introduced by Batina for their wing and panel flutter investigations. While this approach is satisfactory for small mesh deformations induced by small structural displacements, it is not suitable for maneuvering applications where the structure undergoes *large displacements* and *large rotations*. For such applications, it becomes essential to capture first the rigid body components of the motion, apply them to adjust the global position of the fluid dynamic mesh, filter them out, and then update the fluid mesh by deforming it accordingly to the deformation components of the structure surface. Moreover, superposing a lineal spring on the edge of each tetrahedron of the unstructured fluid mesh prevents two vertices from colliding, but does not prevent a vertex from interpenetrating the facet of a tetrahedron. To prevent such a detrimental interpenetration that is more likely to happen when the structure undergoes large motions, torsional springs must be added at the mesh vertices and their stiffnesses must be carefully calibrated. All these issues must be investigated and resolved in order to be able to simulate three-dimensional maneuvers.

Implicit flow solver for CFD computations on moving grids. Our current three-dimensional unstructured flow code combines a Galerkin centered approximation for the viscous terms, and a Roe upwind scheme for the computation of the convective fluxes. Higher-order spatial accuracy is achieved through the use of a piecewise linear interpolation method that follows the principle of the MUSCL (Monotonic Upwind Scheme for Conservative Laws) procedure. The temporal solution can be carried out either via a low-storage 3-step variant of the explicit Runge-Kutta method which is second-order accurate for nonlinear problems, or a first-order accurate backward Euler implicit algorithm. This code is adequately equipped for handling dynamics meshes while respecting the discrete geometric conservation laws corresponding to the explicit Runge-Kutta and first-order implicit backward Euler schemes. Hence, in order to speed-up simulations, a first task is to develop a second-order implicit time-integration algorithm that satisfies the corresponding second-order discrete geometric conservation law. It has been our experience that for basic aeroelasticity problems, a high-order implicit solver allows a CFL number that is 100 to 1000 times larger than that afforded by the explicit Runge-Kutta solver. However, because a simple block-Jacobi algorithm is currently implemented in our code for solving the underlying linearized systems of equations, an overall gain factor in CPU ranging only between 2 and 10 is attainable when selecting the implicit scheme over the explicit one. Clearly, this indicates that implicit time-discretization is the way to proceed, but a better algebraic solver is needed. Therefore, a second task is to develop a fast domain decomposition based iterative solver for the proposed second-order time-accurate implicit scheme.

- Develop a corotational methodology for capturing nonlinear geometric effects during aircraft maneuvering. Indeed, during a realistic three-dimensional maneuver, an aircraft undergoes *large displacements and rotations*. Therefore, simulating the behavior

of the structure in that case cannot be limited to a vibrational analysis around a fixed equilibrium point, as usually done for flutter analysis. Rather, the entire motion of the structure must be tracked, which requires introducing geometric stiffnesses in the structural model and performing a nonlinear analysis.

- Our current fluid/structure coupled solution algorithm is inherently sequential. While it allows for *intra-parallelism* — that is, for parallel computations within the fluid and structure analyzers — it does not allow for *inter-parallelism* between the fluid and structure computations. Currently, the fluid system must be updated before the structural system can be advanced. Hence, another objective of this research motivated by speeding-up the target simulations is to develop a computationally efficient staggered procedure for the solution of coupled fluid/structure problems that combines both *intra-* and *inter-parallelism*.
- Perform the following simulations which address the various difficulties pertaining to three-dimensional high-G maneuvers in an incremental manner
 - Step 1.* Simulation of the aeroelastic response of a wing system with intelligent inputs to the control surfaces.
 - Step 2.* Simulation of the aeroelastic response of a wing-fuselage system subjected to a “tuned” dynamic gust load.
 - Step 3.* Simulation of the aeroelastic response of a complete aircraft system during a maneuver driven by a change of the attitudes of the control surfaces.

2. Accomplishments

During the fiscal years 1997–1999, we have made significant accomplishments in all areas pertaining to our short-term and long-term objectives described above. Here, we summarize some of these. We have already reported on others in our yearly progress reports.

