The Phase Relationship in Laminar Channel Flow Controlled by Traveling Wave-Like Blowing/Suction

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Recently, Min *et al.*[1] proposed a new predetermind control technique, i.e., a traveling wave-like surface blowing/suction as shown in Fig. 1, which acheived the skin-friction drag below the laminar level. This control is attractive for realization of active turbulent drag reduction because it does not require massive micro-sensors. The present work is an extension of the studies of Min *et al.*[1] to explain the mechanism of this drag reduction effect.

The identity equation for the skin-friction drag, D, reads [2],

$$D = 2 + \frac{3}{2}\mathrm{Re}\int_{-1}^{1}(-y)\left(-\overline{u'v'}\right)dy. \tag{1}$$

The second term of the RHS is the increment from a laminar contribution, which is the integration of the y-weighted Reynolds shear stress. This Reynolds shear stress is induced by a non-quadrature between the streamwise and wall-normal velocity disturbances. The detailed phase analysis in the present study reveals that this non-quadrature is decomposed into a base phase relationship and a near-wall phase shift of the streamwise velocity disturbance. The base phase relationship is given by a solution of an inviscid disturbance equation and the near-wall phase shift is induced by the viscosity as shown in Fig. 2. The parametric study for the wider range of the wavespeeds and wavenumbers shows that the base phase relationship depends on the wavenumber and the actuation mode (i.e., varicose or sinuous). The near-wall phase shift, however, depends only on the direction of the traveling wave, i.e., the sign of the wavespeed.

We also show that the control effects can be scaled similarly to the Stokes' second problem. Namely, the dimensionless influence layer thickness is found to take a constant value under various input parameters and Reynolds numbers.

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[1] Min *et al.*, *J. Fluid Mech.* **558**, 309 (2006).
[2] Fukagata *et al.*, *Phys. Fluids* **14**, L73 (2002).

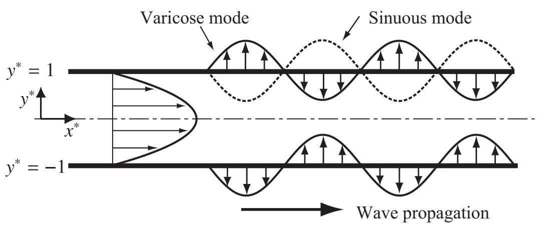

Figure 1: Flow geometry and schematic of control input.

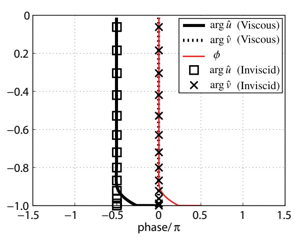

Figure 2: Profile of phases of the Fourier coefficients for viscous and inviscid disturbance in drag reducing case.