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SIMULATION OF FLOW AROUND A SQUARE CYLINDER USING THE DES METHOD WITH AN ADAPTIVE MESH

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Abstract

A 3D numerical simulation of subcritical flow past a square cylinder ($U\infty$ = 17 m/s, d = 0.042 m) was performed using Detached/Delayed Detached Eddy Simulation (DES/DDES) based on the $k-\omega$ SST model. To improve resolution in the shear layers and wake core, anisotropic Hessian-based mesh adaptation was applied, preserving the wall layers (BL) and restricting the wake-box region. The isos of the Q criterion surface, the vortex core region structure, the velocity field, the turbulent kinetic energy, and the turbulence intensity are shown. The adaptive mesh selectively refines along strong gradient lines, providing a detailed picture of three-dimensional vortex dynamics and stable spectral characteristics with a moderate increase in the number of cells. The features of adaptive DES, time/step requirements, and practical tuning recommendations are discussed.

Keywords: Navier–Stokes equations, SST, DES, ANSYS.

1. Introduction

Flow around sharp-edged bodies is a classic problem in fluid dynamics and, at the same time, remains highly relevant in practice. A square cylinder is one of the basic benchmarks: fixed separation points on the edges form powerful shear layers, from which a Karman street develops; recirculation and intense vorticity transport are observed in the near field, while complex three-dimensional turbulence and a cascade of scales are observed in the far field. This multi-scale structure makes the problem sensitive to the quality of discretization, the choice of turbulence model, and the time approximation.

Traditional URANS approaches (including $k-\varepsilon$ and especially $k-\omega$ SST) provide robust solutions and acceptable accuracy for average performance at a moderate cost. The SST model [1], combining the advantages of $k-\omega$ at the wall and $k-\varepsilon$ in the external flow through mixing functions, reliably captures the onset of separation and unfavorable pressure gradients, but requires "up-to-the-wall" integration with a target $y+\approx1$. However, in separated flow, URANS often exhibits excessive numerical diffusion and limited spectral resolution: force and velocity oscillations are smoothed, and energetically significant vortex scales are underresolved.

An alternative is methods focused on resolving unsteady dynamics—LES and hybrid URANS/LES schemes [2]. A full-fledged LES at engineering Reynolds numbers remains resource-intensive primarily due to the requirements for near-wall resolution. In this regard, Detached Eddy Simulation (DES) [3] and its DDES/IDDES modifications have become widespread: in the near-wall regions, URANS (e.g., SST) is used to economically describe the boundary layer, while in the separated flow, the scheme switches to an LES-like regime with a grid-dependent filter. This hybrid provides a compromise between cost and spectral completeness: large wake eddies are resolved, and the region near the wall is described stably and without excessive grid refinement.

The key to the quality of any LES/DES calculation is grid resolution where it is truly needed, that is, along lines of strong gradients (shear layers, wake cores, and regions of intense vorticity). Uniform grid densification leads to an unjustified increase in the number of cells and time consumption; static local densification often "overshoots" dynamically shifting structures. Therefore, increasing attention is being paid to anisotropic grid adaptation based on error indicators, primarily the Hessian of the selected variable (velocity, pressure, vorticity) [4]. The Hessian-based approach generates a metric field that defines the local sizes and orientation of cells: elements are stretched along level lines and compressed across them, which dramatically improves grid efficiency and reduces numerical diffusion.

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For a square cylinder, the combination of DES/DDES and Hessian adaptation is particularly attractive. On the one hand, the hybrid model is capable of reproducing the three-dimensional structure of the Karman street (including vortex filaments, mergers/breakups, and the energy cascade); on the other hand, the adaptive mesh selectively concentrates elements in the wake core and on the shear layers, while preserving the boundary layers near the wall (preserve BL) and limiting mesh growth in the external field. This results in better spectral matching (the position and sharpness of the Strouhal number peak), more realistic amplitudes of force and velocity oscillations, and detailed visualization of 3D structures (according to the Q, λ, vortex-core, etc.) with a moderate number of cells.

Despite significant progress, the literature remains short of comparable studies that systematically analyze in a single experiment: (1) the effect of anisotropic adaptation on the resolution of the near and far wake in the DES formulation; (2) practical adaptation parameters (criterion, wake-box domain, refine/coarsen levels, BL protection); (3) robustness of spectral characteristics and their sensitivity to the time step and target y+. For reproducibility, it is also important to capture the detailed calculation details: the pressure-velocity coupling (PISO), approximation orders, adaptation termination criteria, and the statistical averaging protocol.

