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Calculations of unsteady flows around high-lift configurations based on a zonal approach

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In the framework of the Project, a special attention is paid to numerical simulation of "high-lifting" systems (take-off and landing systems). The purpose of this Work, is to increase the efficiency of numerical solution of non-stationary problem about wing with released high-lift devices in turbulent flow of real gas at critical and supercritical incidence angles. Non-stationary processes have to be described with adequate quality.

The flow near wing with released high-lift devices has a rather complicated structure and an interaction of many physical effects. It is essentially viscous flow, where developed turbulent boundary layers generate the flow structure. In spite of small Mach numbers ($M \sim 0.2$), which correspond take-off and landing regimes, there are supersonic zones in flow around strongly deflected slat. In the case of medium incidence angles, time-averaged flow is stationary and can be simulated numerically with the use of present methods. But there are some problems with correct prediction of drag coefficient and lift coefficient of wing. But more serious troubles arise in the case of large incidence angles, when, because of stall, there are non-stationary processes connected with strong interaction of developed separation zones with non-stationary vortex sheet past the wing.

Because of flow non-stationary, one should to choose explicit schemes for simulation. These schemes permit to describe non-stationary processes with high quality. But the other peculiarity of such problem class is multi-scale: characteristic times and sizes of different physical processes can differ for some orders of value. Therefore, using explicit schemes leads to extremely large calculation time. In the case multi-scale problems, implicit schemes are good; nevertheless, they have very poor quality for description of non-stationary processes.

A possible way out this contradiction is to use *zonal method*. In this method, flow zones with very small scales of physical processes (mainly, inner zones of boundary layers) are calculated using implicit scheme, while the other part of flow is calculated using explicit one. As a result, non-stationary processes in inviscid core of flow are simulated with a high quality. In the inner part of boundary layers, an implicit scheme is used and one may hope for good results, because the information has to be transmitted across the boundary layer and non-stationary processes in the inner zone of boundary layer have mainly to conform main non-stationary processes that take place in inviscid core of flow. This consideration reduces scheme requirements, from the viewpoint of non-stationary process description quality, and permits to use the implicit scheme in such concrete zones.

To speed-up calculations in inviscid core, a *method of fractional time* stepping is used. The idea of fractional time stepping is that the calculation in each cell is performed with the most time step (i.e. with maximal possible Courant number). But the numbers of *interim time steps* are different in different cells and they are chosen so as all the cells achieve the same layer of physical time in some moments. It should be noted that the first description of such method that is known by authors of the current Work was given in the article [1]. All the calculations were calculated on basis of full 3D non-stationary Reynolds equation system closed by Menter SST turbulence model. The basic variant of solver, which had been developed by authors previously, is realized on the basis of finite-volume numerical method of this equation system solution that has the second approximation order in all variables and includes monotonic Godunov-Kolgan-Rodionov scheme for approximation of convective fluxes, central-difference approximation of diffusive fluxes and two-layer point-implicit approximation of source terms. Detailed description of such method is given in [2]. The calculations are performed on multiblock structured grid with hexahedral cells. This grid permits irregular joining the blocks with discontinuity of the grid lines at the boundaries of blocks.

For the development of methodology, it is natural to use 2D test task, because it requires essentially smaller computer resources and allows parametric calculations for the comparison of various variants. For this purpose, the test task based on EUROPIV2 experimental data has been chosen. The experiment had been performed in the Low Speed Wind Tunnel of Airbus Bremen (Germany) in October 2002 [3, 4]. Straight wing (span – 2.1 m) with three-element airfoil RA16SC1 had been tested. The slat and flap angles were set at one position with deflection angles of 30º and 40º, respectively. The reference chord (that corresponds to retracted slat and flap) is equal to $c = 0.5$ m. During the tests, wind-tunnel free-stream speed was equal to 54 m/sec ($M = 0.15$) under atmospheric conditions. The Reynolds number, based on free-stream velocity and on the chord length of the main wing, was equal to $1.7{\times}10^6$. Measurements included both the registration of the static pressure distributions and the mapping of the velocity fields by PIV method.

