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DRAG-REDUCING WALL OSCILLATIONS VIA DIELECTRIC ELASTOMER ACTUATORS IN LOW REYNOLDS NUMBER INTERNAL TURBULENT FLOWS

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INTRODUCTION

Spanwise wall oscillations have been widely investigated since the seminal work of Jung *et al.* [4] as an active means to reduce turbulent skin-friction drag and as a basis for more sophisticated control strategies. In spite of its relative simplicity, the spanwise oscillation concept has been tested mostly numerically and the few experimental realizations are proof-of-principle laboratory experiments in which the spanwise wall velocity is imposed by moving the wall through bulky crank-driven mechanisms. Such solutions are generally energetically inefficient, require significant modifications of the wind tunnel test section and, most importantly, can not be easily integrated into more complex systems. Gouder et al. [3] realised the spanwise oscillating surfaces through a novel actuator concept: the dielectric elastomer actuators (DEAs). However they found this technology to be unattractive due to the fragility of the actuators, having a lifetime of only a few minutes [2].

In the present work, we describe the fabrication and wind-tunnel testing of long-lasting spanwise-oscillating active surfaces based on DEA. We point out some drawbacks of this particular actuator and verify whether potential advantages, such as low power consumption and simplicity, can in fact be realised. The net power saving is experimentally measured for the first time. Possible further developments are suggested, which could enable investigations at higher values of Re. The finite streamwise extent of the actuated area is addressed as a possible source of the well-known discrepancies between numerically and experimentally measured drag reduction.

EXPERIMENTAL SETUP AND METHOD

The wind tunnel employed in the following laboratory investigation is an open-circuit blower tunnel with flat duct test section of inner width $W = 25.2$ mm and height $H = 300$ mm, which extends in the streamwise direction for about 3950 mm, corresponding to $158H$. The Reynolds number $Re_B = U_B H/\nu$, based on the bulk velocity U_B, is varied between 4500 and 15000, corresponding to a Reynolds number Re_τ, based on the friction velocity u_τ, of 180 and 450 respectively.

DEA-based homogeneously spanwise-oscillating surfaces, which improve the design by Gouder et al. [3], are installed into the test section, at least $100H$ past the channel entrance, in two different configurations (fig. 1). The bulk of the measurements has been in the opposite-wall configuration, with two actuators facing each other at the same streamwise position. The effect of the limited streamwise length is addressed by few measurements in which three actuators are cascaded downstream at the top wall of the channel only.

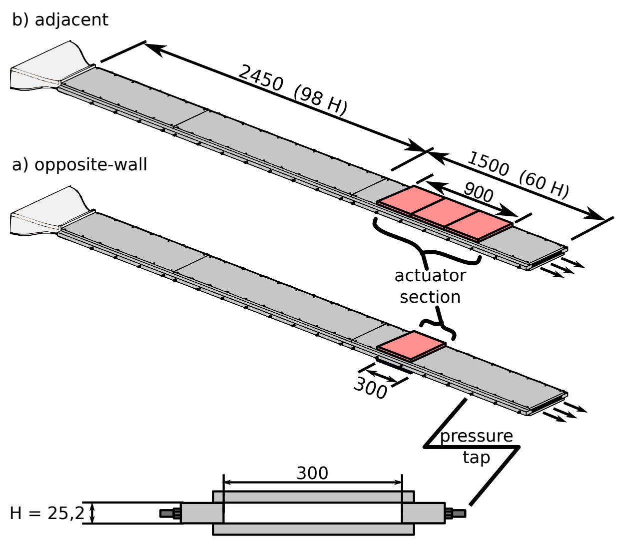

Figure 1: Sketch of the wind-tunnel test section with integrated actuators in two different configurations. All dimensions in mm.

The homogeneously-oscillating surface is 20 cm × 20 cm in size. At their mechanical resonant frequency of 65 Hz, the actuators produce large oscillations of the spanwise wall velocity of about 820 mm/s. As a result, the nondimensional amplitude A^+ and period T^+ of wall oscillation, expressed in viscous units, change as the Reynolds number in the tunnel is allowed to change.

The measurement procedure consists of six measurement sessions, each three minutes long, during which the pressure drop Δp over the actuator section is acquired with a differential pressure transducers (MKS Baratron 698A, accuracy of 0.12% of reading), alternating activating and deactivating of the actuators. The flow rate is computed by acquiring the pressure drop across an orifice flow meter (Setra 239D differential pressure transducer, accuracy ±0.7% FS 125Pa). Temperature at the inlet and outlet of the wind-tunnel, as well as humidity and absolute pressure are measured at the beginning and end of the measurement procedure to correct the value of air density ρ and viscosity ν. The skin-friction C_f

can be computed as:

$$C_f = \frac{WH^3}{\rho L Q^2}\Delta p, \qquad (1)$$

where Δp is the pressure drop across the distance L and Q the volumetric flow rate. The drag reduction rate reads then

$$R = 1 - \frac{C_f}{C_{f,0}}, \qquad (2)$$

where the subscript 0 refers to the unactuated case. Hereinafter the nondimensional viscous "+" units are computed with the friction velocity of the reference flow.

