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LARGE EDDY SIMULATION OF TURBULENT COMPRESSIBLE CHANNEL FLOW OVER RIBLETS

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ABSTRACT

This work presents a numerical study of a weakly-compressible turbulent channel flow with one wall equipped with riblets of low height and of spanwise wavelength equal to 20 wall units. It is found that riblets force the longitudinally of coherent vortices and velocity streaks close to the wall, and widen the width of the latter. A mechanism of extraction of “antivorticity” from the wall by longitudinal vortices is also identified.

KEYWORDS

Large Eddy Simulation, riblets, channel flow, drag reduction, turbulent boundary layer, coherent vortices

1 INTRODUCTION

Figure 1: Three-dimensional view of computational domain: $n_x \times n_y \times n_z = 35 \times 81 \times 70$

Wall roughness is omnipresent in industrial applications and has a non-negligible effect on the boundary layer flow developing over wall surfaces. In particular one type of wall roughness can

be described by streamwise grooves - riblets- which can either enhance or decrease the wall skin friction. Riblets can be an efficient method of passive flow control, know to lead to up to 8 % of drag reduction on an experimental ribbed boundary layer Walsh (1982). This optimal shape of riblets is the sawtooth with acute angles. The thinness of the scales used limits the accuracy of the measurement techniques and places high demands on manufacturing. Therefore, numerical studies, mainly of incompressible flows, have been performed to understand the associated flow structure.

In the present work we carry out a Large Eddy Simulation (LES) of a weakly-compressible turbulent channel flow with riblets. The simulation consists of a minimal periodic plane channel flow having both a flat plane wall and triangular grooves mounted on the opposite wall (see fig. 1). The V-groove riblet geometry corresponds to $s^+ = 21$ and $h^+ = 4$. This small-riblet configuration does not allow a viscous drag reduction, supposing a constant density. However, we have checked by numerical simulations that the increase of the skin friction level (3%) is lower than the rise of the ribbed surface area (5%).

2 COMPUTATIONAL TOOL

2.1 Numerical method

The compressible Navier-Stokes equations for an ideal gas are written in the fast-conservation form (see e.g. Ducros, Comte & Lesieur (1996)):

$$\frac{\partial U}{\partial t} + \frac{\partial F_i}{\partial x_i} = S \quad (1)$$

with

$$U = (\rho, \rho u_1, \rho u_2, \rho u_3, \rho e)^T \quad (2)$$

where u_i is the velocity vector and e the total energy per unit of mass. F_i are the fluxes in the three directions, and S is the source term depending on the reference velocity U_c .

$$S = (0, f(t), 0, 0, U_c f(t))^T \quad (3)$$

It allows to keep the instantaneous mass flux constant. The solver uses a fully-explicit McCormack scheme, which is second order accurate in time and fourth order in space Gottlieb & Turkel (1976). The numerical details can be found in Comte (1993).

2.2 Subgrid-scale model

The subgrid-scale model used here is the Selective Structure Function Model (SSFM, see Lesieur & Métais (1996). In this model, the turbulent eddy viscosity, ν_t , is expressed in terms of the local second order velocity structure function, and set to zero if the flow is not three-dimensional enough. The ratio of mean turbulent to molecular viscosity is close to $\frac{\nu_t}{\nu} \simeq 1$, so the model has a little effect on the results. No Van Driest type damping of the eddy viscosity is made at the wall.

2.3 Dimensionless numbers

The governing equations are non-dimensionalised by the central velocity in a laminar channel flow U_c , the channel half-width H , the wall temperature T_w , the viscosity at the wall temperature μ_w

and the bulk density ρ_b . The dimensionless numbers are the Reynolds and Mach numbers:

$$Re = \frac{\rho_b U_c}{\mu_w} = 4000, \quad Mach = \frac{U_c}{\sqrt{\gamma T_w}} = 0.5 \quad (4)$$

2.4 Computational details

The size of the computational domain is $\frac{8\pi}{7}H \times \frac{\pi}{3}H \times 2H$ for the ribbed channel (see fig. 1). The grid consists of $35 \times 81 \times 70$ nodes with the first grid point at 0.7 wall units. The coordinates system is curvilinear beyond the x - and y -directions and cartesian beyond the z -direction.

3 NUMERICAL CONFIGURATION: THE MINIMAL CHANNEL FLOW

This preliminary simulation of a ribbed channel flow uses a minimal box Jiménez & Moin (1990). This is a useful tool to study wall turbulence, because the background turbulence is reduced and permits to get first-order turbulence statistics in good agreement with one of a full channel (not show here), like the mean velocities or the Reynolds stresses.

On the other hand, the two-point correlation function of streamwise velocity (fig. 2) is not well predicted. This function does not in the two cases (plane and ribbed channel) tend to zero correctly in the streamwise direction. There is a strong correlation between the beginning and the end of the minimal box. In the spanwise direction, the use of a minimal box has not much effect on the autocorrelation, but the riblets modify it near walls and in the center of the channel. We can note a stronger correlation between the riblets (dotted lines).