2.1. Torsional springs for three-dimensional dynamic meshes

As stated earlier, dynamic fluid grids are commonly used for the solution of flow problems with moving boundaries. They are often represented by a network of fictitious lineal springs that unfortunately become unreliable when the fluid mesh undergoes large deformations. In order to address this problem, we have focused initially on the two-dimensional case, then on the three-dimensional one, and proposed to control the arbitrary motion of dynamic unstructured fluid grids with additional torsional springs. We have shown that such springs can be designed to prohibit the interpenetration of neighboring triangles, and therefore to provide the method of spring analogy with the robustness needed for enlarging its range of applications. We have illustrated our new dynamic mesh motion algorithm with several three-dimensional examples that highlight its advantages in terms of robustness, quality, and performance.

2.2. Decoupled rigid/flexible mesh motion scheme for addressing maneuvering

Torsional springs provide great robustness for flutter and/or aeroelastic computations where the fluid mesh undergoes large deformations. However, these springs and most if not all other elasticity based mesh motion schemes are neither sufficiently reliable nor sufficiently performant when the structure undergoes large displacements and rotations, as in maneuvering. For this reason, we have also designed a new corotational-like mesh motion strategy where the motion of the surface of the structure is first decomposed into a rigid body component and a deformational one. First, the rigid body component is transferred to the fluid mesh using simple translations and rotations. Then, the deformational component is applied as a boundary condition to the fluid mesh system, which is then relaxed to achieve equilibrium using the torsional springs. This strategy has enabled the simulation of high-angle pitching and rolling of complete flexible fighter configurations, and has speeded-up simpler simulations that were possible using classical techniques by a factor ranging between 2 and 10, depending on some key configuration parameters.

2.3. Mathematical development of the Geometric Conservation Law

We have established a firm theoretical basis for the enforcement of Discrete Geometric Conservation Laws (D-GCLs) while solving flow problems with moving meshes. The GCL condition governs the geometric parameters of a given numerical solution method, and requires that these be computed so that the numerical procedure reproduces exactly a constant solution. We have shown that this requirement corresponds to both time-accuracy and stability conditions. More specifically, we have proved that satisfying an appropriate D-GCL is a sufficient condition for a numerical scheme to be at least first-order time-accurate on moving meshes. We have also proved that satisfying an appropriate D-GCL is a necessary condition for a scheme to be unconditionally stable on moving grids.

2.4. A second-order space/time accurate methodology for CFD computations on dynamic meshes

We have considered the solution of general two- and three-dimensional unsteady flow problems with moving boundaries using the Arbitrary Lagrangian Eulerian formulation or dynamic meshes. We have focused on the case where spatial discretization is performed by unstructured finite volumes or finite elements. We have formulated the consequence of the Geometric Conservation Law on the second-order implicit temporal discretization of the semi-discrete equations governing such problems, and used it as a guideline to construct a new family of second-order time-accurate and geometrically conservative implicit numerical schemes for flow computations on moving grids. We have applied these new algorithms to the solution of three-dimensional flow problems with moving and deforming boundaries, demonstrated their superior accuracy and computational efficiency, and highlighted their impact on the simulation of aeroelastic nonlinear interaction problems. More specifically,

we have shown that for any specified accuracy, our second-order geometrically conservative time-integration algorithms can employ a time-step that is more than one order of magnitude larger than that of conventional time-integration schemes.

2.5. A fast domain decomposition method for implicit flow solvers

We have developed a variation of the Additive Schwarz Methods called RAS (Restricted Additive Schwarz method) for the fast iterative solution of the systems of equations that arise from the discretization of compressible flow problems. We have shown that this method is cheaper in terms of computations, interprocessor communication, and has a better convergence rate than most iterative algorithms for flow problems we are aware of. In particular, it has speeded up our second-order implicit flow solver, which was initially equipped with Jacobi relaxations, by a factor ranging between 3 and 10, depending on the mesh size. We have also developed a theory that proves estimates of the convergence properties of this method and explains why it is better than the regular Additive Schwarz algorithm.

