Experimental assessment of turbulent drag reduction by wall traveling waves

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Waves of spanwise velocity applied at the wall of a turbulent channel flow and traveling in the streamwise direction have been recently discovered in a numerical study by Quadrio *et al.* [1] to alter the natural turbulent friction significantly. In particular, depending on the parameters that define the waves, drag can be either increased or decreased, and at low Re full relaminarization has been achieved. Large drag reductions are obtained at the expense of very limited expenditure in energy, thus resulting in a largely positive overall energy budget. This paper presents the first experimental assessment of the performance of the streamwise-traveling waves in a turbulent pipe flow.

The waves considered in [1] are described by:

$$w_w(x,t) = A \sin\left(\kappa_x x - \omega t\right), \tag{1}$$

where w_w is the spanwise (z) component of the velocity vector at the wall, x is the streamwise coordinate and t is time, A is the oscillation amplitude, κ_x is the wave number in the streamwise direction and $\omega = 2\pi/T$ is the oscillation frequency. One important parameter of the waves is their phase speed $c = \omega/\kappa_x$. Such waves include and generalize the particular cases of the oscillating wall [2] and the stationary transverse waves described at the last ETC conference [4].

The effects exerted by the wall traveling waves on the turbulent plane channel flow are summarized in figure 1, adapted from [1]. The flow has a Reynolds number of $Re = 3170$ based on the bulk velocity U_b and the channel half-width h. The amplitude A of the waves is kept fixed at $A = 0.75 U_b$. The effect of waves on the drag varies widely depending on their spatial and temporal frequency. The largest drag reduction (about 45% for this value of A) is observed for slowly forward-traveling waves over a wide range of not-too-large wavelenghts. The maximum drag reduction pertains to backward-traveling waves when the wavelength $\lambda = 2\pi/\kappa_x$ of the waves exceeds $\lambda \approx 6h$. At a relatively well-defined phase speed c (indicated in this plot by straight lines passing through the origin), the effect of the waves abruptly becomes

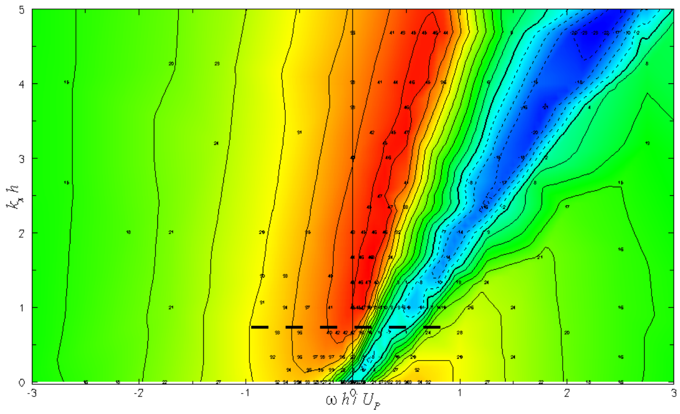

Fig. 1. Map of friction drag reduction (percentage) in the $\omega - \kappa_x$ plane for $A = 0.75U_b$ and $Re = 3170$. Contours are spaced by 5% intervals, loci of zero DR are indicated by thick lines and negative values are represented by dashed lines. The numbers indicate percentage drag reduction at measured points. On the horizontal axis, $U_p = 3/2U_b$. The thick dashed line indicates the range explored in the present experiment, see later fig. 3.

that of drag increase. The straight line with $c = 0.7U_b$ identifies the locus of maximum drag increase.

Aim of the present work is to give the results contained in [1] an experimental confirmation. The cylindrical geometry lends itself to an easier implementation of the traveling waves, owing to the natural periodic spanwise (azimuthal) direction offered by a cylindrical pipe. The wall motion implied by Eq. (1) in the cartesian geometry is implemented by imposing different rotation rates to different longitudinal sections of the pipe, so realizing a discretization of the sinusoidal space variation. In addition to the traveling waves, the setup can be used to obtain both purely temporal (when all the pipe sections have an in-phase alternating motion) and purely spatial (when all the pipe sections steadily rotate at different speed) oscillations.

Water is chosen as the working fluid. The bulk velocity of the flow is $U_b = 0.11$ m/s and the value of the Reynolds number equals $Re = 2450$ (based on pipe inner radius R of 25 mm and U_b), i.e. somewhat lower than the one employed in the DNS for the planar case. The oscillating frequencies of interest are of the order of 1 Hertz; the pressure drop across the moving section is small but still measurable. Most of the difficulties encountered during the present work are related to the need of measuring very small pressure differences.