Figure 2: The two-point spatial autocorrelation function of streamwise velocity along the homogeneous directions, for center of channel (straight line) and wall (dashed and dotted lines for flat and ribbed plane respectively).

However the following simulation still displays the typical near wall structures to allow to sustain turbulence wall.

4 COMPRESSIBILITY

The validity of the code concerning its compressibility aspects was assessed thanks to a comparison in a supersonic channel flow between a Direct Numerical Simulation of Coleman Coleman, Kim & Moser (1995) and our LES at $Mach = 2.25$, based on U_c ($Mach = 1.5$, based on U_b). Our low-order turbulence statistics are in good agreement with the DNS predictions.

Mean pressure and temperature variations are, in our ribbed channel flow simulation, about 1 to 2%. Reynolds stresses and mean streamwise velocity do not seem to be sensitive to compressibility effects, and Favre averaging brings nothing more than Reynolds averaging. The two averages of

streamwise velocity have a similar shape, with the same velocity deficit in the log region near the riblets, which corresponds to an increasing drag configuration. Close to the ribbed wall, locally, some discrepancies persist. This is why an incompressibility assumption has been made in order to compute the wall skin friction.

5 THE TURBULENT BOUNDARY LAYER

We present now the coherent vortices and structures of the turbulent boundary layer in a ribbed channel, both near plane and ribbed walls. Quantities in wall units are denoted by $+$, and the wall Reynolds number is H^+ .

$$H^+ = \frac{H(\frac{\tau_w}{\rho_b})^{\frac{1}{2}}}{\nu_w} = 160. \quad (5)$$

5.1 Coherent vortices and streaks

In the case of the smooth wall, it is well known that quasi-longitudinal vortices exist close to the wall and travel with the mean flow. It is not our purpose to give a review of the numerous works on that topic. We just remind that a nice way of visualizing these vortices in direct- or large-eddy simulations is to consider iso-surfaces of the second-invariant of the velocity-gradient tensor

$$Q = \frac{1}{2}(\Omega_{ij}\Omega_{ij} - S_{ij}S_{ij}) \quad (6)$$

with $\Omega_{ij} = \frac{1}{2}(\partial_j u_i - \partial_i u_j)$ and $S_{ij} = \frac{1}{2}(\partial_j u_i + \partial_i u_j)$, at a given positive threshold. This was done for instance by Dubief & Delcayre (2000) in the case of a channel with a flat wall and the other equipped with two small square grooves in the spanwise direction. The animation of Q iso-surfaces does show on the flat wall hairpin-type asymmetric quasi-longitudinal vortices which creep close to the wall and raise in an arch form away from the wall, due to self-induction. Low-speed streaks can be found between the legs of the vortices (see also Ducros, Comte & Lesieur (1996)), in agreement with arguments based upon velocity induction by vorticity concentration. The diameter of the vortex legs is about 20 to 25 wall units, of the same order of magnitude as the low-speed streaks. In Dubief and Delcayre's work, the two small spanwisely-oriented grooves do not modify much the vortex structure nor the drag. Let us go back to the present channel LES involving longitudinal triangular riblets of low height, for which we are going to compare the coherent-vortex and streak system with the flat-plate case.

First we show evidence for a strong alignment of velocity streaks in the flow direction. We consider this system at $z^+ \leq 9$. This is done in Figure 3, showing isoregions of positive longitudinal velocity fluctuation (threshold 0.4, grey) and negative ones (threshold -0.4, black). Two things can be remarked in the ribbed case: first, the streaks extend now over the whole length of the channel in the streamwise direction; second, the average width of streaks in the spanwise direction has increased. Indeed, there are four streaks in the ribbed case against five for the smooth plate.

Let us look now at the associated coherent vortical structure. We first present on Figure 4 a map of the $Q = 0.1$ regions between the wall and a distance of 7 wall units. Such a map is an indicator of zones of contact of vortices with the wall. In the riblet case, the distance is considered from the tip of the riblets, that is from 4 to 11, since we expect the vortices to be pushed away from the wall by riblets. Indeed, their assumed diameter of 25 wall units forbids them to sit in the riblet valleys, as in the work of Choi, Moin & Kim (1993). It is obvious from the figure that riblets align the vortices in the flow direction close to the wall. In order to provide a more precise picture of the

Figure 3: Velocity streaky structures near the smooth wall for $z^+ \leq 9$ (top view). (a) and the ribbed wall (b). The positive (resp. negative) fluctuating streamwise velocity is grey (resp. black). Spanwise coordinate marks riblets valleys in global units.