This work aims to fill these gaps for subcritical flow past a square cylinder at $U\infty$ on the order of tens of m/s. We apply SST-based DES/DDES and anisotropic Hessian adaptation with wall layer protection and wake-box adaptation domain restriction, demonstrating that this combination ensures robust reproduction of 3D vortex structures and improves the prediction of integral and spectral metrics at a manageable computational cost. The contribution of the work consists of: (1) a careful formulation of 3D DES with adaptation and a transparent description of the numerical settings; (2) an analysis of the fields U, k, turbulence intensity and isos surfaces of the Q criterion on the adaptive grid; (3) a discussion of the sensitivity of the results to the time step, target y+ and adaptation parameters; (4) the formation of practical recommendations for engineering DES calculations of a similar class of problems [5].

2. Physical and Mathematical Formulation of the Problem

We consider the flow around a single square cylinder with side d (in calculations: d=0.042 m) by a two-dimensional flow at an inlet velocity of $U\infty$=17 m/s (subcritical regime, Re≈4.7×104). The computational domain is defined in a Cartesian coordinate system (x, y) so as to exclude the influence of distant boundaries on the wake and forces: inlet: x=−5d, outlet: x=+20d, top/bottom: y=±8d. This choice ensures low blockage: β=d/H≈1/16≈6.25% at a section height of H=16d, which is acceptable for reproducing free flow. The center of the cylinder is located at (x, y)=(0,0); its ribs are oriented parallel to the axes (angle of attack α=0) [5].

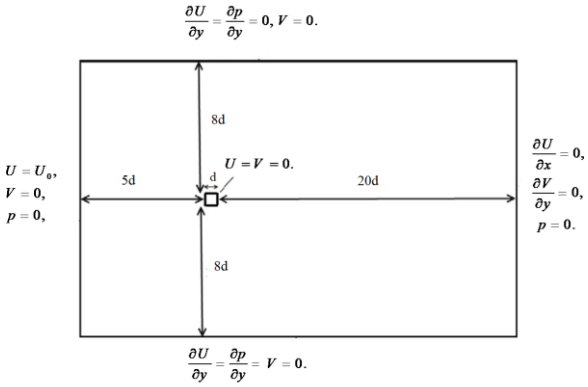


Fig. 1. Two-dimensional computational domain and boundary conditions

3. Boundary conditions

Inlet (velocity-inlet). A uniform velocity profile of $U\infty$=17 m/s and low turbulence corresponding to a wind tunnel are specified: intensity TI=0.5% and integral length L≈0.07d. Outlet (pressure-outlet). Zero excess static pressure (0 Pa). The backflow parameters are taken consistently with the inlet: TI=0.5%, L≈0.07d (or $\mu t/\mu$=1−2). Top/bottom. Symmetry-type boundaries (sliding plane) to exclude parasitic viscous effects from the "tubule walls". Cylinder surface. No-slip, isothermal solid wall.

4. Mathematical model

DES-SST (Detached Eddy Simulation – Shear Stress Transport) turbulence model

The DES-SST model is a hybrid approach that combines the advantages of two methods: RANS (Reynolds Averaged Navier–Stokes) for describing near-wall regions and the boundary layer, LES (Large Eddy Simulation) for resolving large eddies in the outer flow and in separation zones. DES is based on the SST (Shear Stress Transport) model, which describes boundary layers and separated flows well. The DES modification extends its capabilities to more complex zones where the dynamics of large eddy structures is important. The main idea of DES-SST near the wall is to use the standard SST (k–ω) model [1], which works like classical RANS, which reduces computational costs. In areas with developed turbulence (outside the boundary layer), the model switches to the LES mode,

resolving large eddies. This hybrid approach allows us to obtain a more detailed picture of turbulence at lower computational costs compared to full LES. The LES (Large Eddy Simulation) model is a numerical modeling method for turbulent flows that is based on the idea of separating the turbulent field into large-scale and small-scale eddies. In LES, the dynamics of large eddies are modeled, while small eddies are filtered and their influence is taken into account through the effective turbulent viscosity.

