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Direct Fem-Simulation of turbulent bluff body flow

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Summary. We simulate slightly viscous turbulent low Mach number 3d bluff body flow (including streamlined bodies) by computational solution of the incompressible Navier-Stokes equations with a slip boundary condition modeling observed small skin friction, by using a residual stabilized adaptive finite element method, referred to as Direct Fem-Simulation or DFS since no turbulence beyond residual stabilization is used. We find by duality based a posteriori estimation that mean value quantities such as drag and lift are computable to accuracies comparable to experiments. As a key example, we show that the turbulent flow around a complete airplane is computable and inspecting the solutions leads to a new theory flight essentially different from the accepted theory by Kutta-Zhukovsky-Prandtl developed 100 years ago. We find that turbulent bluff body flow in general can be described as potential flow modified by rotational slip separation as a flow which is both resolvable computationally using millions of mesh points, except in a far-field wake of no impact on lift and drag, and also is understandable through a stability analysis.

Key words: turbulence, bluff body, direct numerical simulation, aerodynamics

From Prandtl 1904 back to Euler 1757

Turbulent bluff body flow is considered as a main unsolved problem of classical mechanics beyond theoretical description and also beyond computational simulation, because of thin no-slip boundary layers dictated by Prandtl in 1904 [7] requiring trillions of mesh points to be resolved. In recent work we have discovered that using a slip boundary condition as a model of the small skin friction of slightly viscous turbulent flow, allows predictive simulation of mean value quantities such as drag and lift of turbulent bluff body flow (including streamlined bodies), with instead millions of mesh points. Basic aspects of turbulent flow from applications point of view thus show to be computable by stabilized finite element methods with automatic turbulence modeling from residual stabilization, referred to as Direct FEM-Simulation (DFS), which opens large areas for exploration.

As a key example the we show that the turbulent flow around a complete airplane is computable. From an idea that a computable phenomenon is also understandable mathemaically, we are led to a new theory flight [2, 3] essentially different from the accepted theory by Kutta-Zhukovsky-Prandtl developed 100 years ago. With evidence from computation and basic stability analysis we have been led to the conclusion that turbulent bluff body flow, including the aerodynamics of flight, can be described mathematically as potential flow modified by a phenomenon of *rotational slip separation* as a both computable [4] and understandable flow, in accordance with Euler's original dream formulated in 1757 [1].

Neumann boundary conditions

The key to the break of the Prandtl spell, which has blocked development for 100 years, is the from mathematical point of view obvious realization that Navier-Stokes equations as an accurate model of fluid mechanics can be combined with either Dirichlet or Neumann type boundary or combinations thereof. For slighly viscous flow the skin friction is observed to be very small which allows accurate modeling by a slip boundary condition as a combined Dirichlet-Neumann condition. Using a slip condition eliminates no-slip boundary layers and thus circumvents the computational impossibility dictated by Prandtl and therefore opens to progress. Simulations show good agreement with observations for drag and lift (and more generally for pressure distributions), leading to the conclusion that Prandtls conjecture of a main role of no-slip boundary layers is false.

Rotational Slip Separation

The key to understanding bluff body flow is its description as potential flow modified by rotational slip separation as a generic quasi-stable gross pattern flow resulting from a generic instablity of potential flow at separation [6]. The flow in the vicinity of the body thus shows to be resolvable computationally with millions of mesh points with quasi-stable features and total turbulent dissipation under mesh refinement. The turbulent dissipation occurs mainly in the far-field wake which increases in length under refinement keeping total dissipation nearly constant, without changing the pressure distribution on the body. The flow field thus appears as a bride sweep which gets longer under refinement without changing drag or lift on the body.

References

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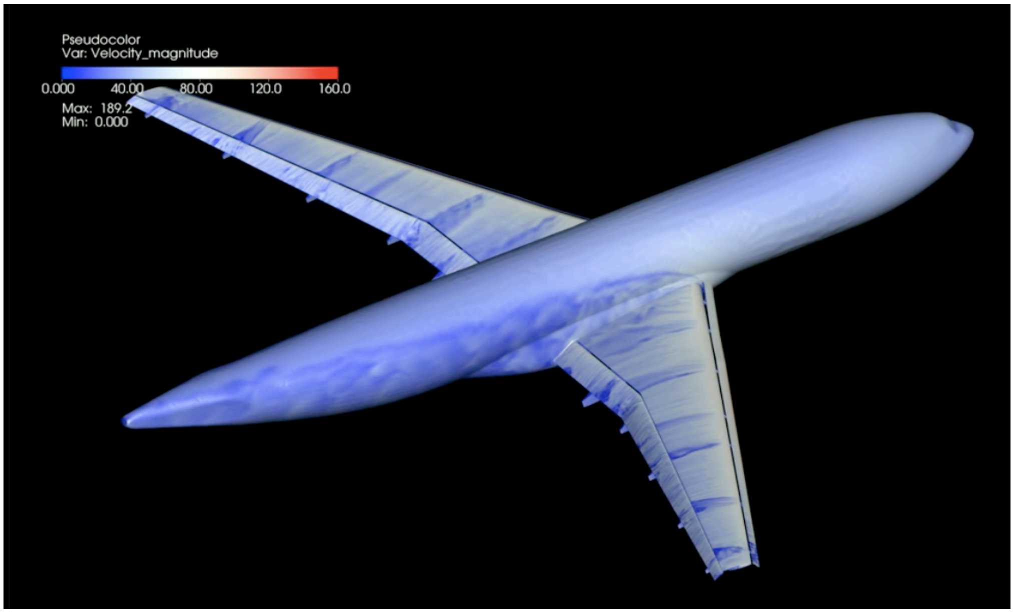

