3-D Wing Simulation with Design Optimization on Grid Computing Environment

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In this paper, we implement aerodynamic design shape optimization technique to 3-dimensional wing on GRID computing environment. As a metacomputing toolkit, the Globus is used as a middleware connecting the geographically-distributed and heterogeneous computing resources. Before solving the grand problem on this environment, we experimented with geometrically simple 2- and 3-dimensional wing design problem on GRID computing environment. We introduce the brief overview of GRID computing and efficient design optimization algorithm. The experiments were performed on a simple GRID testbed consisting of Linux PC clusters. On the base of this work, aerodynamic design shape optimization technique will be implemented to a large-scale complicated design problem.

Introduction

Recently, a new high performance computing technology has been developed in computer science. This technology is called GRID computing. Resources for GRID computing include the vast, heterogeneous, and geographically-distributed resources. So, middlewares such as Globus have been developed for computations that integrate heterogeneous, geographically-distributed computational resources. On the middleware, we can work in high level programming environment and transparent computational environment even between different computer architectures. Since difficulties related to different characteristics such as OS, location, size, connectivity, name, and so on, can be hid by using interface such as Globus, users can utilize the system as a unified machine. The main objective of GRID computing is to challenge extremely large computations that are currently intractable on conventional tightly-coupled parallel supercomputers. In the CFD area, flow simulations that need large number of grid points such as DNS, 3-D full-body aircraft or rotorcraft computations, aerodynamic design optimizations with large number of design variables and grid points, multi-disciplinary design optimization considering structure, heat transfer, and aero-acoustic problems could be solved based on this GRID technology. Among these applications, aerodynamic design optimization can be the killer application suitable for the GRID computing because of its expensive computational cost, problem size, and importance of design technology in the industrial world. So, in this work, using high level programming environment and tools to support distance computing on heterogeneous distributed commodity platforms and high-speed networks, spanning across labs and facilities, we perform an optimum shape design of 3-dimensional wing under transonic turbulent flow conditions.

The aerodynamic design optimization method is accepted as a very useful tool by the aerospace and mechanical industries. However, it has not been widely used in the industry since the computing cost is too expensive for practical 3-dimensional problems. Recently, an efficient aerodynamic design optimization method is developed for practical large-scale problems [17]. The gradient-based numerical optimization method is used to find optimum design and the flow fields are modeled by the compressible Navier-Stokes equations. The three ingredients of design

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optimization algorithm - flow solver, sensitivity method and optimization method - are modified or newly developed to improve the overall efficiency of design optimization. The flow solutions are computed by a new multigrid DADI algorithm which is designed for fast convergence of steady-state solutions. A continuous adjoint formula is derived from the discrete form of the flow equations to compute more accurate sensitivities. The design equation, derived from the optimality conditions, is introduced to make a simultaneous design optimization algorithm. The flow and adjoint solver are tightly coupled with the optimization procedure. The flow and adjoint solvers are parallelized with the domain decomposition method. The efficiency and accuracy of the present method are assessed by the drag minimization problems of wing and airfoil. The result shows that an optimum shape of 3-dimensional wing under transonic turbulent flow conditions can be found in less than 8 times of flow analysis cost.

GRID computing

GRID computing is an important and popular new field. It is distinguished from conventional distributed computing in that it focus on large-scale resources sharing, innovative applications. Large-scale science and engineering is typically done through the interaction of people, heterogeneous computing resources, multiple information systems, and instruments, all of which are geographically and organizationally dispersed. The overall motivation for “GRIDs” is to enable the routine interactions of these resources to facilitate this type of large-scale science and engineering [1].

Several types of science and engineering applications are being performed under GRID technology. There are scientific data analysis and computational modeling with a world-wide scope of participants(e.g. high energy physics data analysis), large-scale, multi-institutional engineering design and multi-disciplinary science(e.g. design of next generation space shuttle, etc.), real-time data analysis for on-line instruments(e.g. LBNL’s and ANL’s synchrotron light sources, etc.) and generation and management of large, complex data archives(e.g. DOE’s human genome project data, NASA’s earth observing system data).