Filtering equation: In LES, the calculations are based on filtering the Navier-Stokes equations, which allows separating large-scale components from small-scale ones:

$$\frac{\partial \overline{u}_i}{\partial t} + \frac{\partial \overline{u}_i \overline{u}_j}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \overline{p}}{\partial x_i} + \nu \frac{\partial^2 \overline{u}_i}{\partial x_j^2} + F_i \quad (1)$$

here $\overline{u}_i$ - filtered velocity components, $\overline{p}$ - filtered pressure, F_i - external force.

Turbulent Viscosity Model: LES uses effective turbulent viscosity to account for the effects of small-scale eddies. This viscosity is typically modeled using Smogorinsky-type models [2–3]:

$$v_t = (\Delta)^2 \cdot C_s \cdot \left|\overline{S}\right|. \quad (2)$$

here: vt — turbulent viscosity, Δ — grid cell size, Cs — Smogorinsky constant, $\left|\overline{S}\right|$ — the magnitude of the strain tensor. The LES model is a powerful tool for numerical modeling of turbulent flows, which allows one to effectively solve complex problems that require high accuracy in describing large eddies and flow dynamics.

In DES-SST the same system of equations is solved as in the SST model. equation for turbulent kinetic energy k,equation for specific dissipation ω. The DES modification is introduced into the equation for the length of the turbulent scale:

$$L_{DES} = \min\left(L_{RANS}, C_{DES}\Delta\right). \quad (3)$$

where: L_{RANS} is the characteristic turbulence length from RANS, Δ is the local grid cell size, C_{DES} is an empirical constant (usually about 0.65). Thus, for a sufficiently fine grid in the separation or vortex region, the model automatically switches from RANS to LES. Advantages: Combines the accuracy of LES and the robustness of RANS, Reproduces large eddy dynamics, recirculation, and unsteady structures well, More economical than full LES or DNS, Suitable for calculating highly swirling flows and separation regions.

5. Grid adaptation

The calculations used anisotropic Hessian-based mesh adaptation in ANSYS Fluent: the Hessian of the velocity modulus (Velocity Magnitude) was used as an indicator, while cells with a normalized metric above the threshold of 3.5 were marked as refined (velx_hessian_refinement), and below 1.0 - as coarsen (velx_hessian_coarsening), which ensured thickening in the shear layers and the core of the wake and rarefaction in the external field; Autoadaptation was run every 100 time steps (Frequency), with the following constraints: Maximum Refinement Level = 6, Minimum Edge Length = 0.00042 m, Additional Refinement Layers = 2, quality control (Minimum Cell Orthogonal Quality = 0.00042), and Anisotropic (Hessian) mode with boundary layer protection enabled (Preserve/Protect BL, Prismatic Adaption — off); the adaptation region was limited to the "wake-box" to avoid affecting the input and far field; The cycle was performed using the Mark → Refine/Coarsen → Continue scheme until the stop conditions were met: the proportion of marked cells was < 5% per cycle and the change in key metrics (St, Cd, Cl, $U/U0$ profiles) was < 2–3%, while maintaining CFL ≤ 1, taking into account the decreased Δmin; the result was a selective increase in resolution and a decrease in numerical diffusion in significant flow zones with a moderate increase in the total number of cells.

6. Solution method

The calculations were performed in ANSYS Fluent with the pressure-based solver (Pressure-Based), in a non-stationary formulation (Transient, gravity disabled, Velocity Formulation = Absolute). The pressure-velocity coupling was implemented using the PISO scheme with Skewness-Neighbor Coupling enabled, Skewness and Neighbor corrections by 1, and Rhie-Chow interpolation (momentum-based, Auto-select). Spatial approximation: Least Squares Cell-Based gradients; pressure — Second Order; momentum — Bounded Central Differencing (parameter BCD Scheme Boundedness = 1); turbulence equations — Second-Order Upwind (for both Turbulent Kinetic Energy and Specific Dissipation Rate). For time, the Second-Order Implicit scheme was used; there is no pseudo-time (Pseudo Time Method = Off). Subrelaxation: pressure 0.3, momentum 0.7, k 0.8, ω 0.8, density/turbulent viscosity 1.0. Basic integration parameters: time step Δt=1.5×10−5 s, maximum 20 iterations per step, reporting interval 1, total 58,000

steps; the choice of Δt ensured CFL≤1 at the minimum cell size and stable convergence in residuals and integral metrics.

7. Results and Discussion

Figure 2 shows an anisotropic adaptive Hessian-based mesh: the near-wall (BL) layers are preserved for the square cylinder, the shear layers and wake core are automatically refined in areas of strong gradients, and the outer field is coarsened. This approach directs computational resources to dynamically significant areas and improves the resolution of fine flow structures.

