Old Dominion University Research Foundation

DEPARTMENT OF AEROSPACE ENGINEERING
COLLEGE OF ENGINEERING & TECHNOLOGY
OLD DOMINION UNIVERSITY
NORFOLK, VIRGINIA 23529

DOMAIN DECOMPOSITION FOR AERODYNAMIC AND AEROACOUSTIC ANALYSES, AND OPTIMIZATION

By

Oktay Baysal, Principal Investigator

Final Report
For the period ended September 30, 1995

Prepared for
National Aeronautics and Space Administration
Langley Research Center
Hampton, VA 23681-0001

Under
Research Grant NAG-1-1499
James L. Dillon, Technical Monitor
ADYD-Super/Hyper Aerodynamic Branch

Submitted by the
Old Dominion University Research Foundation
P.O. Box 6369
Norfolk, Virginia 23508-0369

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§.1 Summary

The primary objective of this program was to provide the financial support for the graduate students involved in the above named research topics under the supervision of the Principal Investigator. The overarching theme was the *Domain Decomposition*, which intended to improve the numerical solution technique for the partial differential equations at hand; in the present study, those that governed either the fluid flow, or the aeroacoustic wave propagation, or the sensitivity analysis for a gradient-based optimization. The role of the domain decomposition extended beyond the original impetus of discretizing geometrically complex regions or writing modular software for distributed-hardware computers.[1] It induced function-space decompositions and operator decompositions, that offered the valuable property of near independence of operator evaluation tasks.

The objectives have gravitated about the extensions and implementations of, either the previously developed or concurrently was being developed, methodologies under the Grants NAG-1-1188 and NAG-1-1150:

(i) aerodynamic sensitivity analysis with domain decomposition (SADD)[2];
(ii) computational aeroacoustics of cavities[3];
(iii) dynamic, multi-body computational fluid dynamics using unstructured meshes[3];

The program was intended to be a three-year project and started on June 1, 1993. However, the funding supporting the project was abruptly cut in January 1995 due to the severe shortages experienced at the funding agency. The project was subsequently closed in August 1995. Nonetheless, each of the problems stated above benefited from the program,

[1]Superscripts indicate reference numbers

which provided *partial* support for one Ph.D. and three Master's students (K.P. Singh, J.C. Newman, J.M. Lacasse, F.O. Vanel).

In the remainder of this report, an overview of each of the technical approaches and a synopsis of their achievements are presented in §.2-§.4. The details are available in the technical publications listed in §.5 and sampled by their cover pages in §.6.

§.2 Sensitivity Analysis with Domain Decomposition (SADD) - multielement airfoil

In 1990, an aerodynamic sensitivity analysis method[4] was presented for the compressible Euler equations. This method was then applied to the design of a scramjet-afterbody configuration for an optimized axial thrust.[5] Then, the issue of computational efficiency was addressed by the development of the multiblock sensitivity analysis scheme SADD.[6] The SADD scheme was later extended to three dimensions, where the conjugate-gradient-like method GMRES was also incorporated[7] and applied in the optimization of a nacelle near a wing.[8] This scheme was motivated by the need to address the computer memory issues in the direct inversion of the sensitivity equation's coefficient matrix, which becomes particularly large. It induced function-space decompositions and operator decompositions, that offered the valuable property of near independence of operator evaluation tasks. Another benefit was its applicability to problems involving complex and multicomponent geometries, around which structured grids can only be generated by the use of domain decomposition techniques.

The impetus for the present extension[9,10] was to study some issues relevant to SADD, and test it through 2-D applications. One conceivable area of its potential application was the design of a high lift device, for instance, a multielement airfoil. Therefore, it was aimed at demonstrating the following:

(i) the aerodynamic shape optimization methodology on a multiblock domain;
(ii) multiblock capability in optimizing a highly nonlinear (transonic) flowfield;
(iii) the simultaneous reshaping of aerodynamically interfering elements.

First, a transonic airfoil was optimized to investigate the behavior of the method in highly nonlinear flows as well as the effect of different blocking strategies on the procedure. A supercritical airfoil was produced from an initially symmetric airfoil with multiblocking affecting the path but not the final shape. Secondly, a two-element airfoil was shape optimized in subsonic flow to demonstrate the present method's capability of shaping aerodynamically interfering elements simultaneously. For a very-low- and a very-high-Reynolds-number cases, the shape of the main airfoil and the flap were optimized to yield improved lift-to-drag ratios.