2.6. Two second-order space/time accurate high-performance algorithms for solving coupled fluid-structure interaction problems

Partitioned procedures and staggered algorithms are often adopted for the solution of coupled fluid/structure interaction problems in the time domain. However, both sequential and parallel partitioned procedures that are popular in computational nonlinear aeroelasticity have limitations in terms of accuracy and numerical stability. We have developed two new second-order accurate serial and parallel staggered algorithms for the solution of coupled transient aeroelastic problems, and demonstrated their superior accuracy and computational efficiency with the flutter analysis of the AGARD Wing 445.6. We have contrasted our results with those computed by other investigators at NASA Langley and NASA Dryden, and validated them with experimental data. We have shown that our algorithms are capable of reproducing the experimental data using a computational time-step that is 20 times larger than that used at NASA Langley, and 50 times larger than that used at NASA Dryden. For maneuvering applications where the geometric nonlinearities of the structure must be accounted for, and where the fluid and structure computations are well-balanced, the newly developed parallel (*intra-* as well as *inter-*parallelism) partitioned procedure provides almost a speed-up of 2 over that allowing only *intra-*parallelism, which is a major achievement.

2.7. A conservative algorithm for exchanging aerodynamic and elastodynamic data

We have considered the realistic situation where the fluid and structure subproblems have different resolution requirements and their computational domains have non matching discrete interfaces, and addressed the proper discretization of the governing interface

boundary conditions. We have developed a new algorithm for converting the fluid pressure and stress fields at the fluid/structure interface into a structural load, and for transferring the structural motion to the fluid system. We have shown that this algorithm conserves both the momentum and energy at the fluid/structure interface, even when the fluid and structure meshes have non matching discrete interfaces.

2.8. Simulation of the aeroelastic response of a wing model driven by intelligent inputs to its control surface

We have successfully performed the simulation of the transient aeroelastic response of a three-dimensional wing driven by intelligent inputs to its control surface. More specifically, we have considered the AGARD 445.6 wing, equipped it with a control surface (a flap), modeled the hinges and actuators, and implemented a simple control law for driving the flap. We have validated this model and used it to investigate an aileron reversal problem.

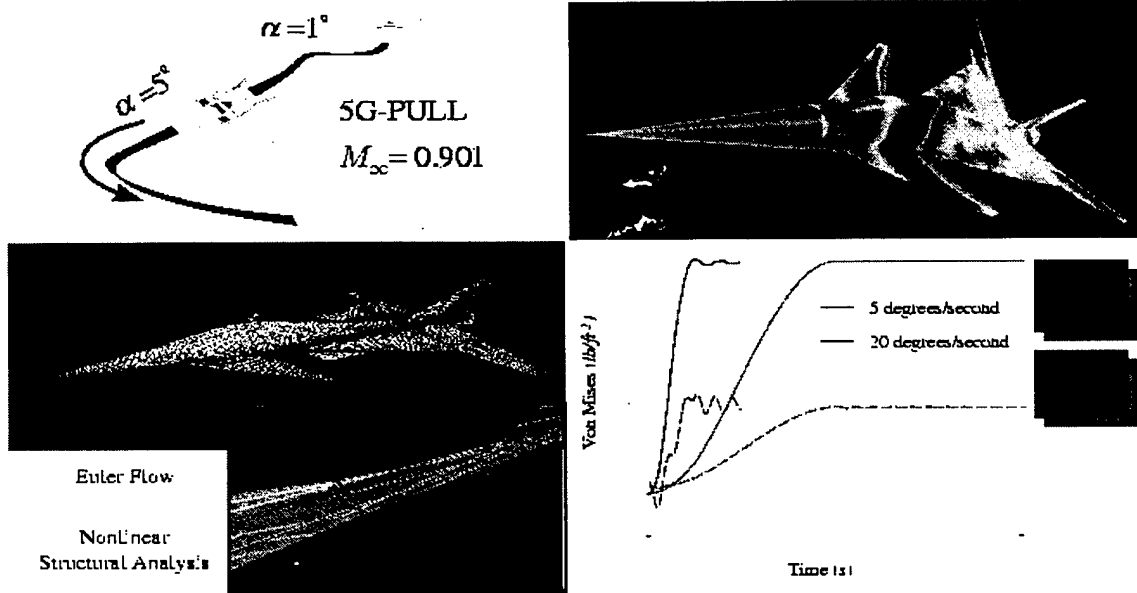
2.9. Simulation of the pitching motion of a complete fighter flexible configuration

