DNS OF COMPRESSIBLE FLOW OVER ROUGH SURFACES WITH AN ADAPTIVE WENO/CD SCHEME

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Abstract. In this study, Direct Numerical Simulation (DNS) of compressible flow over a set of smooth and rough surfaces is carried out in a turbulent channel flow configuration. The aim is to quantify the Hamas roughness function for different rough wall geometries under the effects of compressibility. For this study, a flow with bulk Reynolds number 6000 and Mach number 1.5 is considered. A level-set ghost-fluid method is used to represent the rough wall geometry. The rough surfaces considered are a grit-blasted sample, graphite and a manufactured sawtooth geometry with the same mean roughness height as the grid-blasted surface. It was found that the grit-blasted surface has the largest roughness function as compared to the other ones. Although the sawtooth and grit-blasted surfaces have the same mean roughness height, the difference in their roughness function suggests that other topological features of the rough surface can influence the roughness function independently of the mean roughness height.

1 INTRODUCTION

Rough surfaces affect the flow in many engineering systems, as many processes can cause surface roughness. Roughness can be a side-effect of the production of a surface, where a higher level of finishing would be uneconomical, or can develop over time due to erosion or the accumulation of deposits. In the context of hypersonic flows, the severe high enthalpy environment generated by vehicles entering into atmospheres at hypersonic speeds has led to the use of material ablation as a means of alleviating the high heat flux. However, the ablation of the surface material can significantly alter the surface properties and hence the flow behaviour close to the surface. Despite the fact that most rough surfaces are irregular, most of the fundamental research on turbulent flow over rough surfaces has mainly concentrated on highly regular roughness geometries [1]. In addition, DNS studies of turbulent flow over rough surfaces have been mainly limited to the incompressible flow regime. There is evidence to suggest that compressibility effects can be important. For example, experimental investigations have shown that shock and expansion waves, which span the boundary layer, can be produced by a rough surface in supersonic flow. The bulk Reynolds number in this study is defined based on the full

channel height; from the minimum roughness height of the bottom wall to the minimum roughness height of the top wall. A brief overview of the numerical methodology followed by a comparison of the Van Driest transformed velocity profiles of the different surfaces are presented.

2   NUMERICAL SET-UP

The compressible Navier-Stokes equations are solved for a perfect gas in dimensional form. A time-dependent forcing term, that preserves the bulk density and momentum of the system, is added as a source term to the x-momentum, energy and continuity equation. The source term for the mass and momentum equation can be seen as a correction to recover the lost momentum in the entire domain from the previous time step. The source term added to the energy equation represents the work done by the pressure gradient on the system. The nonlinear convective terms are discretized using a locally conservative finite difference approach based on the hybrid WENO-CD (Weighted Essentially Non Oscillatory - Centered Difference) scheme. For the purpose of ensuring nonlinear stability, the nonlinear convective fluxes are written in a skew symmetric form [2] before the application of the WENO-CD scheme. Unresolvable discontinuities are handled by the shock-capturing (upwinding) WENO method and the turbulent regions are computed accurately using a central difference method optimized for minimum dispersion error [2].

For the representation of the roughness geometry, our in-house solver framework AMROC uses a distance function to represent complex geometry implicitly in a level-set function on the Cartesian mesh [3]. A specially developed algorithm is applied to compute the distance information for arbitrarily complex embedded surface triangulations when the evolving Cartesian multi-resolution mesh is modified at run time. For the sawtooth surface, there is a total of 36 streamwise sawtooth elements. An illustration of the 3 rough surfaces is given in Fig. 1.
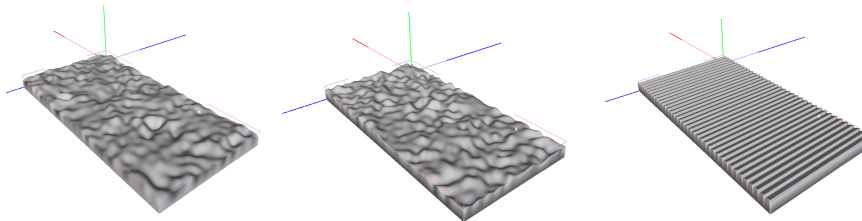

Figure 1: Grit-blasted Surface, Graphite Surface and Sawtooth Surface (left to right)

Periodicity is enforced in the homogeneous wall parallel directions and a no-slip isothermal boundary condition is imposed at the channel walls. A representative illustration of the mesh refinement level and scheme switching flag indicator are shown in Fig. 2.
The grid spacings used in the wall parallel directions, Δx^+ and Δz^+, is about 5 at the finest level and the grid spacing used in the wall normal direction, Δy^+ is about 0.8 at the finest level. The base grid has the size of $(N_x, N_y, N_z) = (220, 350, 110)$ cells or 8.47 million cells in total. The mesh refinement factor is set to 2. For a mesh refinement

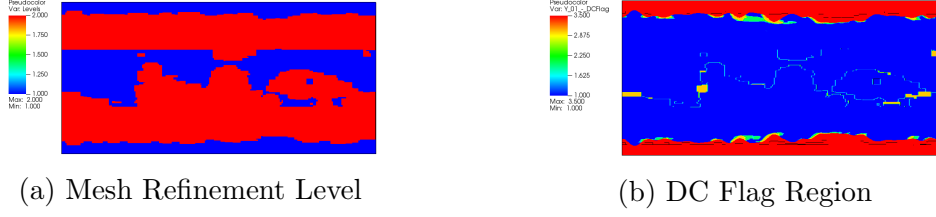(a) Mesh Refinement Level

(b) DC Flag Region

Figure 2: Mesh Refinement Level and Discontinuity Flag Region of the Graphite Surface

factor of two, the maximum possible number of cells corresponds to about 67.76 million. In order to ensure that the grid spacing is fine enough to resolve the viscous sub layer, the finest grid region extends from the wall up to the end of the buffer layer region. In Fig. 2b, it can be seen that the discontinuity indicator is usually activated in the region close to the rough surface, especially where there is an abrupt change in the roughness topology.