Finally, the results of this investigation has partially laid the foundation to a follow-up project, supported under another grant (NAG-1-1576).[11]

§.3 Methods for Aeroacoustic Wave Propagation

Previously, an unsteady computational fluid dynamics (CFD) method was used to simulate the flowfield and the aeroacoustic field of a 2-D cavity.[12] The effects of two suppression devices on the generated tones and the broadband noise were computed. The comparisons with experimental data were acceptable for engineering purposes. However, it was realized that a typical second-order CFD method was too dispersive and diffusive for the long-term wave propagation.

Also, various studies[13] had suggested, that the direct simulations of the flow equations for the acoustic wave propagation using the higher order CFD schemes on fine meshes could become prohibitively expensive, since the number of grid points per wavelength should ideally not exceed ten. Hence, a fourth-order accurate *dispersion-relation-preserving* method was investigated for a number of benchmark wave propagation problems.[14,15]

Furthermore, ways to evaluate and interpret the often intractable amount of time-dependent data generated was still an unsettled issue. Hence, it was concluded that higher-fidelity methods to integrate the flow equations and better spectral methods for the time series analysis were needed. Therefore, the relative merits of three spectral analysis methods were considered[14,15]. For simple, periodic waves with steep-sloped spectra, the periodogram method produced better estimates than the Blackman-Tukey method, and the Hanning window was more effective when used with the former. For chaotic waves, however, the weighted-overlapped-segment-averaging and Blackman-Tukey methods were better than the periodogram method. Therefore, it was observed that the spectral representation of time-domain data was significantly dependent on the particular method employed.

Had the project not been closed prematurely, it was intended to decompose the domain into three concentric subdomains, where the DRP method, a second-order CFD method, and an acoustic analogy method (Kirchoff formulation) would have been coupled in these subdomains. Hence, the domain decomposition would have allowed a convenient and judicious choice of couplings for efficient simulations.

Finally, the results of this investigation have partially laid the foundation to a current project supported under another grant (NAG-1-1653).[16]

§.4 Dynamic Unstructured Method for Moving Multibody Configurations

The objective of a prior project, funded under the Grant NAG-1-1150,[3] had been the development of computational fluid dynamics (CFD) methodologies for complex missiles and and stores in relative motion. These flowfields involved multi-body configurations, where at least one of the objects was engaged in a relative motion. The two most important issues that had to be addressed were: (i) the *unsteadiness* of the flowfields (time-accurate and efficient CFD algorithms for the unsteady equations), and (ii) the generation of *grid systems* which would permit multiple and moving bodies in the computational domain (dynamic domain decomposition). Further, the fluid dynamics equations had to be coupled with those of the rigid body dynamics for the involved multi-body problems.

The study produced two competing and promising methodologies, and their proof-of-concept cases, which have been reported in the open literature:

1) Unsteady solutions on *dynamic, decomposed grids*, which may also be perceived as moving, locally-structured grids,[17-19]
2) Unsteady solutions on *dynamic, unstructured grids.* [20]

Along with the numerous advantages of the developed dynamic domain decomposition methodology,[19-21](D^3M) some of the disadvantages were also recognized; in particular, the difficulty of generating overlapped grids when the clearings between the bodies (or components) were exceedingly small, and sometimes, the excessive man-hours involved in generating the composite grids.

Hence, the second approach (*dynamic, unstructured grids)* was further investigated as a competing technology. Note that although the subdomains of the D^3M were structured grids, the composite grid was not. Therefore, it might be viewed as a *locally-structured* grid. If the subdomain grids were taken to the limit such that each one consisted of only one cell, an unstructured grid would be obtained. With this frame of thinking, a previously developed unstructured code, USM3D,[21] for steady flows past static bodies was used as a starting point, and a series of assessment studies were conducted to compare the two approaches.[22]

Then, a three dimensional, unstructured-mesh methodology was developed[23,24]. The method coupled the equations of fluid flow and those of rigid-body dynamics, and captured the time-dependent interference between stationary and moving boundaries.

The flow solver and the adaptation scheme were validated by simulating the transonic, unsteady flow around a wing undergoing a forced, periodic pitching motion, then, comparing the results with the experimental data. To validate the trajectory code, the six-degrees-of-freedom motion of a store separating from a wing was computed using the experimentally determined force and moment fields, then comparing with an independently generated trajectory.

At the end, the overall methodology was demonstrated by simulating the unsteady flowfield and the trajectory of a store dropped from a wing. The methodology, its computational cost notwithstanding, has proven to be accurate, automated, easy for dynamic gridding, and relatively efficient for the required man-hours.

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