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The purpose of this research is to develop a dynamic simulation approach to per-form efficient large scale simulations of full aircraft configurations, with the capabil-ity of including six-degrees-of-freedom (6-DOF) corresponding to realistic aeroelastic motions. While there has been some progress in the aeroelastic problem in previ-ous efforts, the flow component has been crudely modeled using either Euler inviscid description or the Reynolds averaged Navier-Stokes equations, both of which have proven to be inaccurate and thus inadequate for the Air Force needs. The emphasis of the completed work has been on capturing very accurately the vorticity generation process and the unsteady three-dimensional separation phenomena on the body by resolving all energetic flow scales in the near-wall and near-wake regions. Away from the body a subgrid model will be used to account for the reduced resolution. A new simulation paradigm has been developed for such flows employing the concept of dy-namic simulation based on surgical p-refinement for transitional and turbulent flows at high speed, where significantly energetic flow scales are resolved dynamically as they are convected downstream or as new structures are generated and shed off from the body.

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Dynamic DNS/LES of transition and turbulence in high-speed flows and flow-structure interactions

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Objectives

The purpose of this research is to develop a *dynamic* simulation approach to perform efficient large scale simulations of full aircraft configurations, with the capability of including six-degrees-of-freedom (6-DOF) corresponding to realistic aeroelastic motions. While there has been some progress in the aeroelastic problem in previous efforts, the flow component has been crudely modeled using either Euler inviscid description or the Reynolds averaged Navier-Stokes equations, both of which have proven to be inaccurate and thus inadequate for the Air Force needs. The emphasis of the completed work has been on capturing very accurately the vorticity generation process and the unsteady three-dimensional separation phenomena on the body by resolving all energetic flow scales in the near-wall and near-wake regions. Away from the body a subgrid model will be used to account for the reduced resolution. A new simulation paradigm has been developed for such flows employing the concept of *dynamic* simulation based on surgical *p-refinement* for transitional and turbulent flows at high speed, where significantly energetic flow scales are resolved dynamically as they are convected downstream or as new structures are generated and shed off from the body.

Major Accomplishments

- **Development of a new projection formulation of hyperbolic and parabolic problems using a discontinuous Galerkin formulation:** These new projections were used to develop a high-order finite-volume type formulation for high-speed flows that is conservative and does not require the use of any limiters. For smooth regions a high-order representation is employed, whereas for regions containing strong shocks adaptive h-refinement is employed recovering the standard finite volume formulation. This is the first ever formulation that provides high-order accuracy on standard unstructured and viscous grids while maintaining element-wise conservativity and monotonicity, which are key features for simulating accurately high-speed flows.

- **Development of an Arbitrary Lagrangian Eulerian (ALE) formulation for moving and time-dependent domains:** Specifically, the ALE formulation has been implemented within the Discontinuous Galerkin framework. It allows the computations of flows around moving and deforming bodies. A novel development is an efficient algorithm for mesh movement around deforming bodies that does not require matrix inversion. In fact, the entire formulation is matrix-free.

• **Development of dynamic h-refinement of the mesh around discontinuities:** In regions of large gradients, high-order elements are subdivided into a set of smaller triangles in two-dimensions or tetrahedra in three-dimensions. Stable upwind schemes are applied on these smaller elements. If the gradient decreases, these elements are interpolated back to the polynomial space. This h-p adaptive algorithm allows great flexibility in computing flows with discontinuities (supersonic flows) without loss of accuracy.

• **De-Aliasing on Unstructured Grids:** Aliasing errors can produce erroneous results in turbulence simulations and in any other long-term integration of nonlinear unsteady problems. While de-aliasing rules for Fourier methods have been established and shown to be very effective (e.g. the 3/2 rule), there are currently no procedures to remove aliasing errors on non-uniform grids. We have developed the first such effective procedure and apply it to DNS of flows past bluff bodies. Specifically, the algorithm consists of a super-collocation procedure followed by a Galerkin projection. The typical number of extra quadrature points is twice the number of degrees of freedom (for the discretization of nonlinear terms only). We have performed tests with computational complexity equivalent to the 3/2 rule, and the results are very good.

• **The Spectral Vanishing Viscosity (SVV) Method.** This formulation is based on a rigorous theoretical framework: It guarantees *monotonicity* of the solution while it preserves the fast *exponential convergence* of spectral discretization. This result, which was first obtained for nonlinear conservation laws, leads to high accuracy and great efficiency in LES as it avoids filtering and excessive dissipation. Specifically, the Navier-Stokes equations are enhanced with a viscous convolution operator described by a mode-dependent viscosity which acts only on high modes unlike the classical eddy-viscosity models that modify the entire spectrum including the low-wave number energetic scales. It resembles *hyperviscosity* which is often used with success in homogeneous turbulence simulations in order to achieve high Reynolds number turbulence. However, the important difference is that in the SVV approach all parameters are given by the theory, and also the convolution operator is second-order, which means that it can be used in conjunction with finite element and finite volume techniques unlike the hyperviscous kernels.

