Direct numerical simulation of streamwise traveling wave induced turbulent pipe flow relaminarization

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Abstract:
For technically relevant flows with high Reynolds numbers, more than 90% of the energy required to pump fluids through pipes is dissipated by turbulence near the wall. However, Koganezawa et al. [1] showed for the low friction Reynolds number of $\mathrm{Re}_\tau = u_\tau R/\nu = 110$—where u_τ is the friction velocity, ν is the kinematic viscosity and R is the pipe radius—that for certain wave parameters, streamwise traveling waves of wall blowing/suction can lead to relaminarization, thereby significantly reducing drag. However, as reported in the recent review paper by Fukagata et al. [2], higher Reynolds number data are required for engineering applications. Therefore, we have adapted our fourth-order finite volume solver [3] to perform direct numerical simulations of turbulent pipe flow with streamwise traveling wave boundary conditions of the wall-normal velocity of friction Reynolds numbers up to $\mathrm{Re}_\tau = 720$. For each Reynolds number the optimal set of the blowing/suction parameters is determined in terms of the drag reduction rate $R_D = (C_{f0} - C_f)/C_{f0}$, where $C_f(C_{f0})$ is the skin friction drag of the (un)controlled flow. In addition to the drag reduction rate R_D, the net energy saving S is a crucial metric for evaluating the efficiency of the control method. The net energy saving is defined as $S = (W_{p0} - (W_p + W_a))/W_{p0}$, where $W_p(W_{p0})$ is the driving power of the (un)controlled flow and W_a is the actuation power of the control. Figure 1 shows the net energy saving map at $\mathrm{Re}_\tau = 180$ and a wavelength of $\lambda^+ = 360$ wall units. As illustrated in Figure 1, downstream traveling waves with $\lambda^+ = 360$, $c = U_{c,lam}$, and $a = 0.07U_{c,lam}$ induce relaminarization and a maximum of net energy saving of approximately 80%. Here, $U_{c,lam} = 1/2\mathrm{Re}_\tau u_\tau$ is the centerline velocity of the corresponding laminar flow. In addition, standing waves ($c = 0$) with low amplitudes ($a \leq 0.15U_{c,lam}$) and slow upstream traveling waves ($c = 0.1U_{c,lam}$) lead to positive net energy savings. In the following, we are performing a parametric study by varying Re_τ, as well as the traveling wave amplitude a, length λ, and velocity c. At the conference we will present the Reynolds number scaling of the blowing/suction parameters that lead to relaminarization, minimum drag, and maximum net energy saving, and elucidate the underlying mechanisms. Figure 2 presents the Reynolds number scaling of the turbulent kinetic energy decay rate of flow cases with relaminarization.