The GRIDs can be classified as COMPUTAIONAL GRID, DATA GRID, and ACCESS GRID. COMPUTATIONAL GRID is the conventional metacomputing infrastructure, DATA GRID is for the purpose of large scale data processing and management that require the participation of world wide researchers, and ACCESS GRID provide human interface for COMPUTAIONAL GRID and DATA GRID(e.g. real time video conference with P2P based remote control).

The Globus Toolkit is the most widely-used middleware for GRID computing. Globus provides core services required for the distributed computing, including the management of resource information such as location and size, reliable data transfer, more robust resource allocation, fault detection, remote data access, and authenticated communication with enhanced security,. Communication is implemented through MPICH-G2, a Globus-enabled device for the public-domain implementation of MPI, and process creation through allocation, communication, gathering unified resource information, authentication, remote process the co-allocation service accessed via the globusrun utility used to interface with local schedulers. While Globus is used to make the two remote parallel computers recognize each other, the entire application is run as a single message-passing program under MPICH, and the application programmer need not be aware of any distinction between the two machines [2].

Aerodynamic Design Optimization

In this paper, an efficient aerodynamic design optimization method for 3-dimensional shape has been used [17]. A gradient-based optimization method is used for optimization in conjecture with the design sensitivity computed from the continuous adjoint equations [5,6,7].

Using the adjoint sensitivity analysis method, we can obtain the sensitivity information through solving adjoint equations once without many flow field analyses.

In the traditional design optimization method, the optimization method and the flow analysis are loosely coupled. Therefore, in each optimization step, the flow solutions are fully converged according to the prescribed tolerance. The total number of flow analyses during the optimization is about a hundred. On the other hand, one can simultaneously solve the flow field equations, sensitivity equations and the optimization problem. In this approach, only several time steps are applied at each optimization step instead of fully converged solutions. The optimization problem is also treated as differential equations. The gradient equation for the object function can be used for the governing equations of the design problem, since it should be zero at the optimum. Then, the design equations become ordinary differential equations for design variables. The gradients of object function are the residual for design equations, and the step size in line search algorithm is used for the time step in solution procedure. The similar approaches are suggested by Kuruvila et al [8], Ta'asan [9], and Fung and Pulliam [10]. These methods are classified into the 'tightly coupled' approach since all equations are solved with tightly coupled manner. The computational cost of tightly coupled approach is significantly lower than that of loosely coupled approach. The tightly coupled algorithm solves the flow field and adjoint equations simultaneously with design optimization. The expensive line search algorithm is substituted by simple step size estimation. In addition, the flow and adjoint equations are not fully converged at each design step. Only several time steps are applied for the field equations. While the flow and adjoint variables are not converged during the design iterations, they converged when the design variables arrive in optimum value.

The 3-dimensional compressible turbulent Navier-Stokes equations are used for flow analysis, which are solved by the 2nd-order upwind TVD scheme with Roe's flux-difference splitting (FDS) [11] and a multigrid DADI method [12] for convergence acceleration. The far field boundary condition for the Navier-Stokes equation is the characteristic boundary condition using Riemann invariants. The no-slip conditions and zeroth-order extrapolations are enforced at the body surface [12,14].

The continuous adjoint equations are derived from the Navier-Stokes equations, which are solved with the same procedure. All the design optimization procedures are parallelized with domain decomposition method. To reduce computing time, the tightly coupled approach with step size estimation is adopted.

The description of detailed derivations can be found in the literature [6,7,8]. Adjoint Equations for the Navier-Stokes equations and discretization of the derived continuous adjoint equations can be found in the literature [17,18,19].

In this work, Hicks-Henne function [20] is used as the shape function and linear interpolation method is used for the field grid point modification. Hicks-Henne function was used by many researchers for airfoil and wing design problems [5,6,7].