We have also successfully performed the simulation of the transient aeroelastic response of a complete Langley Fighter configuration during a forced pitching motion in transonic free streams. For this purpose, we have employed a detailed finite element structural model that accounts for the spars, ribs, skin, fuselage, and continuous as well as discrete masses. We have considered two different rates of pitching (5 degrees per second and 20 degrees per second) and a variation of the angle of incidence from 1 degree to 5 degrees, which corresponds to a net acceleration of 5G. We have observed a 5-fold increase of the lift, as expected. We have also captured the transient behaviour of the structure after the angle of incidence is frozen to 5 degrees, and investigated the history of the maximum Von Mises stresses in the canards and the wings. We have videotaped this simulation and featured it in our paper entitled "CFD Based Simulation of the Unsteady Aeroelastic Response of a Maneuvering Vehicle" and which has been accepted for presentation at the AIAA Reno Meeting in January 2000.

3. Sample simulation

Here, we include a graphical summary of the simulation of the transient aeroelastic response of a complete aeroelastic configuration of the Langley Fighter during a 5G pull-up maneuver in a transonic free stream.

Coupled Fluid/Structure/Control Simulation



Simulation of a 5G pull-up maneuver in the transonic regime

4. Publications that have resulted from the support by this Grant

Monographs and Book Chapters

1. C. Farhat, B. Koobus, and H. Tran, "Simulation of Vortex Shedding Dominated Flows Past Rigid and Flexible Structures," *Computational Methods for Fluid-Structure Interaction*, ed. T. Kvamsdal, I. Enevoldsen, K. Herfjord, C. B. Jenssen, K. Mehr and S. Norsett, Tapir, pp. 1-30 (1999)
2. C. Farhat and M. Lesoinne, "Fast Staggered Algorithms for the Solution of Three-Dimensional Nonlinear Aeroelastic Problems," AGARD Report R-822, Numerical Unsteady Aerodynamic and Aeroelastic Simulation (l'Aérodynamique instationnaire numérique et la simulation de l'aéroélasticité), North Atlantic Treaty Organization (NATO), March 1998.
3. C. Farhat, "Parallel and Distributed Solution of Coupled Nonlinear Dynamic Aeroelastic Response Problems," *Solving Large-Scale Problems in Mechanics: Parallel and Distributed Computer Applications*, ed. M. Papadrakakis, J. Wiley, pp. 243-302 (1997)