The longitudinal sinusoidal variation of the transversal velocity required by (1) is discretized through up to 6 independent pipe segments for each wavelength. Each segment has an axial length of 36.55 mm. The total length of the pipe section with rotating segments is about 2.2 m, that amounts to no less than 10 wavelengths. The lineup of the different segments is achieved by mounting each segment with two rolling-contact bearings co-axial to the pipe and aligned to a steel rail. The need for controlling the frequency of the sinusoidal variation of the angular speed, and in particular for implementing a constant-speed motion, poses a number of constraints on the transmission system, that is based on timing belts moved by 6 independent D.C. motors, each driven by a purposely designed closed-loop controller. The pipe section with rotating segments is part of a large closed-circuit pipe. The whole apparatus is approximately 250 diameters long, thus ensuring a fully developed turbulent flow. Fig.2 illustrates the experimental setup.

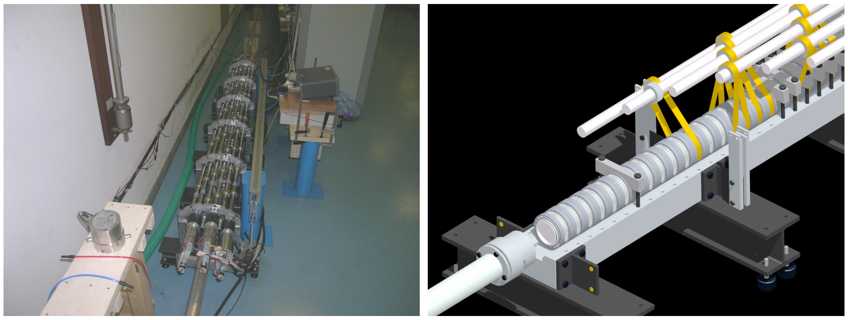

Fig. 2. Left: picture of the experimental setup. The return pipe can be seen on the far left, the moving segments are on the center, hidden by the transmission shafts and 3 D.C. motors. Right: close-up of a schematic of the trasmission system: shafts, belts and segments.

A preliminary set of results is shown in figure 3. Percentage changes in friction drag are plotted against the oscillation frequency; the oscillation amplitude is kept fixed at $A = 0.73 U_b$. Each sinusoid in space is discretized with 6 segments, thus yielding a wavelength of $\lambda = 8.78R$. The frequency of the wave is varied, thus observing how the turbulent friction changes along the points indicated by the dashed line in fig.1. Drag is evaluated by measuring the pressure drop between two points located immediately upstream the first rotating segment and immediately downstream the last one.

The results strongly resemble the data available for the cartesian geometry. Friction drag is reduced over a wide range of frequencies, except for a small range where drag increases. The maximum of drag is attained for the wave with phase speed of $c = 0.57 U_b$, whereas the drag minimum takes place for slowly backward-traveling wave, with $c = -0.05 U_b$. The actual amount of maximum drag reduction, however, turns out to be underestimated by approximately 50%. More than one reason can explain this discrepancy. First of all, the main mechanism suggested [3] to drive the modification of turbulent friction drag in plane channel flow is quantitatively different from what happens in the cylindrical geometry. Moreover, our experimental setup differs in some respects from the idealized setting of a DNS. Most important is the presence

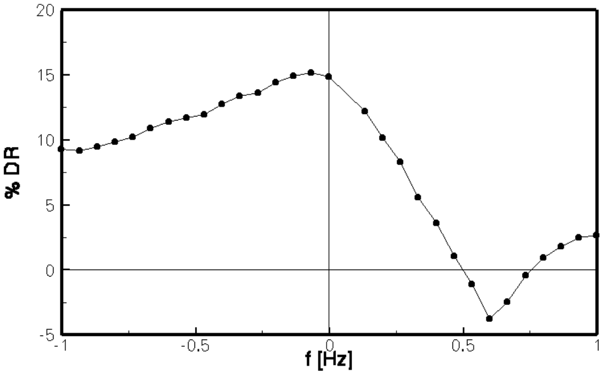

Fig. 3. Friction drag reduction (in percentage of the reference friction) due to waves with $\lambda = 8.78R$ and $A = 0.73U_b$, as a function of the oscillation frequency.

of a spatial transient, where the turbulent friction gradually decreases from the unperturbed level. Our estimate, based on the DNS in cartesian geometry, is that this transient region extends over thousands of wall units. However, the measured pressure drop is an integral measure over the entire length of the active pipe, and as such it yields an underestimated drag reduction. Moreover, the friction factor for the pipe with fixed segments is higher than expected. This may be due to localized roughness effects, either due to the design of the pipe segments, or – most probably – due to debris that accumulates in the measuring section. We are still working to sort out this issue.

In conclusion, the experiment described here has succesfully demonstrated the capability of the wall traveling waves to yield large reductions of drag in the laboratory. We are still working towards a better quantitative characterization of their performance. An accompanying effort is that of understanding the traveling wave working mechanism in the cylindrical geometry.

References

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