RESULTS

Figure 2 shows the amount of drag reduction achieved in the opposite-wall configuration for various combinations of A^+ and T^+, obtained by increasing Re_B. Both the partial averages during each of the three couples of sessions and the total averages are shown, which confirm the high accuracy on R to be $\pm 0.4\%$ in the very low range of Re. The two curves correspond to two measurement batches, carried out before and after reassembling the test section. The smallest misalignment in the experimental set-up can increases the reference skin-friction and affecting the achievable R.

Once we account for the streamwsie spatial transient during which the drag reduction decreases from the uncontrolled value at the leading edge of the actuator to the drag-reduced one, the curves agree with the prediction of the empirical correlation proposed by [5] as regards to the position of the relative maximum of R. The measurements in the adjacent configuration confirm that the streamwise controlled length plays an important role in determining the achievable R, which increases to about 5%. However, the amount of drag reduction is lower than what has been obtained in a bespoke Direct Numerical Simulations at the same set of control parameters and Re, consistently to what was reported by [3] in integral measurements.

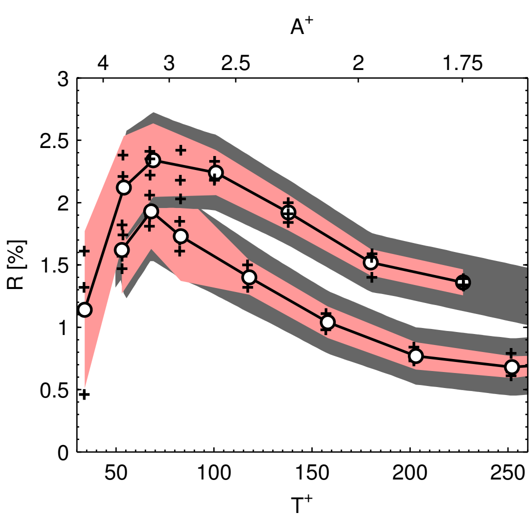

Figure 2: Drag reduction versus period T^+ and amplitude A^+ of wall oscillation. —o—: average data over multiple runs; +: single measurements; ■: uncertainty at 95% confidence level, accounting for stochastic pressure drop fluctuations only; ■: maximum uncertainty, accounting for reproducibility of pressure drop and flow rate measurements.

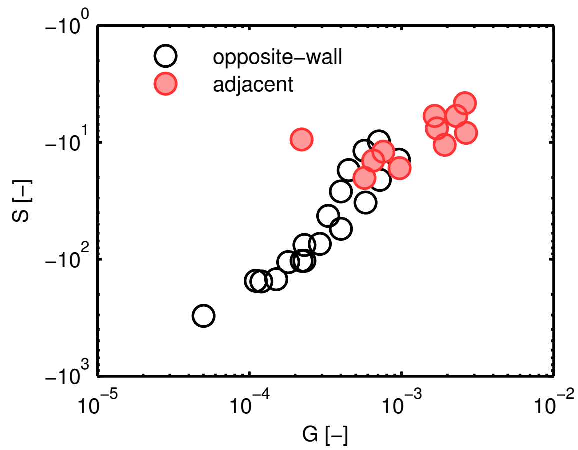

Figure 3: Map of the control gain $G = (P - P_0)/P_{\text{in}}$ versus net power saving rate S.

For the first time in the field of spanwise oscillation we measure the control power budgets. The DEA-based actuators consumed a real power P_{in} as low as 192 mW per actuator, while the pumping power P_0, here defined as the power spent by the friction on the actuator section, ranged between 13 mW and 300 mW in this very low Reynolds number range. As a result, the maximum net power saving rate S that we achieved, defined as $S = R - P_{\text{in}}/P_0$, was $S = -5$. Even though a positive S could not be achieved, the DEA low power consumption yielded a result which is several order of magnitude larger compared to previous estimations for conventional technologies ($S \approx -10^4$ in [1]). We will show that considerable scope for improvements still remains, both to increase Re and regarding the performance of the actuator.

At the workshop, we will focus also on the effect of localized actuation, by comparing the present experimental results with Direct Numerical Simulations of channel flows in which only a part of the wall is oscillating. We will show that the streamwise transient cannot alone explain the discrepancy between numerical and experimental results.

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