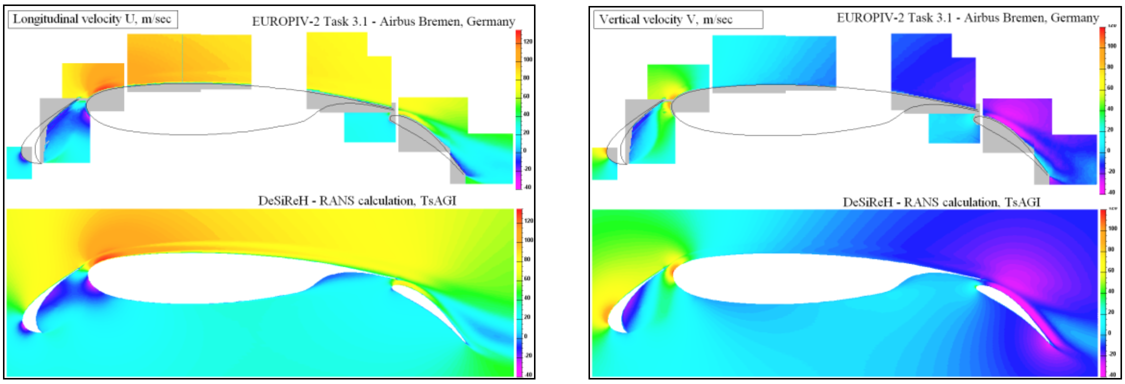

Fig.1. Comparison of PIV–measured velocity fields with computation

In Figure 1 fields of horizontal and vertical components of velocity, obtained by PIV method within the EUROPIV2 Project for the angle of attack $\alpha = 12°$, are compared with analogous fields, obtained in computation for the angle of attack $\alpha = 9°$. At first sight, these fields are very similar; however, the experimental picture shows the separation on the flap upper surface; to the contrary, in the computation this separation is practically absent. Accordingly, the flow deceleration above the flap is stronger in computation – because of the more sharp turn of the flow before the flap trailing edge.

To choose an optimal variant of numerical methodology for calculation of flows around wing at high angles of attack, additional computations of flow around the EUROPIV2 airfoil have been performed for one high value of the angle of attack – $\alpha = 19°$. The following variants of numerical method have been considered: **Implicit scheme with dual-time stepping** (below this scheme will be named as "**dual**"). This scheme has nominally 2nd approximation order in physical time (and first order in pseudo–time). Calculations were performed with constant step in physical time $step\_time_{unsteady}$. **Zonal decomposition method** (below this scheme will be named as "**zonal**"). In this case in near–wall layer of blocks the calculation was performed using implicit scheme with global time stepping. In Region Of Interest, the explicit scheme with fractional time stepping was used In Fig.2 we compare the efficiency of "zonal" approach with the efficiency of "dual implicit" scheme. Along the vertical axis the parameter $\lg\left(\frac{step\_time_{unsteady}}{T_{global}}\right)$ is plotted, where T_{global} is CPU time. Figure 2 shows that "zonal" method becomes more efficient than "dual" at $step\_time_{unsteady} < 10^{-4.8} \approx 0.000016$ sec. Accordingly, "dual" calculation with $step\_time_{unsteady} = 0.00005$ sec advances in physical time faster than "zonal" method, and only in the case $step\_time_{unsteady} = 0.000005$ sec "zonal" method becomes more efficient (approximately 3 times faster) than "dual implicit" calculation.

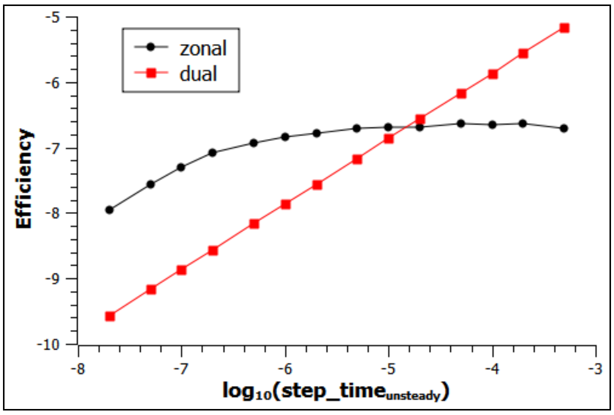

Fig.2. Computational efficiency of zonal approach for airfoil

To verify the working capacity and efficiency of chosen numerical approach for solution of real 3D problems, during the current Project, a test based on the experiments in European transonic wind tunnel (ETW, Cologne, Germany) has been chosen in the framework of EUROLIFT II project. In this Project, the tested model has been named as TC217. It is a fuselage with a wing. Three-element wing KH3Y with a slat and a flap along whole wingspan has been used. During the experiment, integral forces over the model (forces and moments) and pressure distributions were measured. The results of calculation are presented in Fig.3, where charts $C_D(\alpha)$, $C_L(\alpha)$ obtained using different schemes are presented.