Results and discussions

To show the efficiency of present design method, a viscous drag minimization of RAE 2822 airfoil under a transonic turbulent flow condition was performed. The flow condition is as follows; Mach number 0.729 at an angle of attack of 2.31 degrees and the Reynolds number is 6.5 million. Used grid system is C-type 383x65 with 24,895 points. The objective function for aerodynamic design is a penalty function form to keep the lift coefficient constant, which can be written as

$$I = \frac{1}{2}(C_L - C_{L0})^2 + \frac{10}{2}(C_D)^2$$

where C_L, C_{L0}, C_D are the lift coefficient, the initial lift coefficient, and the drag coefficient, respectively. 10 Hicks-Henne functions are used to modify the upper surface of airfoil while the lower surface is kept to its initial shape. Left figure of Fig. 1 shows the histories of aerodynamic coefficients. The objective function is converged to 76.4% of its initial value after 13 design iteration. The lift and drag coefficients are 99.7% and 87.3% of its initial values. The C_p

distributions of RAE 2822 and designed airfoil are displayed in right figure of Fig. 2. A shock-free airfoil can be obtained after the design optimization.

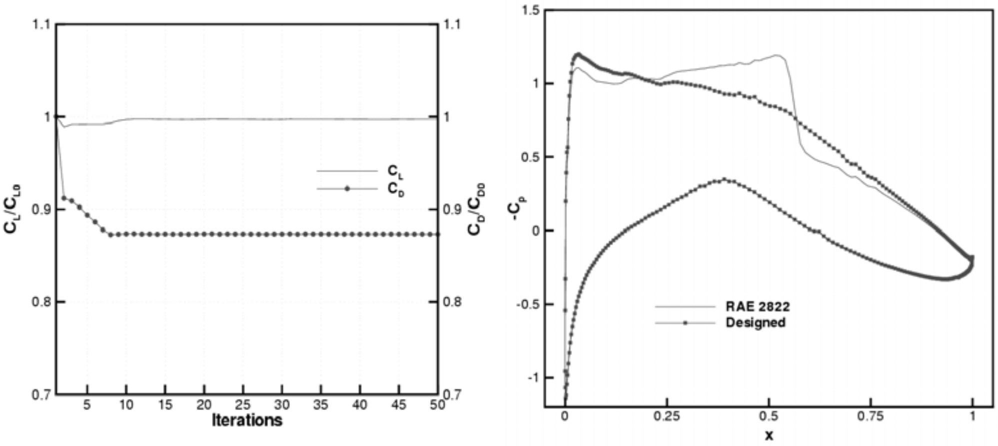

Fig. 1. Histories of aerodynamic coefficients(left) and C_p distributions on the surface(right)

Table 1. Computation Time (unit: seconds)

device resource	Flow analysis (ch_p4)	Design (ch_p4)	Flow analysis (globus2)	Design (globus2)
I	158.0	467.7	158.7	478.9
II	388.8	1166.7	392.9	1170.4
III			410.9	1432.1

Table 1 shows the computation time for each test case. A communication channel ch_p4 is the one used in MPICH and globus2 is the device used in MPICH-G2. For flow analysis 500 multigrid cycles are run and design procedure is started from the steady solution. In the table 1, I indicates the resources which have 4 nodes with 1.7GHz Pentium 4 CPU and 512M memory, II the resources which have 4 nodes with 450MHz Pentium 2 CPU and 256M memory, III the resources that have 2 nodes at I and 2 nodes at II. In cases I and II, computation times are similar each other for ch_p4 and globus2. While MPICH-G2 has properties such as reduced latency for intramachine messaging and increased latency for intermachine messaging, and network performance between intermachines is a little poor, the CASE III shows more or less poor computing performance, but it is tolerable. So if network performance is appropriate for distributed computing, difference between devices ch_p4 and globus2 is negligible, but in case of high latency we should be cautious of the load balancing.

Another test case is the drag minimization of the ONERA M6 wing. The flow condition is Mach number 0.84 at an angle of attack of 3.06 degrees and the Reynolds number is 11.7 million. The computatioinal grid system is C-O type 193x49x33 with 273,867 points. With the initial wing, 196 multigrid cycles and 2047.7 seconds are required to reduce the RMS error of density down to 10^{-4}. 50 Hicks-Henne functions are used as design variables and 5 sections are selected basis sections. The objective function is converged to 77.0% of its initial value after 12 design iterations and the lift and drag coefficients are 97.9% and 87.2%, respectively. The elapsed time is 15674.0 seconds and the cost ratio to flow analysis is 7.65. It shows that the tightly coupled algorithm is very efficient for both the 2-and 3-dimensional aerodynamic design optimization problems.