References

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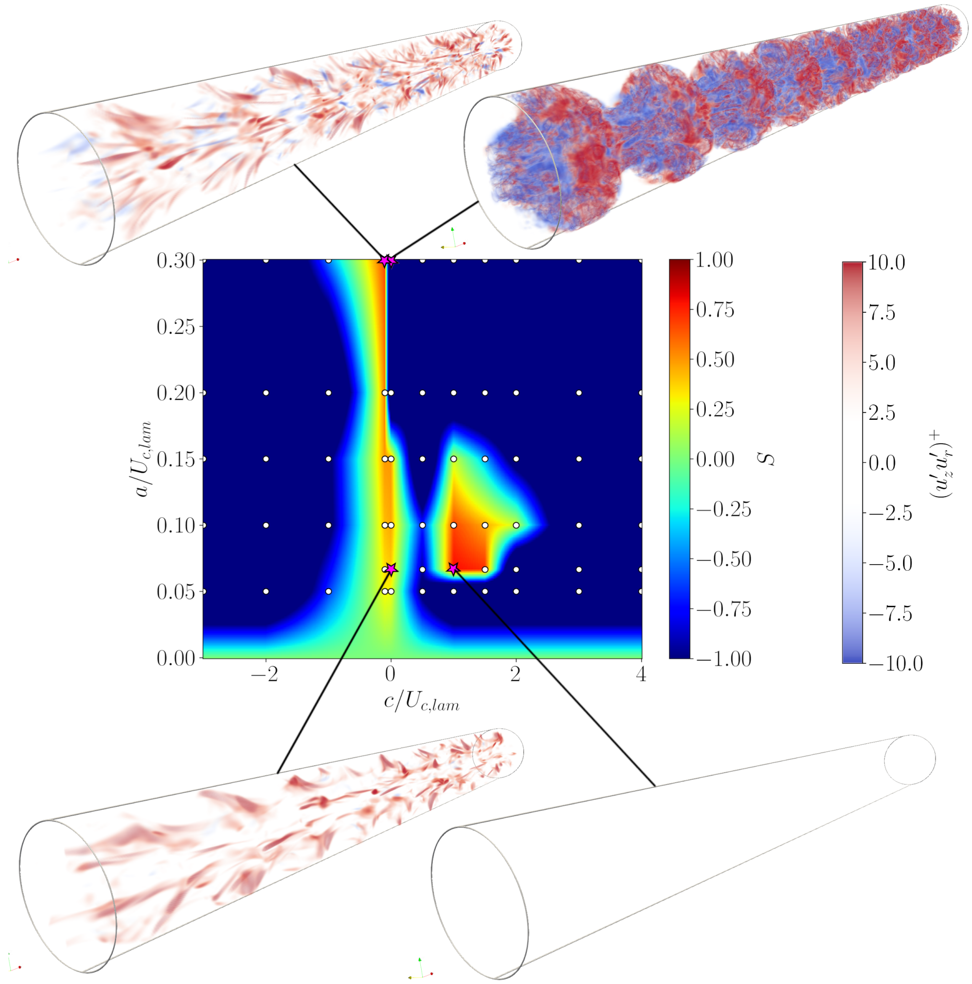

Figure 1: Net energy savings S for $\mathrm{Re}_\tau = 180$ and $\lambda^+ = 360$ as a function of wave amplitude a and velocity c normalized with $U_{c,lam}$. For selected cases, the volume rendering of the instantaneous Reynolds shear stress $u_z' u_r' = u_z u_r - \langle u_z \rangle_\varphi \langle u_r \rangle_\varphi$ normalized in wall units at time $t = 7.5 u_\tau/D$ after the start of the control is shown.

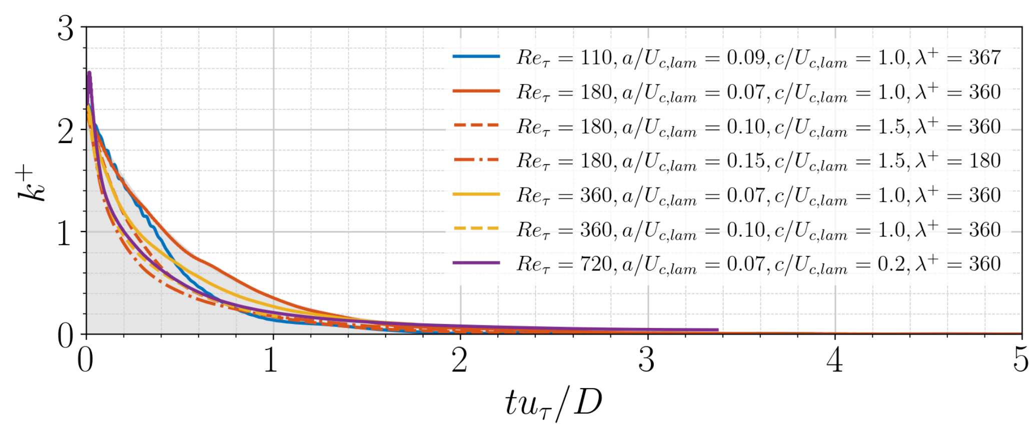

Figure 2: Turbulent kinetic energy decay for streamwise traveling wave-induced relaminarization at different Re_τ, a, c, and λ. $k^+ = 1/2(\langle u_z' u_z' \rangle^+_{r\varphi z} + \langle u_\varphi' u_\varphi' \rangle^+_{r\varphi z} + \langle u_r' u_r' \rangle^+_{r\varphi z})$. The shaded area indicates the exponential decay function $k^+ = 2.2\exp(tu_\tau/D/0.55)$.