Specific tasks we performed included parametric studies and comparisons with standard DNS benchmarks revealing a two-orders of magnitude savings in CPU simulations, and high Reynolds number simulations past a cylinder ($Re = 160,000$, for first time).

• **Simulation and VR-Visualization of a full F15 configuration.** This is the first time that such simulations are performed on a Linux cluster of PCs! The simulation employed about 150,000 tetrahedra elements describing accurately the geometry of the F15 with fourth-order Jacobi polynomials. The SVV-LES approach described above was used in the simulations. The average CPU time per time step on a cluster of 20 PC/Linux (Road Runner in University of New Mexico) cluster was 30 seconds. This simulation demonstrates that very-large-scale simulations of interest to AFOSR will be possible in the near-future on relatively small clusters of PCs.

In addition to the simulation of the unsteady flow, 3D visualizations in the CAVE (virtual reality facility) have been developed and applied to the F15 simulation data. Dr. Sakell (the AF PM of this project) was invited to view and interact with this data in this new and potentially breakthrough simulation and visualization environment. The PI has been collaborating with computer scientists to develop novel interaction and visualization tools for external flows, using a kit of virtual tools, including rakes of streamlines, particles, vector, pressure iso-surfaces, vorticity and other aerodynamic-specific quantities. Particular attention has been paid to visualizing in real time both the global (entire) field as well as details of the flow, e.g. horseshoe vortex around the rudder. This was accomplished using the *intrinsic hierarchy* in modal space of the spectral/*hp* element method that the PI and his students have developed with the sponsorship of AFOSR.

Personnel

• Faculty: G.E. Karniadakis, Professor of Applied Mathematics

• Collaborators and PhD Students: Prof. S.J. Sherwin, Prof. C.-H. Su, I. Lomtev, R.M. Kirby, T.C. Warburton, V. Symeonidis, D. Xiu.

Publications

1. I. Lomtev, "A discontinuous Galerkin method for the compressible Navier-Stokes equations in stationary and moving 3D domains", PhD thesis, Brown University, (completed in 1999; supervised by the PI).

2. G.-S. Karamanos and G.E. Karniadakis, "A spectral vanishing viscosity method for large eddy simulations", J. Comp. Phys., vol. 162, pp. 22-50, 2000.

3. C. Evangelinos, S.J. Sherwin and G.E. Karniadakis, "Parallel DNS algorithms on unstructured grids", Comp. Meth. Appl. Mech. Engr., vol. 184, pp. 401-425, 2000.

4. I. Lomtev, R.M. Kirby and G.E. Karniadakis, "DNS for flow past a 3D flexible wing", Proceedings of Recent Advances in DNS and LES, pp. 279-290, Kluwer, 1999 (also cover of the book).

5. R.M. Kirby, T.C. Warburton, I. Lomtev and G.E. Karniadakis, "A discontinuous Galerkin spectral/*hp* method on hybrid grids", Applied Numerical Mathematics, vol. 33, pp. 393-405, 2000.

6. "Discontinuous Galerkin Methods: Theory, Computation and Applications", (editors: B. Cockburn, G.E. Karniadakis and C.-W. Shu), Lecture Notes in Computational Science and Engineering, Springer, 2000.

7. B. Cockburn, G.E. Karniadakis and C.-W. Shu, "The development of discontinuous Galerkin methods", Proceedings on Discontinuous Galerkin Methods: Theory, Computation and Applications", pp. 3-50, Springer 2000.

8. C. Evangelinos, I. Lomtev and G.E. Karniadakis, "Shedding patterns in flow-structure interactions", J. Visualization, vol. 2(2), pp. 135-142, 1999.

9. G.E. Karniadakis and S.J. Sherwin, "Spectral/*hp* Element Methods for CFD", Oxford University Press, 1999.

10. I. Lomtev, R.M. Kirby and G.E. Karniadakis, "A discontinuous Galerkin method in moving domains", Proceedings on Discontinuous Galerkin Methods: Theory, Computation and Applications", pp. 375-383, Springer 2000.

11. I. Lomtev, R.M. Kirby and G.E. Karniadakis, "A discontinuous Galerkin ALE method for compressible viscous flows in moving domains", J. Comp. Phys., vol. 155, pp. 128-159, 1999.