Figure 4: Top view of $Q = 0.1$ isosurfaces for : a) smooth wall ($0 < z^+ < 7$), b) ribbed wall ($4 < z^+ < 11$).

vortical distribution in the ribbed case, we present now cross sections close to the wall ($z^+ \leq 60$) in planes perpendicular to the mean flow of longitudinal vorticity and isolines of positive Q at downstream locations (first third of the domain, Figure 5, second third of the domain, Figure 6). Positive vorticity means that the longitudinal vortices are oriented in the streamwise direction.

On Figure 5-top, one sees very clearly an intense negative vortex forming a sort of dipole like structure with a weaker positive vortex above, while inducing “antivorticity” (due to the no-slip condition at the wall) on the l.h.s. of the riblet underneath (this can be checked by looking at the color visualizations). In the center of the figure, there is another weaker dipole positive-negative (from left to right). The Q isolines keep the signature of these structures. The same structures are present in Figure 6. However, we have checked that the positive part of the positive-negative dipole on the left is a result of an extraction and entrainment of the positive antivorticity by the negative vortex of the l.h.s. of Figure 5-top. In the same way, a longitudinal positive vortex at the wall will extract from the riblets negative antivorticity and transport it. This mechanism might explain why so many dipole-like vortical structures are found in the flow close to the wall. Let us now look at the coherent-vortex structure away from the wall. Figure 7-b shows a global view of the longitudinal vorticity map in half the channel above the ribbed wall. One can see arch-like vortices raised above the wall by self induction, and resembling analogous vortices found in the flat-wall case. Figure 7-a isolates the vortex which is on the r.h.s. of Figure 7-b. This vortex is shown with the help of fluctuating vorticity lines.

6 CONCLUSION

A large eddy simulation of turbulent weakly-compressible channel flow over sawtooth-shape riblets was carried out. The riblets height is low, and this increasing drag configuration allows to analyze the dynamical effect of the riblets upon the flow at a low computational cost. The main results found are that the low- and high-speed streaks system extend over the whole length of the channel, and that the quasi-longitudinal vortices close to the wall align in the flow direction. We have also identified a mechanism of extraction of antivorticity from the wall by these vortices.

Figure 5: Cross section ($z^+ \leq 60$) at the first third of the domain of longitudinal vorticity (top-grey, positive; black, negative) and $Q \geq 0$ (bottom). (Note that the cross-section does not show the full extent of the computational domain along the normal direction. The ribbed wall is on the bottom.)

REFERENCES

- Walsh M. J. (1982). Turbulent boundary layer drag reduction using riblets. AIAA Paper 82-0169.
- Hoosmand D., Youngs R. and Wallace J.M. (1983). An experimental study of changes in the structure of a turbulent boundary layer due to surface geometry changes. AIAA paper 83-0230.
- Lesieur M. and Métais O. (1996). New trends in large eddy simulations of turbulence. Appl. Sci. Research 28:45-82.
- Dubief Y. and Delcayre F. (2000). On coherent-vortex identification in turbulence. J. of Turbulence 1.
- Choi H., Moin P. and Kim J. (1993). Direct numerical simulation of turbulent flow over riblets. J. Fluid Mech. 255:503-539.
- Jiménez J. and Moin P. (1990). The minimal flow unit in near-wall turbulence. J. Fluid Mech. 225:213-240.
- Kim J., Moin P. and Moser R. (1987). Turbulence statistics in fully developed channel flow at low Reynolds number. J. Fluid Mech. 177:133-166.
- Ducros F., Comte P. and Lesieur M. (1996). Large-eddy simulation of transition to turbulence in a boundary-layer developing spatially over a flat plate. J. Fluid Mech. 326:1-36.
- Coleman G.N., Kim J. and Moser R.D. (1995). A numerical study of turbulent supersonic isothermal-wall channel flow. J. Fluid Mech. 305:159-183.
- Gottlieb D. and Turkel E. (1976). Dissipative two-four methods for time-dependent problems. Math. Comp. 703-723.

Figure 6: Same as preceding figure in the second third of the channel.

Figure 7: Half-channel near ribbed wall: a) fluctuating vorticity lines showing a particular hairpin vortex. b) isosurfaces of streamwise vorticity.

- Jiménez J. (1994). On the structure and control of near wall turbulence. *Phys. Fluids* 6:2, 944-953.
- Hamilton J.M., Kim J. and Waleffe F. (1993). Regeneration of near-wall turbulence structures. ninth symposium on "TURBULENT SHEARFLOWS". Kyoto, Japan.
- Comte P. (1993). Numerical methods for compressible flow. Les Houches, session LVIX, Elsevier.
- Smith C.R. and Walker J.D.A. (1995). SI Green. Turbulent wall-layer vortices. *Fluid vortices*. Kluwer academic publishers.
- Lesieur M. (1996). *Turbulence in fluids*. Kluwer academic publishers.
- Cousteix J. (1989). *Turbulence et couche limite*. Cepadues editions.