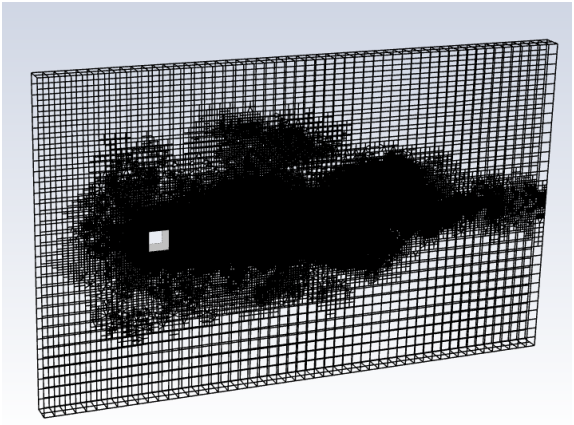
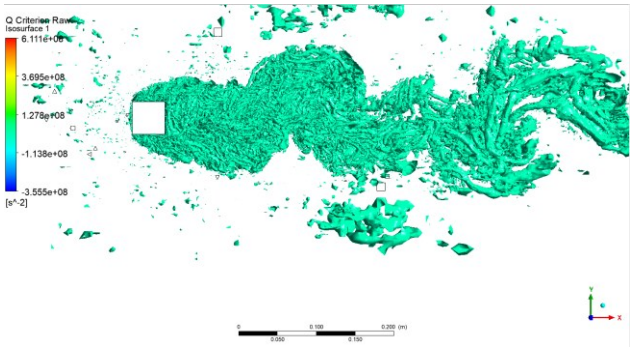
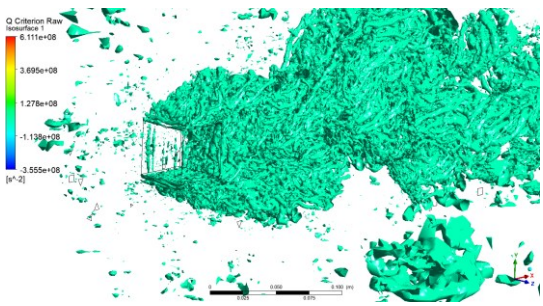


Fig. 2. Anisotropic adaptive mesh based on the Hessian



a)

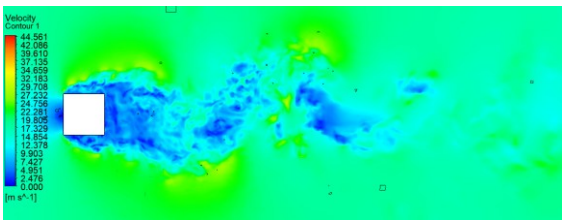


b)

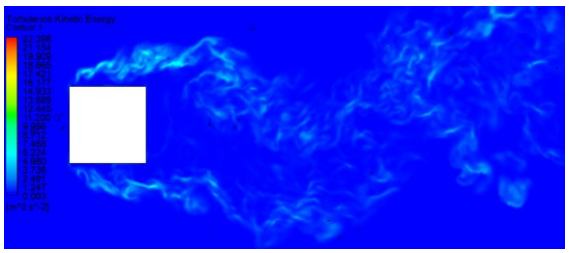
Fig. 3. The isos surface of the criterion Q is shown

Fig. 3 shows the isos of the Q criterion surface (instantaneous 3D vortex structures) for flow past a square cylinder with DES on an adaptive (Hessian) grid: A) general view of the wake — alternating "rope" coherent structures forming the Karman street, as well as secondary vortices and their decays; B) enlarged fragment of the near wake near the cylinder — the twisting of shear layers (roll-up), merging/separation of vortex filaments and the emergence of three-dimensionality are clearly visible.

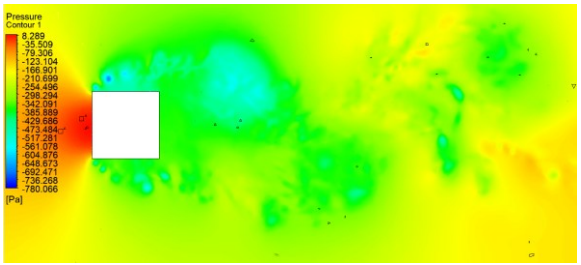
The color scale corresponds to the Q [s−2] values; the adaptive grid provides selective thickening in the wake core and better resolution of fine vortex structures.