Refereed Journals

4. H. Guillard and C. Farhat, "On the Significance of the Geometric Conservation Law for Flow Computations on Moving Meshes," *Computer Methods in Applied Mechanics and Engineering*, (submitted for publication)
5. M. Lesoinne, M. Sarkis, U. Hetmaniuk, and C. Farhat, "A Linearized Method For the Frequency Analysis of Three-Dimensional Fluid/Structure Interaction Problems in all Flow Regimes," *Computer Methods in Applied Mechanics and Engineering*, (in press)
6. C. Felippa, K. C. Park and C. Farhat, "Partitioned Analysis of Coupled Mechanical Systems," *Computer Methods in Applied Mechanics and Engineering*, (in press)
7. S. Piperno and C. Farhat, "Partitioned Procedures for the Transient Solution of Coupled Aeroelastic Problems - Part II: Energy Transfer Analysis and Three-Dimensional Applications," *Computer Methods in Applied Mechanics and Engineering*, (in press)
8. C. Farhat and M. Lesoinne, "Two Efficient Staggered Procedures for the Serial and Parallel Solution of Three-Dimensional Nonlinear Transient Aeroelastic Problems," *Computer Methods in Applied Mechanics and Engineering*, (in press)
9. B. Koobus and C. Farhat, "On the Implicit Time-Integration of Semidiscrete Viscous Fluxes on Unstructured Dynamic Meshes," *International Journal for Numerical Methods in Fluids*, Vol. 29, No. 8, pp. 975-996 (1999)
10. B. Koobus and C. Farhat, "Second-Order Time-Accurate and Geometrically Conservative Implicit Schemes for Flow Computations on Unstructured Dynamic Meshes," *Computer Methods in Applied Mechanics and Engineering*, Vol. 170, pp. 103-130 (1999)
11. C. Farhat, C. Degand, B. Koobus and M. Lesoinne, "Torsional Springs for Two-Dimensional Dynamic Unstructured Fluid Meshes," *Computer Methods in Applied Mechanics and Engineering*, Vol. 163, pp. 231-245 (1998)
12. M. Lesoinne and C. Farhat, "A Higher-Order Subiteration Free Staggered Algorithm for Nonlinear Transient Aeroelastic Problems," *AIAA Journal*, Vol. 36, No. 9, pp. 1754-1756 (1998)
13. C. Farhat, M. Lesoinne and P. LeTallec, "Load and Motion Transfer Algorithms for Fluid/Structure Interaction Problems with Non-Matching Discrete Interfaces: Momentum and Energy Conservation, Optimal Discretization and Application to Aeroelasticity," *Computer Methods in Applied Mechanics and Engineering*, Vol. 157, pp. 95-114 (1998)
14. X.-C. Cai, C. Farhat and M. Sarkis, "A Minimum Overlap Restricted Additive Schwarz Preconditioner and Applications in 3D Flow Simulations," *Contemporary Mathematics*, Vol. 218, pp. 478-484 (1998)
15. H. Tran, B. Koobus and C. Farhat, "Numerical Simulation of Vortex Shedding Flows Past Moving Obstacles Using the $k-\epsilon$ Turbulence Model on Unstructured Dynamic Meshes," *La Revue Européenne des Eléments Finis*, Vol. 6, No. 5/6, pp. 611-642 (1998)

Refereed Proceedings

16. H. Guillard and C. Farhat, "On the Significance of the GCL for Flow Computations on Moving Meshes," *AIAA Paper 99-0793, 37th Aerospace Sciences Meeting and Exhibit*, Reno, Nevada, January 11-14 (1999)
17. X.-C. Cai, C. Farhat and M. Sarkis, "Variable Degree Schwarz Methods for Unsteady Compressible Flows," in: *Domain Decomposition Methods for Partial Differential Equations*, ed. by P. Bjorstad, M. Espedal and D. Keyes, Domain Decomposition Press, Bergen, pp. 682-689 (1998)
18. C. Farhat and M. Lesoinne, "Enhanced Partitioned Procedures for Solving Nonlinear Transient Aeroelastic Problems," *AIAA Paper 98-1806, 39th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, Long Beach, California, April 20-23 (1998)
19. C. Farhat, C. Degand, B. Koobus and M. Lesoinne, "An Improved Method of Spring Analogy for Dynamic Unstructured Fluid Meshes," *AIAA Paper 98-2070, 39th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, Long Beach, California, April 20-23 (1998)
20. C. Farhat and M. Lesoinne, "Higher-Order Staggered and Subiteration Free Algorithm for Coupled Dynamic Aeroelasticity Problems," *AIAA Paper 98-0516, 36th Aerospace Sciences Meeting and Exhibit*, Reno, Nevada, January 12-15 (1998)
21. C. Farhat and M. Lesoinne, "A Conservative Algorithm for Exchanging Aerodynamic and Elastodynamic Data in Aeroelastic Systems," *AIAA Paper 98-0515, 36th Aerospace Sciences Meeting and Exhibit*, Reno, Nevada, January 12-15 (1998)
22. B. Koobus and C. Farhat, "Second-Order Implicit Schemes that Satisfy the GCL for Flow Computations on Dynamic Grids," *AIAA Paper 98-0113, 36th Aerospace Sciences Meeting and Exhibit*, Reno, Nevada, January 12-15 (1998)
23. X.-C. Cai, C. Farhat and M. Sarkis, "Schwarz Methods for the Unsteady Compressible Navier-Stokes Equations on Unstructured Meshes," in: *Domain Decomposition Methods in Sciences and Engineering*, R. Glowinski, J. Périaux, Z. Shi and O. Widlund, eds., John Wiley & Sons, Ltd., pp. 453-460 (1997)