Figure 1. The velocity field of DFS with 3 million mesh points for an landing airplane at large angle of attack.

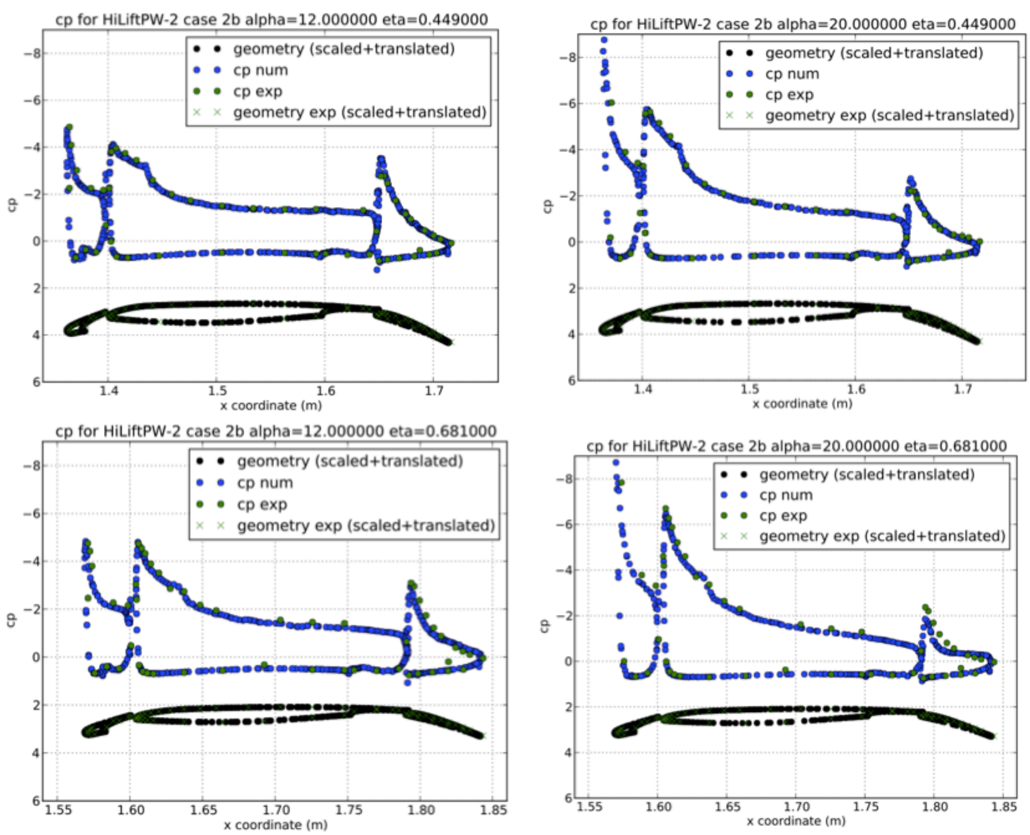

Figure 2. Comparison between simulation and experimental observation.