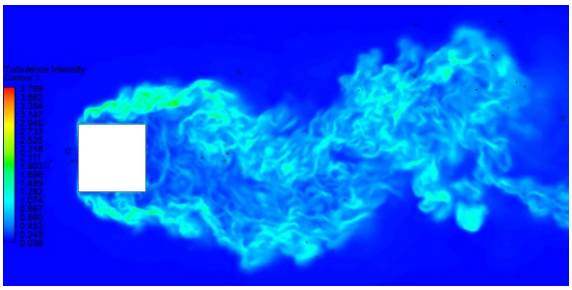
a)



b)



c)



d)

Fig. 4. Flow fields for DES on an adaptive (Hessian) grid

Fig. 4 shows the flow fields for DES on an adaptive (Hessian) grid: A) velocity modulus U — the stagnation zone on the windward face, the recirculation “bubble”

and the unstable wake are visible; B) turbulent kinetic energy k — the maxima are concentrated in the shear layers and the wake core; C) turbulence intensity TI — "ribbons" of increased intensity accompany the turn and interaction of vortices; D) static pressure p — a high-pressure region at the leading edge and alternating spots along the wake, phase-matched with the Karman street.

Figure 5 shows the velocity vector field (color indicates the absolute value of U, m/s) for DES on an adaptive (Hessian) grid. A general view of the wake and two enlarged fragments near the cylinder are shown. A recirculation "bubble" forms in the zone behind the body, from the edges of which shear layers develop with successive "roll-ups" and the formation of coherent vortices. Alternating acceleration/deceleration regions are then observed, corresponding to the Karman street and the processes of external flow entrainment (entrainment).

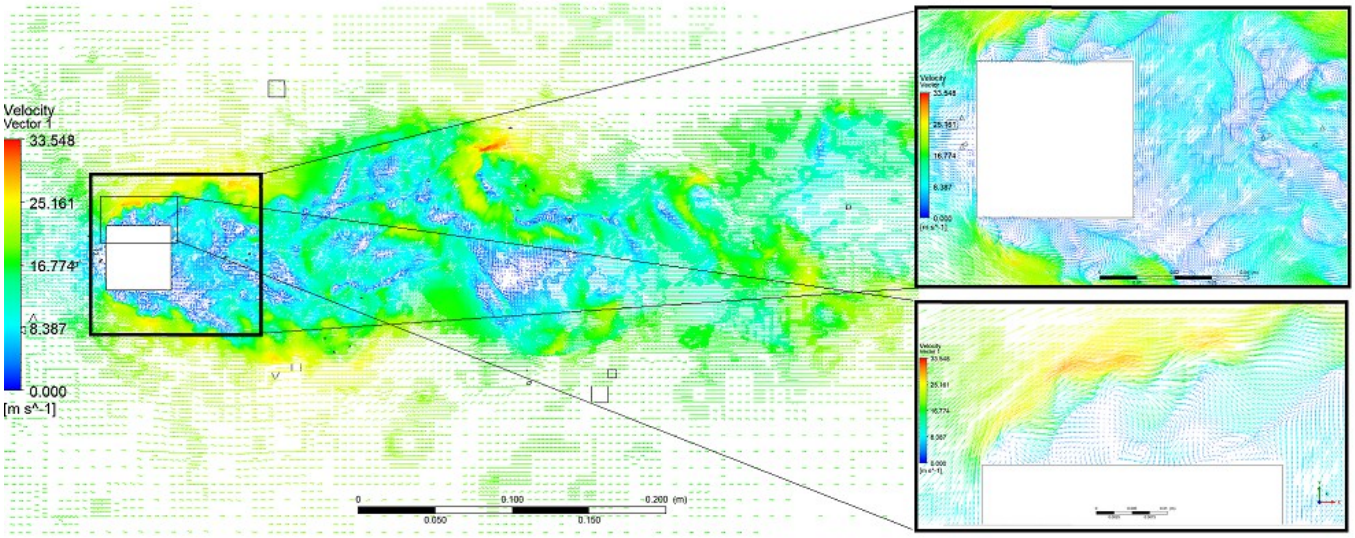


Fig. 5. Velocity vector field.

The enlarged regions reveal fine structural detail: local shear zones, convexity and reversal of vectors at the edges, and interactions between adjacent vortex cores. Anisotropic adaptation ensures selective condensation in these regions, leading to better resolution of vector orientations and reduced numerical diffusion in the wake core.