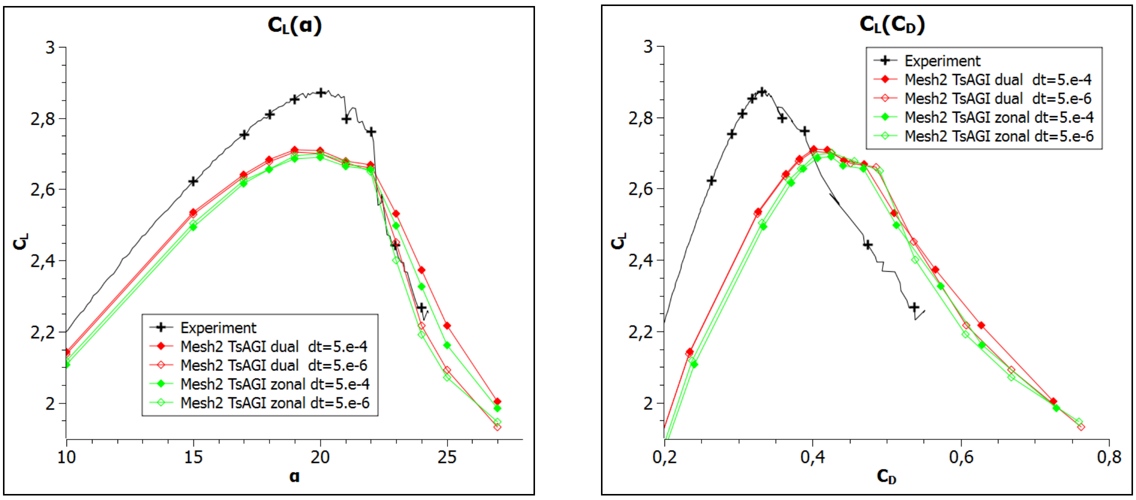

Fig.3. Comparison of calculations using "dual" scheme and zonal approach with experiment

The behavior of charts in zone of flow without separation is practically coincident; therefore, the data for incidence angles that are more than 10º are presented. It is easy to see that, in the case of similar time steps, the curves obtained using "dual" scheme and zonal approach are close to each other. In diminishing the global physical time step, there is a calculation data tendency to the experimental curve. In the case of "dual" scheme, such improvement of solution is achieved at the high cost: the calculation time increases for 100 times. The calculation time, in the case of the zonal approach, doesn't practically change.

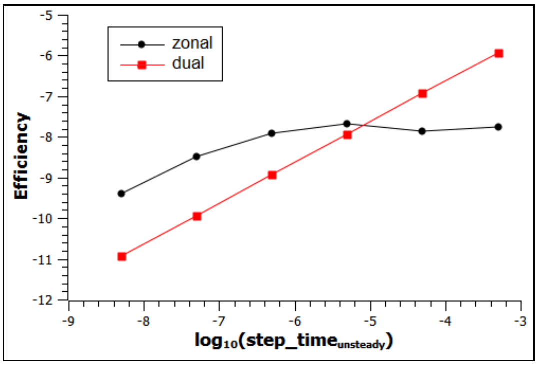

Fig.4. Computational efficiency of zonal approach for wing

Calculations of unsteady flows around high-lift configurations can be performed with large Courant numbers at the deep of boundary layers, if the condition Cu~1 is satisfied in the outer part of the boundary layer and in the zone of inviscid flow. In this case, the proposed zonal approach permits to accelerate the description of non-stationary processes in comparison with the standard approach based on using implicit scheme with dual-time step. For the three-element airfoil RA16SC1 the acceleration is more than 10 times. For the model TC217 the acceleration is more than 2 times.

Zonal approach and dual time stepping provide the same quality of calculations around high-lift configurations if the Courant number is the same.

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