The C_p distributions on the wing surface is displayed in Fig. 3. The strong λ-shape shock waves are smeared by the design optimization. Fig. 4 shows C_p distributions on the selected wing sections.

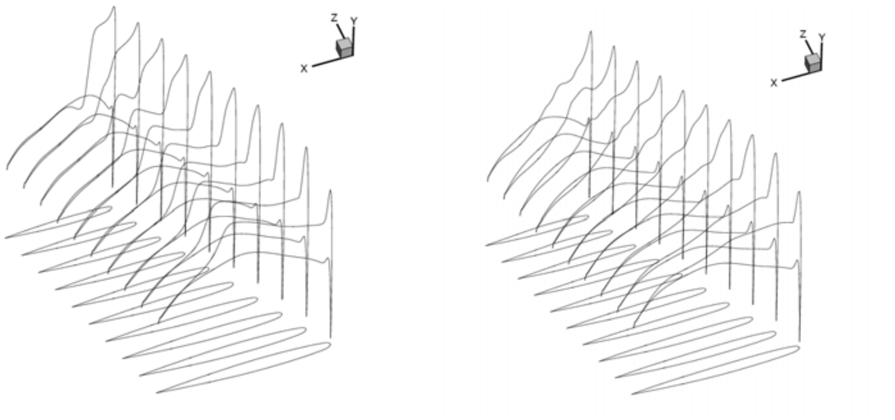

Fig. 2. Pressure distributions on the wing surface before and after design

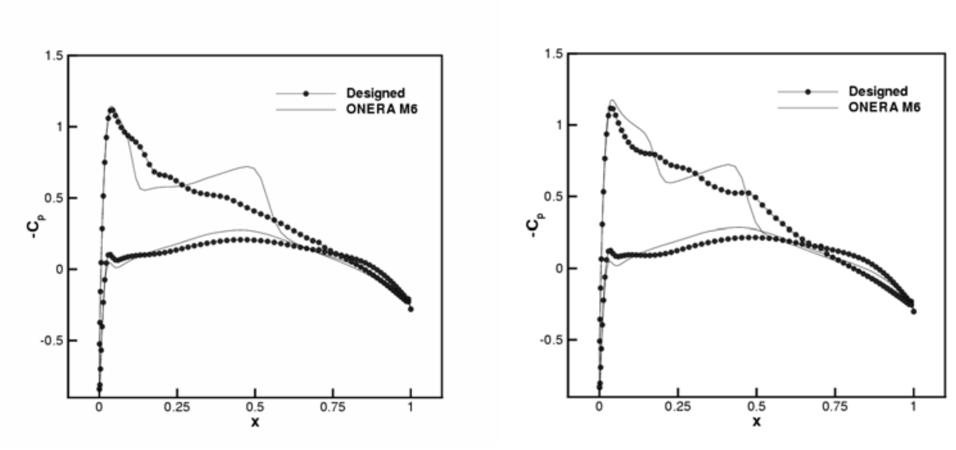

Fig. 3. Comparison of C_p distributions on selected wing sections(left:44% span, right:65% span)

Conclusions

As a starting point to a large-scale problem simulation and design in aerodynamics, 2- and 3-dimensional aerodynamic design optimization for the compressible turbulent Navier-Stokes equations are implemented on GRID environment. For more fast design compared with conventionally used loosely coupled algorithm, a tightly coupled algorithm is used. The present method uses a continuous adjoint method for sensitivity analysis which is adequate for large-scale design problems. The relative cost of used design optimization algorithm is less than 8 times of a flow analysis. The accuracy and robustness of this method are also sufficient to find a shock-free solution, at least for the present test cases. The tightly coupled algorithm is found to be affordable for practical three-dimensional design optimization problems and it can be also extended to the multi-point design problems. On GRID computing environment, without severe loss of efficiency, we can implement flow analysis and design, near future more complicated design will be performed based on GRID computing using more vast resources. Since network latency is an important element for computing efficiency, it is necessary to consider more cautiously dynamic load balancing or to develop a dynamic load balancing method considering the current network speed and information of all resources available.

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