3 RESULTS

The rough channel simulations were carried out on the Archer 2 supercomputer. Each test case requires about approximately 122,880 CPU hours to reach a statically converged result. The computations were run on 10 nodes, with 128 processors per node for about 96 hours wall clock time. A representative view of the three-dimensional velocity field is shown in Fig. 3a. A comparison of the Van Driest transformed velocity profiles of the different rough surfaces, as compared to the smooth channel case, is shown in Fig. 3b. It can be seen that the grit-blasted surface has the largest drop in U^+ at the middle of the channel as compared to the smooth channel. A comparison of the values of the roughness function of the different surfaces is given in Table 1.

(a) 3D velocity field

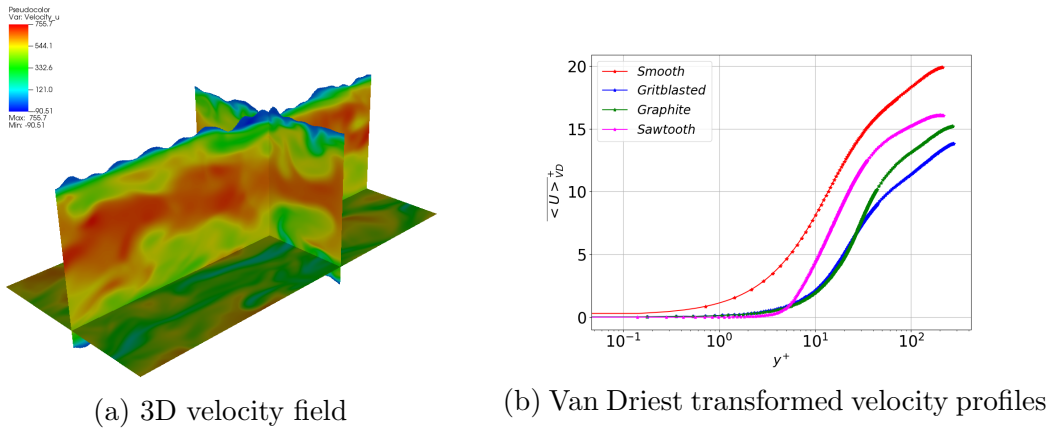(b) Van Driest transformed velocity profiles

Figure 3: Velocity field and transformed velocity profiles

It can be seen that although the sawtooth and grit-blasted surfaces have the same mean roughness height, the difference in their roughness function suggests that other topological features of the rough surface can influence the roughness function independently of the

Table 1: ΔU^+ of the different rough surfaces

Roughness Function	Grit-blasted	Graphite	Sawtooth
ΔU^+	6.4	5.1	3.9

mean roughness height. Furthermore, the use of the hybrid WENO-CD discretization is crucial in ensuring that a non-dissipative central difference method is used in the smooth region of the flow to allow the flow to quickly transit into a turbulent state. The parameter value that governs the switch from a central scheme to the WENO scheme is selected such that the central scheme is used almost everywhere in the domain, except the near-wall region where the WENO scheme is activated. Discontinuities arising from either the boundary or shock waves require the activation of the WENO scheme to avoid numerical instabilities. A comparison of the discontinuous flag indicator of the different surfaces is shown in Fig. 4. It can be seen that the DC flag is only activated at the near-wall region.
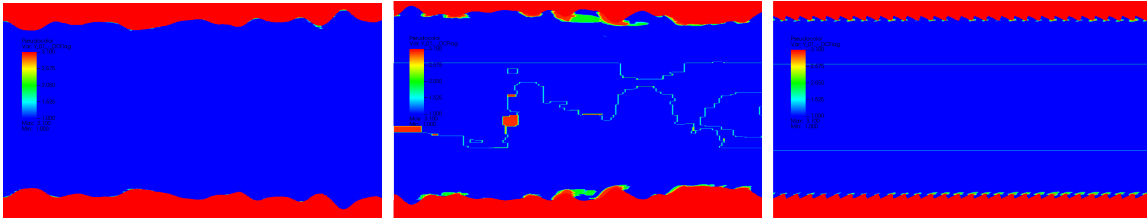

Figure 4: DC Flag Region of grit-blasted, graphite and sawtooth surfaces (left to right).

4   CONCLUSIONS

In this work, DNS of compressible flow over a set of smooth and rough surfaces is carried out in a turbulent channel flow configuration. In particular, adaptive mesh refinement is used for the first time in such a flow configuration. It is found that permanently flagging a fixed region near the wall with a finer mesh while providing an adaptive mesh at the region closer to the outer layer of the boundary is the most optimal meshing approach. Furthermore, the selection of an appropriate parameter value that governs the switch from a central to WENO scheme is necessary to minimize numerical dissipation and allow the flow to quickly transition into a turbulent state while ensuring numerical stability.

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