12. I. Lomtev, and G.E. Karniadakis, "A discontinuous Galerkin method for the Navier-Stokes equations", Int. J. Num. Meth. Fluids, vol. 29, pp. 587-603, 1999.

13. G.E. Karniadakis, "Simulating turbulence in complex geometries", Fluid Dynamics Research, vol. 24 (6), pp. 343-362, 1999.

14. T.C. Warburton, S.J. Sherwin and G.E. Karniadakis, "Basis functions for triangular and quadrilateral high-order elements", SIAM J. Scientific Computing, vol. 20(5), pp. 1671-1695, 1999.

15. T.C. Warburton, I. Lomtev, Y. Du, S.J. Sherwin, and G.E. Karniadakis, "Galerkin and discontinuous Galerkin spectral/hp methods", Comp. Meth. Appl. Mech. Engr., vol. 175, pp. 343-359, 1999.

16. "Spectral, Spectral Element and *hp* Methods for CFD", guest editor of Comp. Meth. Appl. Mech. Engr., (co-editors: M. Ainsworth and C. Bernardi), vol. 175, 1999.

17. G.S. Karamanos, C. Evangelinos, R. Boes, R.M. Kirby and G.E. Karniadakis, "DNS of turbulence on a PC/Linux cluster: Fact or Fiction?", Proc. SuperComputing 1999.

18. R.M. Kirby, T.C. Warburton, S.J. Sherwin and G.E. Karniadakis, "The NEKTAR code: Dynamic simulations without refinement", Second International Symposium on Computational Technologies for Fluid/Thermal/Chemical Systems with Industrial Applications, August 1-5, Boston MA, 1999.

Interactions/Transitions

The PI organized (with B. Cockburn and C.-W. Shu) the first International Symposium on Discontinuous Galerkin Methods on May 24-26, in Newport, RI USA.

The PI organized a mini-Symposium on "Large Eddy Simulations Using Finite Elements" in the *International Conference on Finite Elements in Flow Problems* held in Austin, Texas (May 30 - April 4, 2000). He has also continued his interactions with Boeing personnel (Dr. D. Young and Dr. A. Cary) for comparisons between LES-SVV results and Boeing's experimental and numerical results.

The AFOSR-sponsored research was presented in the past three years at:

- DOE/Oakridge Workshop on Discontinuous Galerkin Methods for Materials (1998)
- NSF Woskshop on New Computational Challenges (1998)
- AIAA Fluid Dynamics Conference on LES (1998)
- ICOSAHOM'98 Symposium on Corner Singularities (1998)
- Japanese Society of Fluid Mechanics 30th Anniversary Symposium (1998)
- University of Tokyo, Department of Mechanical Engineering (1998)
- Turkey Workshop on Industrial and Environmental Applications of DNS/LES (1998)
- Los Alamos National Laboratories (1999)
- First International Symposium on DGM, Newport RI (1999)
- DOE Workshop on mesh generation, Argonne National Lab (1999)
- DoD High Performance Computing, Monterey CA (1999)
- Second International Conference on DNS/LES, Rutgers University (1999)
- ASME CFD Symposium on Flow-Structure Interactions, Boston (1999)
- National Congress on Computational Mechanics, Boulder Co (1999)
- CISM, Udine, Italy (1999)
- Los Alamos National Laboratories (1999) (invited)
- Supercomputing'99, Portland (1999)

- American Physical Society, DFD Meeting (1999) (invited/keynote)
- AFOSR/NSF Workshop on LES (1999) (invited participant)
- p- and hp Finite Element Methods, St. Louis (2000) (invited)
- Flow Induced Vibration Conference, Switzerland (2000)
- Simulation Based Design Workshop, Newport RI/NUWC (2000) (invited)
- IUTAM Conference on Wakes & Flow Structure Interactions, France (2000)
- DOD-HPCMP Users Group Conference, Albuqurque/NM (2000)
- International Conference on Finite Elements For Flow Problems (2000)
- HPC Defence Science Board (2000) (invited)

Technology Transfer

The code **NEKTAR** has been disributed to more than one dozen Universities and Laboratories. Some of them include Boeing, Inc., AF Kirkland Lab, MIT, Caltech, UC Berkeley, Cornell University, Penn State University, University of Wisconsin, Imperial College, Oxford Computing Laboratory, University of Tokyo, University of Bologna, Norwegian University of Science & Technology, North Carolina University, Florida State University, Sandia, OAK Ridge Labs, Nielsen, Inc. etc. There is now documentation of the code both for users as well as developers. This is an OpenSource code that runs on all available platforms including clusters of PCs.