DIRECT NUMERICAL SIMULATION OF SPANWISE LORENTZ FORCE OSCILLATIONS IN TURBULENT CHANNEL FLOW AT LOW REYNOLDS NUMBER

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Abstract Direct numerical simulations (DNS) of a turbulent channel flow at low Reynolds number (Re_τ = 180, based on the wall-shear velocity and channel half width) are performed. We applied an idealized oscillating Lorentz force to the bottom of the channel and we compared the results for the applied force and the no-force cases both in the upper half of the channel and the lower half of the channel. In recent years there has been an increasing attention to the work based on turbulence drag reduction using an imposed Lorentz force. However, there is still a need for investigating the flow field structures changes in the applied force case compared to the no-force case. We have analyzed the two point correlation to explain the effect of the Lorentz force on the vorticity structures. Our results lead us to establish an explanation of the effect of the sweep and ejection events on the mean vortex structures in the flow field. We also depicted the turbulence production rates for both cases and compared them for the lower and upper half of the channel.

INTRODUCTION AND BACKGROUND

Flow control using the Lorentz force was used to performed for delaying the transition of turbulence (3) and also for turbulence suppression (1), (2), (4). The present paper presents DNS simulations of channel flow (Reynolds number of 180) in which Lorentz force excitation is applied along the spanwise direction (see figure 1) in order to investigate the potential of drag reduction. The aim of the paper is to give a better understanding of the mechanism of drag reduction via Lorentz forcing. We will relate flow field variables with turbulence structures for both the applied force and the no-force cases.

METHODOLOGY

The governing equations for an electrically conducting, magnetically permeable, incompressible Newtonian fluid are Navier-Stokes equations together with Maxwell equations. With the assumption of low conductivity fluid like seawater, neglecting the time-variation of the magnetic field, and assuming that the induced magnetic field is small compared to the applied magnetic field, we have a potential function ϕ for electric field, such that $\mathbf{J} = -\sigma\ \nabla\phi$, in which $\mathbf{J}$ represents current density vector. The governing equation for ϕ and magnetic flux density, $\mathbf{B}$ are Laplace equations. With appropriate boundary conditions and by taking the vector product of the current density and the magnetic flux density, the resulting force distribution acts only in the spanwise direction (see (1) for further details). The resulting force can be estimated as a body force and directly added as a body force term to the Navier-Stokes equations as below.

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u}\cdot\nabla\mathbf{u} = -\nabla\mathbf{p} + \frac{1}{Re_\tau}\nabla^2\mathbf{u} + St\ (\mathbf{J}\times\mathbf{B}), \tag{1}$$

$$\nabla\cdot\mathbf{u} = 0, \tag{2}$$

where Re_τ is the Reynolds number based on u_τ (wall shear velocity) and δ (half channel height). $St = J_0 B_0 \delta/[\rho u_\tau^2]$, is the Stuart number which represents the relative strength of the Lorentz force with respect to the inertia force, where J_0, B_0 and ρ are the current density, the magnetic flux density values at the wall and fluid density respectively.

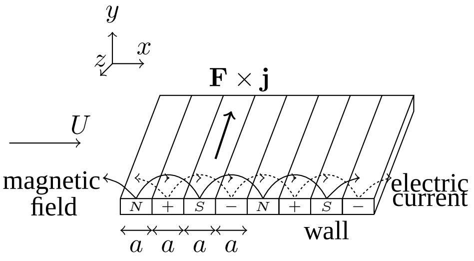

Figure 1. Illustration of magnets and electrodes arrangement for generating a Lorentz force along the spanwise direction.

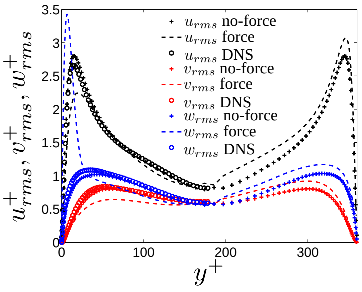

Figure 2. RMS velocity fluctuations.

DIRECT NUMERICAL SIMULATIONS

An incompressible, finite volume code is used (5). The numerical procedure is based on an implicit, fractional step technique with a multigrid pressure Poisson solver and a non-staggered grid arrangement. A constant volumetric driving force is used in the streamwise momentum equation by which the frictional Reynolds number, $Re_\tau = 180$, is prescribed. The domain size is $2\pi\delta \times \pi\delta \times 2\delta$ in the streamwise, spanwise and wall-normal directions, respectively with grid size $98 \times 98 \times 98$. In this work u, v, w represents the streamwise, wall-normal and spanwise velocities, respectively. Before applying any forcing, all simulations are allowed to reach a fully developed turbulent flow state.

