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Synthetic particle group method for Three-dimensional shock wave/turbulent boundary layer interaction

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Abstract

The shock wave and turbulent boundary layer interaction (SWBLI) can affect the local aerodynamics and dynamic loads of hypersonic vehicles, resulting in very highly dynamic and thermal loads, leading to the structural failure, even flight failure. The separation caused by SWBLI is usually small scales and contains unsteady three-dimensional (3-D) flow structures. And it poses a great challenge to simulate the SWBLI. Despite direct numerical simulation (DNS) and large-eddy simulation (LES) can offer the possibility of more accurate predictions, these two methods are quite expensive when resolving the boundary layer. The Reynolds Averaged Navier-Stokes (RANS)-LES hybrid method, such as improved delayed detached eddy simulation (IDDES), can achieve both the computational accuracy and efficiency. However, it does fail to resolve the small-scale turbulent structures in the attached boundary layer or limited separation, which often lead to obvious inaccuracy in the SWBLI region.

To better predict the separation and unsteady flow caused by SWBLI, a new non-zonal embedded synthetic turbulence generation method, named as Synthetic Particle grOup Method (SPOM), is proposed, validated and applied to predict the SWBLI. The principle of SPOM is to construct the SPOs, whose shape is dominated by certain kernel functions. And then these SPOs can induce the turbulent coherent structures in the attached boundary layer. Figure 1 shows the shape of the SPO, including a central large particle with positive perturbation and two surrounded smaller particles with negative perturbation. The SPO looks like the flow strips element by Jimenez[1].

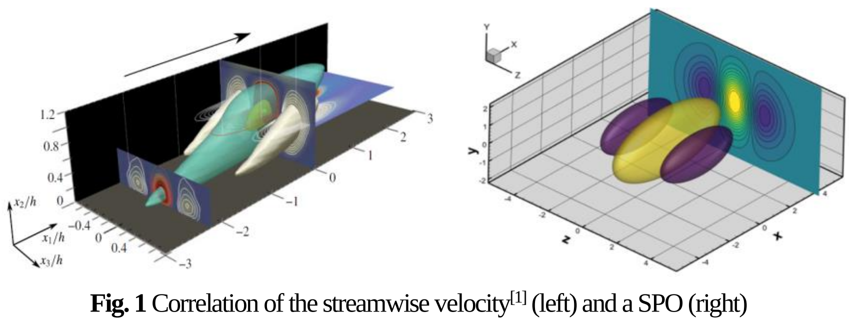

Fig. 1 Correlation of the streamwise velocity[1] (left) and a SPO (right)

The newly developed SPOM, coupled with IDDES (IDDES-SPOM), is validated by simulating the supersonic flat plate flow and the compression ramp flow at Mach 2.25. After the injection of SPOs, the 3-D turbulent perturbations are introduced to induce the small-scale structures, as shown in Figure 2. In this figure, the iso-surface of Q criterion is shown.

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It is noted that the typical hairpin eddy structures start to be generated after some streamwise distance, which is called as the initial recovery of the turbulent boundary layer.

In the compression ramp flow, many small-scale structures are resolved and the separation caused by SWBLI is also predicted by IDDES-SPOM, as shown in Figure 3. Compared with the results by original IDDES and DNS[2], IDDES-SPOM is much more accurate than the original IDDES when predicting the separation length.

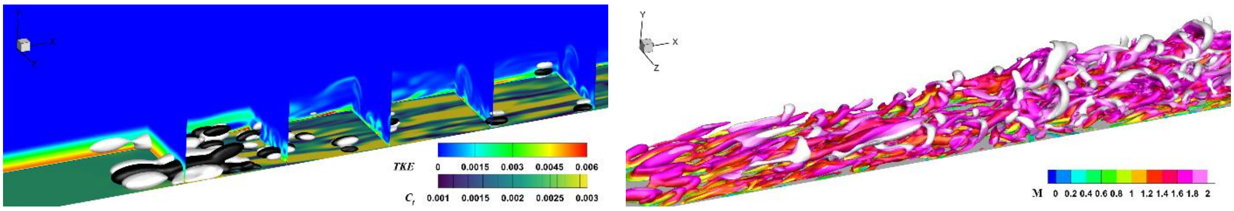

Fig. 2 Distribution of SPOs and instantaneous field of TKE (left) and iso-surface of Q criterion (right)

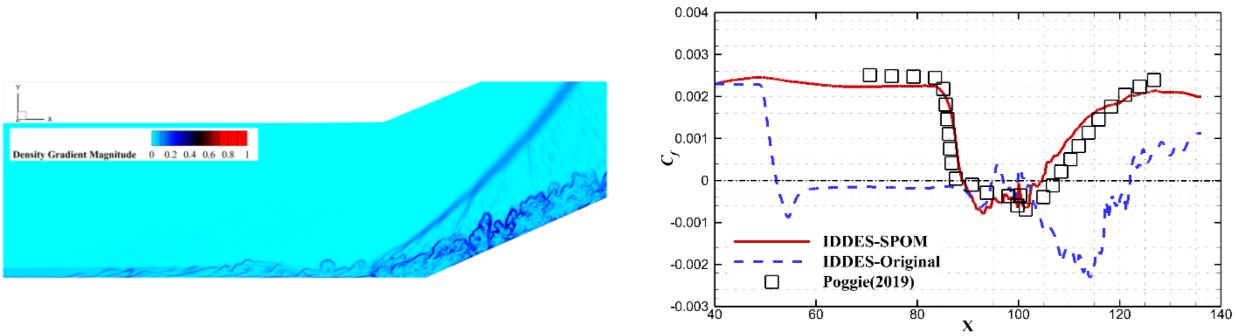

Fig. 3 Instantaneous density gradient magnitude (left) and time-averaged skin friction coefficient near the ramp (right)

To simulate the 3-D complex flows of SWBLI, the flow past a hypersonic intake is calculated. As shown in Figure 4, the typical 3-D turbulent structures can be found near all the wall, with and without SWBLI. The real 3-D turbulent boundary layer is triggered by IDDES-SPOM, while other conventional synthetic turbulence methods can only be used for the quasi-3D flows[3]. The separation induced by shock wave in the intake has a complex 3-D pattern, including the central separation bubble near the bottom wall and the vortex structure near the side wall.

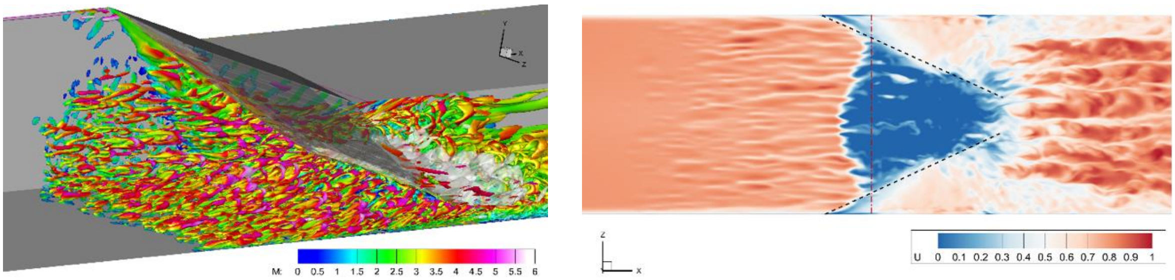

Fig. 4 Iso-surface of Q criterion for 3-D intake (left) and instantaneous streamwise velocity at wall-normal section (right)

Keywords: SWBLI, hybrid RANS-LES method, SPOM, separation, hypersonic intake

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