Figure 6 shows the isos surface of the vortex core region (vortex core), colored by the absolute value of the velocity U (m/s), for flow past a square cylinder using DES on an adaptive (Hessian) mesh. The three-dimensional topology of the wake is visible: extended coherent filaments form from the recirculation "bubble" immediately behind the body, which disintegrate into smaller structures as they move away; simultaneously, the characteristic diameter and velocity in the vortex cores decrease.

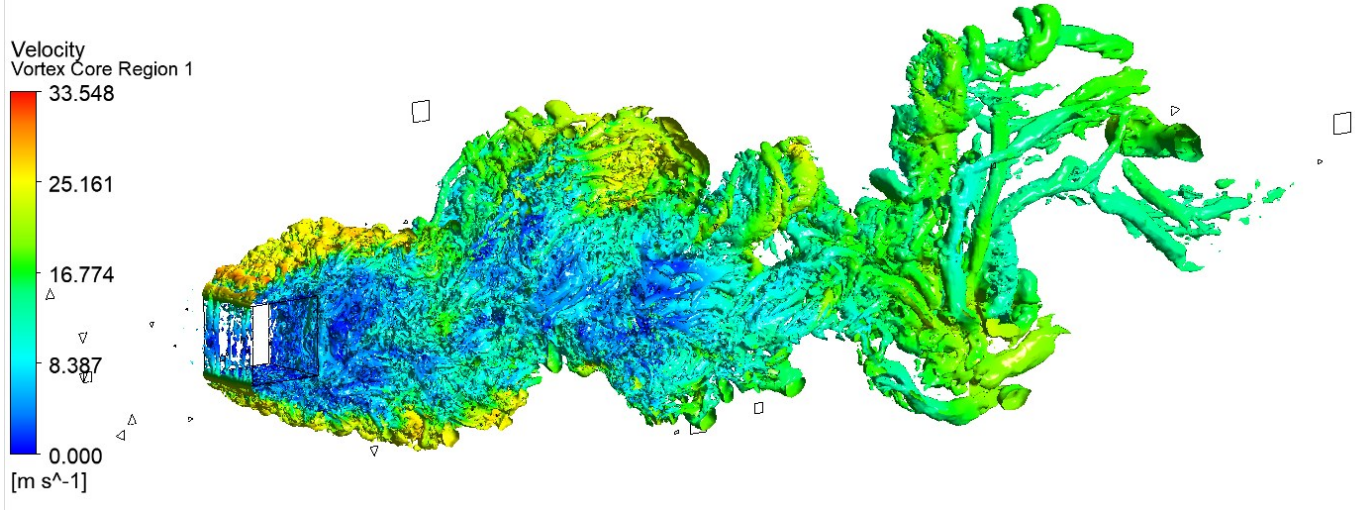


Fig. 6. Isos surface of the vortex core region.

Anisotropic thickening in the shear layers and the wake core provides detailed visualization of "rope-like" structures and reduces numerical diffusion in the far field.

Conclusions

A 3D simulation of the flow past a square cylinder demonstrated that the hybrid SST-based DES/DDES approach, combined with anisotropic Hessian mesh adaptation, provides a robust and physically plausible reproduction of the Karman street and the three-dimensional vortex topology of the wake: the isos surfaces Q and the vortex-core region clearly reveal "rope-like" coherent structures, their twisting, merging, and decay; the U, k, TI, and pressure fields are consistent with each other and reflect the development of shear layers and recirculation. The adaptation selectively concentrates elements in the wake core and on strong gradient lines, reducing grid-induced diffusion and improving spectral characteristics (peak position and sharpness in St), while the integral metrics Cd and Cl remain within the expected limits with a moderate increase in the number of cells. The practically important settings, confirmed by calculations, are: integration to the wall with $y+\approx 1$, PISO coupling and second orders in time and space, CFL ≤ 1, an autoadaptation frequency of the order of hundreds of steps and threshold values of the Hessian criteria for refine/coarsen, limiting the adaptation domain "wake-box" and protecting the boundary layers. Limitations of the work are related to the dependence of DES on the grid/time step and the lack of validation over a wide range of Re; In the future, parametric studies of adaptation thresholds and comparison with IDDES/high-resolution LES, as well as the introduction of metric quality criteria (energy spectra, three-dimensional correlations) for the final assessment of the gain in “accuracy/cost” would be advisable.

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