RESULTS AND DISCUSSION

DNS results are presented for analyzing the Lorentz force effect. We found that the mean velocity in the fully turbulent region is much larger for the applied force case than for the no-force case and also Reynolds shear stress has much lower value compare the no-force case which are not shown here. Figure 2, present the resolved turbulent fluctuations for applied force and no-force cases. Smaller velocity rms values are obtained for all three velocities in the lower half of the channel and a peak is observed for the spanwise velocity rms value which is the result of the spanwise forcing.

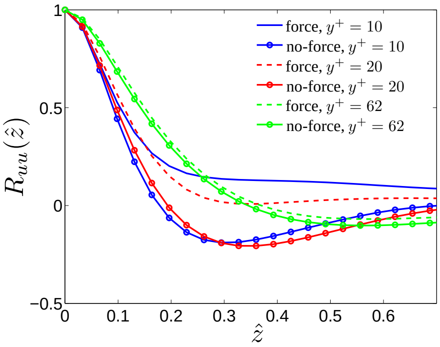

Figure 3. Applied force and no-force cases, lower wall.

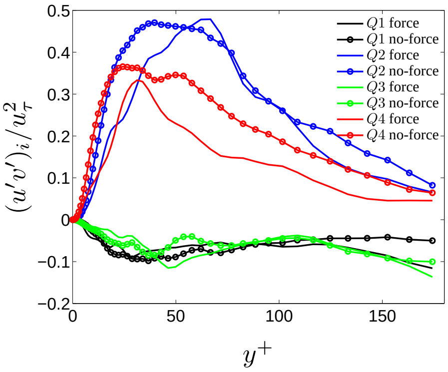

Figure 4. $Q1 - Q4$ are normalized by u_τ^2.

Two point correlation values in z direction are analyzed for all three velocity components, but only streamwise velocity two point correlation values depicted here (see figure 3) which has information about mean separation of the streaks. In figure 3, the no-force two-point correlations become negative and reach a minimum at $\hat{z} = 0.3$ for $y^+ = 10$ and 20, which provides an estimate of the mean separation between the high and low speed fluid; the mean spacing between the streaks should be roughly twice the distance (6). For the applied force the correlations do not go negative but there is a weak minimum at $y^+ = 20$ which proves that there is a significant change of separation between high and low speed fluid. Quadrant analysis of the Reynolds shear stress was performed. To get an accurate statistics, 400 samples were used for each y^+. In figure 4 $Q1 - Q4$ are normalized by the friction velocity, u_τ^2. It is obvious that in the force case there is a shift of sweep and ejections which indicates that in the force case vortex structures change as we move away from the wall. In Ref. (6) the observed that the streamwise vorticity provides information about the streamwise vortex structures: the location of minimum streamwise vorticity value gives the edge of the mean Rankine vortex structure, and the location of the maximum value corresponds to the center of the mean Rankine vortex. We found that for the no-force case minimum and maximum points are more separated compared to the applied force case which are not depicted here. This means we have smaller radius of mean vortex in the force case compared to the no-force case, also absolute difference of sweep and ejections are smaller compare to no-force case. The production of turbulent kinetic energy was also analyzed. We found that at the lower wall the production for the force case is smaller than the no-force case; at the upper wall it is vice versa.

References

[1] T. W. Berger, J. Kim, C. Lee, and J. Lim. Turbulent boundary layer control utilizing the Lorentz force. *Phys. Fluids.* **12**: 631–649, 2000.

[2] C. H. Crawford, and G. E Karniadakis. Reynolds stress analysis of EMHD-controlled wall turbulence. Part I. *Phy. Fluids.* **9**: 788–806, 1997.

[3] A. K. Gailitis, and O. A. Lielausis. On the possibility of drag reduction of a flat plate in an electrolyte. *Appl. Magnetohydrodyn. Trudy Inst. Fisiky AN Latvia SSR.* **12**: 143–146, 1961.

[4] C. Hennoch, and J. Stace. Experimental investigation of a salt water turbulent boundary layer modified by an applied streamwise magnethydrodynamic body force. *Phy. Fluids.* **7**: 1371–1383, 1995.

[5] L. Davidson, and S.-H. Peng. Hybrid LES-RANS: A one-equation SGS Model combined with a $k - \omega$ model for predicting recirculating flows. *Int. J. Numer. Fluids.* **43**: 1003–1018, 2001.

[6] J. Kim, P. Moin, and R. Moser. Turbulence statistics in fully developed channel flow at low Reynolds number. *J. Fluid Mech.* **177**: 133–166, 1987.