NATIONAL TECHNICAL UNIVERSITY OF ATHENS
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PhD Thesis

MULTIGRID TECHNIQUES AND PARALLEL PROCESSING FOR THE NUMERICAL PREDICTION OF FLOW FIELDS THROUGH THERMAL TURBOMACHINES, USING UNSTRUCTURED GRIDS

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Summary

The incorporation of a Navier-Stokes solver into the design-optimization process of Turbomachinery cascades or aircraft parts is nowadays a necessity. This kind of research is carried out on multiprocessor platforms using multi domain structured or unstructured grids (UG) containing 10^6 to 10^7 nodes. Although parallel processing affords the dramatic reduction of execution time, there is an urgent need for the acceleration of the algorithm convergence history which is considerably decelerated in high Reynolds flows calculations using bulky anisotropic grids.

Multigrid Techniques (MGT) and parallel processing are combined together to afford the solution of such computational problems even for industrial use. Although the development of MGT on structured grids has reached a certain degree of maturity, ongoing research is still carried out on MGT using UG. This is mainly due to a series of difficulties appearing on UG related to the creation of coarser grids and the discretization of flow equations on them, the development of the interpolation operators (restriction and prolongation) between successively coarser grids, as well as the implementation of MGT on turbulence model equations. These problems are intensified by the use of highly anisotropic grids in the vicinity of the wall so that low Reynolds turbulence models are properly implemented. Furthermore, the parallelization of the code, according to multi-domain concept, which facilitates parallel processing on distributed memory clusters is a burdensome computational task. The correct implementation of the above mentioned acceleration tools, so that high Reynolds flows are simulated on bulky and anisotropic UG is the major goal of the present work.

This thesis focuses on the incorporation of MGT into the existing software that simulates 2D and 3D compressible flows on UG with the use of parallel processing based on multi-domain concept carried out through the PVM library on PCs clusters. This software adopts the finite volume method on UG consisting of triangles (2D) or pyramids (3D). As far as the discretization of the convective terms is concerned, they are carried out with the use of the Roe's approximate Riemann solver which is second order accurate. As regards turbulence, all

turbulence models implemented are based on the Boussinesq assumption and they are in widespread use in industry.

The present thesis consists of the following major parts:

- Development of the MGT on UG, so that 3D Navier-Stokes solvers, with some turbulence models incorporated, are accelerated. The flows in interest are external flows as well as through turbomachinery cascades.
- Development of techniques related to the construction of coarser grids.
- Investigation on interpolation operators (restriction and prolongation) which facilitate the data transfer between the successively coarser grids. These operators were proven to play a significant role in stabilization and efficiency of multigrid algorithms.
- Development of discretization schemes on coarser grids that regard mean flow and turbulence model equations.
- The parallelization of the MGT algorithm. According to the method adopted, the coarser grids are irrelevant to the initial grid partition into multi-domains so that additional memory requirements and time overhead are minimized.
- Validation of the simulation accuracy as well as the efficiency of the acceleration tools (parallel processing and MGT, one by one and in combination) by investigating a series of 2D and 3D test cases of internal and external aerodynamics.

The major conclusions drawn are the following:

- On coarser grids the edge-based viscous terms computation is recommended since it helps overcoming the lack of strictly defined edges. This approach is in contrast to other methods based on algebraic multigrid or the finite elements theory which are proven to be insufficient.
- The incorporation of the MGT into the turbulence model equations with stiff source terms in the vicinity of the walls require the use of modified restriction and prolongation operators, ensuring the positiveness of the turbulence variables over all derivative grids.
- The algorithm of the isotropic agglomeration of control volumes is robust and quick but it can be applied only on relatively coarse grids. An effective approach of directional agglomeration, particularly in areas meshed with high aspect ratio triangles, was demonstrated.
- The efficiency of MGT is degraded in cases of supersonic flows characterized by shock waves. The grid anisotropy is also a major factor that has a negative impact on the MGT efficiency.
- The parallelization of the MGT algorithm is robust and accurate since it reproduces the results of the serial version of the code. The additional memory requirements and the inevitable parallel efficiency degradation, in comparison with the single grid solver, are also minimized.
- MGT efficiency can be investigated only if the convergence history of flow equations shows a reduction of residual by several orders of magnitude. This can be achieved by the use of proper limiting functions in discretizing the convective terms so that flow variables monotonicity as well as convergence of flow equations are achieved. In the present work, the limiting function initially proposed by Venkatakrishnan for 2D non-viscous supersonic flows is extended and investigated in 2D and 3D viscous flows on highly anisotropic UG.

In conclusion, the present thesis focuses on a relatively new scientific field such as the incorporation of multigrid techniques and parallel processing into Navier-Stokes using unstructured grids. In all cases, significant multigrid speed up, by a factor of 3 in 2D and between 2 and 3 in 3D, for high Reynolds simulations by the use of highly anisotropic grids were achieved. Furthermore, the parallel version of the code proved to be robust and accurate incurring a slight time and memory overhead.