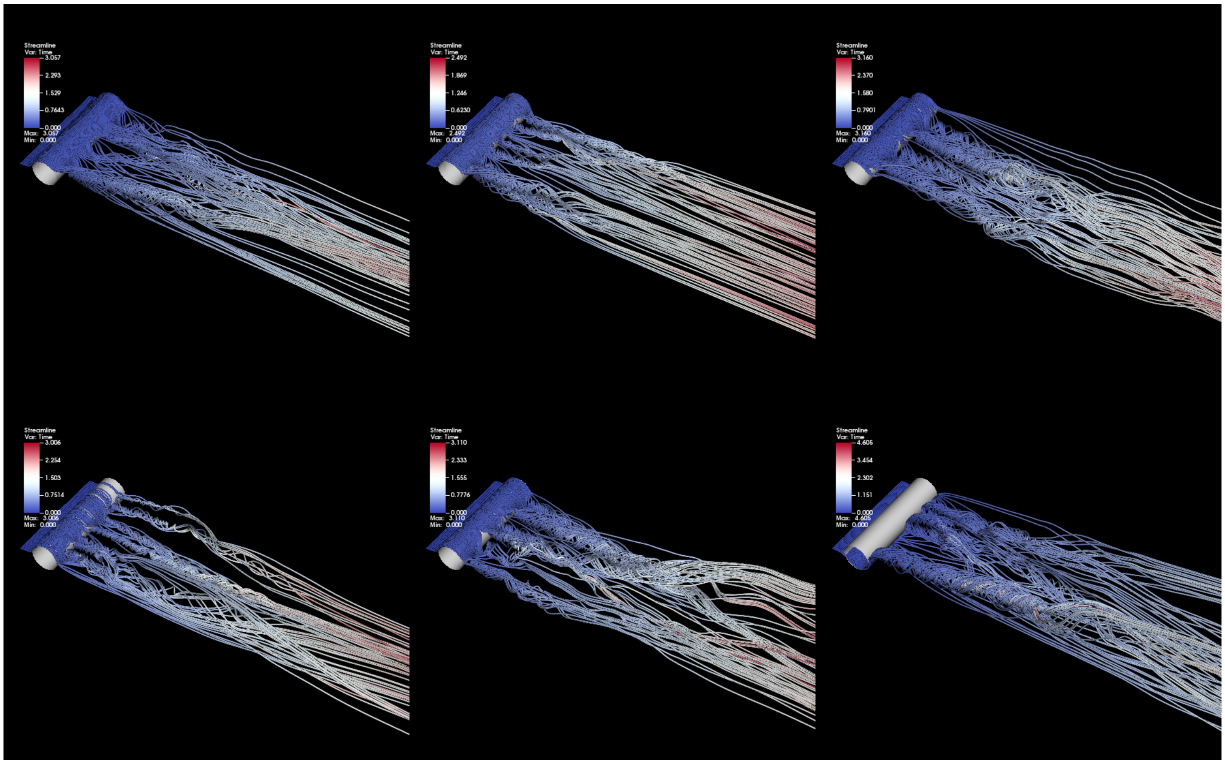

Figure 3. Quasi-stable rotational slip separation for slightly viscous incompressible flowcircular cylinder with the length of the turbulent wake increasing under refinement.

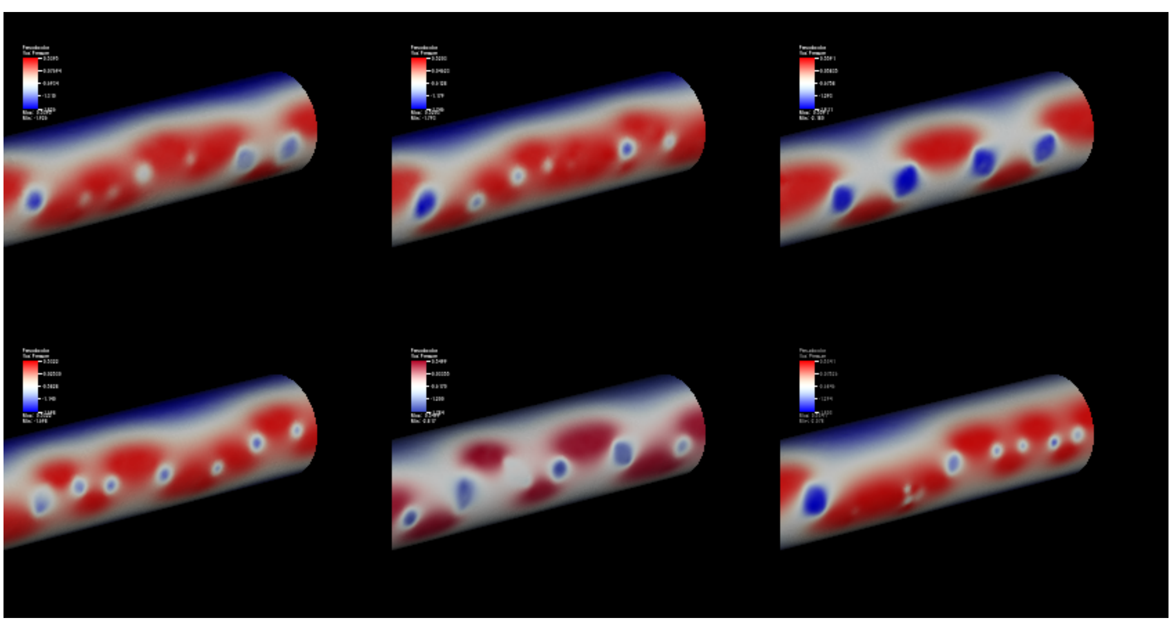

Figure 4. Corresponding surface pressure distribution showing stability of total pressure under mesh refinement.