Positivity Preserving Finite Element Technique for Delayed DES Modeling of Fluid-Structure Interaction

Vaibhav Joshi

PhD Student
Department of Mechanical Engineering
National University of Singapore, Singapore

Rajeev K. Jaiman

Assistant Professor
Department of Mechanical Engineering
National University of Singapore, Singapore

A simple finite element stabilization is proposed to solve the Spalart-Allmaras (S-A) turbulence model in the Delayed Detached Eddy Simulations(DDES) for fluid-structure interaction. The S-A model equation has the effects of convection, diffusion as well as reaction. Moreover, the reactive term can change signs pertaining to production or destruction phenomenon in the modeled turbulence effects. The stablization relies on a mixed form the Galerkin/Least Squares (GLS) - Sub-Grid Scale (SGS) while maintaining the positivity-preserving property of solution field. The motivation behind this investigation arises from the modeling of vortex-induced vibration (VIV) in deep-water drilling risers. The ocean current in deep-waters can reach up to high Reynolds number of the order $10^5 - 10^6$ which can lead to higher bending stress and fatigue failure of riser system. Our ultimate aim is to predict the effect of the VIV on the riser system connected with drill ship undergoing surge and heave movement in harsh deepwater environment.

For such coupled systems, we need a robust turbulence model to analyse fluid-structure interaction. Since both Direct Numerical Simulation (DNS) and Large Eddy Simulation (LES) are beyond the capacity of current computer hardware for high Reynolds number and Unsteady RANS (URANS) is not reliable for massively separated vortex flows, we consider Detached Eddy Simulation (DES) formulation for the coupled analysis of offshore riser system. The underlying S-A equation of DES is phenomenological and several numerical challenges are faced while dealing with it, namely (a) the inclusion of the reactive terms, (b) the production and destruction effects, and (c) spurious oscillations near the boundary and internal layers. Conventional stabilization methods mainly focus on the stability of convection dominated flows, but hardly take into account the reaction-dominated flows. Several stabilization methods have been proposed to stabilize the convection-diffusion-reaction equation based on the Streamline Upwind Petrov-Galerkin and Galerkin-Least Squares method, but they fail to stabilize the solution when the reaction coefficient becomes negative. However, the Sub-Grid Scale method offers a solution to this issue but the solution is highly diffusive for certain positive reactive coefficients and boundary conditions. Hence, we propose a combination of these two methods which behaves as GLS in the positive reaction coefficient regime and as an SGS method pertaining to negative reaction coefficient.

In this work, our strategy is to employ the Discrete Upwind algebraic operator to maintain positivity in the solution at the element level matrix. This guarantees that the numerical solution does not manifest spurious oscillations near the internal as well as boundary layers, which allows to cover all the possible regimes of the canonical equation while maintaining the monotonicity property. Error analysis in one dimension showed reduced L_2 error for the proposed method with varying non-dimensional numbers based on the equation considered - $Da = sl/u$ for convection-reaction equation, $\omega = sl^2/k$ for diffusion-reaction equation and $Pe = ul/2k$ for convection-diffusion equation, with u, k, s, l being the advection velocity, diffusion coefficient, reaction coefficient and element length respectively. We employ the proposed idea to the DES for demonstrating the effectiveness of the method for partitioned iterative fluid-structure solver [1].

References

[1] Jaiman, R. K., Pillalamarri, N.R., Guan, M.Z. (2016), A stable second-order partitioned iterative scheme for freely vibrating low-mass bluff bodies in a uniform flow, Computer Methods in Applied Mechanics and Engineering, 301:187-215.