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Extension of Near-Wall Domain Decomposition to Modeling Flows with Laminar-Turbulent Transition

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Abstract. The near-wall domain decomposition method (NDD) has proved to be very efficient for modeling near-wall fully turbulent flows. In this paper the NDD is extended to non-equilibrium regimes with laminar-turbulent transition (LTT) for the first time. The LTT is identified with the use of the e^N-method which is applied to both incompressible and compressible flows. The NDD is modified to take into account LTT in an efficient way. In addition, implementation of the intermittency expands the capabilities of NDD to model non-equilibrium turbulent flows with transition. Performance of the modified NDD approach is demonstrated on various test problems of subsonic and supersonic flows past a flat plate, a supersonic flow over a compression corner and a planar shock wave impinging on a turbulent boundary layer. The results of modeling with and without decomposition are compared in terms of wall friction and show good agreement with each other while NDD significantly reducing computational resources needed. It turns out that the NDD can reduce the computational time as much as three times while retaining practically the same accuracy of prediction.

AMS subject classifications: 65B99, 65D17, 65N06, 76F06

Key words: Domain decomposition, laminar-turbulent transition, interface boundary condition, near-wall flow, low-Reynolds-number model.

1 Introduction

The problem of modeling a laminar-turbulent transition (LTT) is of great interest in the aircraft design since the turbulence of flow can have a significant impact on aerodynamic characteristics. In industrial applications, the direct numerical simulation (DNS) and

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large eddy simulation (LES) methods are not often used for modeling LTT. Instead, models based on the Reynolds-Averaged Navier-Stokes equations (RANS) are applied. In such models, as a rule, the LTT is set explicitly. LTT can be instant as in the Spalart-Allmaras one-equation model with the trip term [1]. On the other hand, some other models can take into account a transition region between the laminar and turbulent parts of the flow [2]. Regardless of a RANS model, computations can be time-consuming. At the same time, calculations in the near-wall region can take up to 90 % of all time expenses. This is caused by the requirement to resolve a very thin laminar sublayer which is always present thanks to the no-slip boundary condition and damping effect of the wall.

The classical way to reduce the computational time for RANS calculations is to use the wall functions. The use of wall functions allows us to avoid detailed resolution of the near-wall region and reduce the time cost. This approach represents a simplest way for domain decomposition when Dirichlet boundary conditions are prescribed at the cell center of the nearest to the wall cell in one way or another way. The wall functions are semi-empirical and replace the effect of the wall for the outer flow. As well known, despite a certain success with this approach, the wall functions have a number of limitations. They inevitably contain parameters to be tuned. Most of them do not take into account the effect of pressure gradient and other forces, and the obtained solution can be significantly mesh sensitive. For these reasons, the applications of wall functions to flows with complex geometries and boundary layer separation are very problematic. There are some advanced wall functions (see e.g. [3–6]) in which some of these problems are resolved. However, they are not able to overcome all the problems since they have a very limited basis. In addition, the use of wall functions can be problematic in cases with LTT, since they presume the presence of a fully developed turbulence.

The near-wall domain decomposition (NDD) method [7–9, 11] represents an alternative way to reduce the computational time. In this approach the computational domain is split into two blocks. One of these two blocks covers a near-wall region. Such kind of domain decomposition immediately follows from the physics of the problem when the inner region is characterised by both high-gradients of the solution and small scale in the normal to the wall direction. The solution of the entire problem is realized via a non-overlapping domain decomposition. The boundary-value problems in each region are linked with each other via interface boundary conditions (IBCs) of Robin type. In the original formulation of NDD, an approximate NDD (ANDD) is realized. This is achieved with the use of the Thin Boundary Layer Equations (TBLE) in the inner region. The IBCs are obtained via transfer of the boundary conditions from the wall to the interface boundary [39, 40]. As can be shown, in one-dimensional case the Dirichlet boundary condition can be exactly transferred to the interface boundary in the form of an IBC of Robin type. The location of the interface boundary y^* allows the trade-off between the accuracy and computational time to be efficiently controlled. As shown in [10] for incompressible flow in a diffuser, an abatement in accuracy as much as a few percents allows the computational time to be reduced by one order of magnitude. Recent investigations have shown