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# Drag reduction of wall bounded incompressible turbulent flow based on active dimples/pimples*

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**Abstract:** The control of turbulence by dimples/pimples has drawn more and more attention. The objective of this paper is to investigate the effectiveness of the active dimples/pimples for the drag reduction in the incompressible turbulent flow. Firstly, the drag reduction by the opposition control based on active dimples/pimples at the lower wall is studied via the direct numerical simulation of the turbulent channel flow. It is found that large active dimples/pimples can not suppress the streamwise vortices significantly and thus almost no drag reduction is achieved. Small active dimples and pimples with the diameter of one fourth of the streak width can both reduce the friction drag, but pimples will induce a larger pressure drag than dimples. Then the suboptimal control scheme is examined based on small active dimples using the spanwise wall shear information only. It is shown that the friction drag decreases by about 4.5% but the total drag is only reduced by about 2.7% abated by the pressure drag. Compared with the actuation of the all-point blowing/suction or the all-point wall movement, the effectiveness of the turbulent drag reduction based on active shallow dimples is much smaller.

**Key words:** Turbulent drag reduction, active dimple, opposition control, suboptimal control

## Introduction

Generally, the turbulent friction drag contributes a large proportion of the total drag for the vehicles moving in the fluid. For the conventional ships or the aircraft under the cruising state, the turbulent frictional drag can attribute 50% of the total drag, while for the torpedoes, the submarines and other underwater vehicles, the ratio can be as high as 70%. The issue of high friction of the turbulence is also encountered in other engineering applications, such as the high-speed train and the pipeline. Studies show that for a transport aircraft, if the total drag is reduced by 10 percent, $3 billion's fuel might be saved in a year for the U.S. airline industry. For an underwater vehicle, under a certain power and energy condition, if the resistance is reduced by 10%, its cruising speed and range can increase approximately by 3.75%[1]. Therefore, the study of the turbulent drag reduction is very important, especially in the modern society with problems of growing energy shortage and environmental pollution.

In view of the convenience of the application, many passive control methods were proposed, such as the bio-inspired riblets, the compliant wall, and the superhydrophobic surfaces[2,3]. But most of the passive control techniques have quite limited effects. Hence, the active turbulent drag reduction becomes a new research focus aiming to improve the situation. The discovery of the coherent structures near the wall makes a theoretical breakthrough for the turbulent drag reduction, which may serve as a theoretical guidance for the turbulence control design and application. Based on the close relationship between the near-wall coherent structures and the high skin-friction in the wall turbulence[4], many active drag-reduction control schemes were developed by instantaneously interfering with the evolution of the near-wall coherent structures. Based on the physical model of streamwise vortices, Choi et al.[5] proposed the opposition control by app-

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lying the reverse blowing/suction on the wall to inhibit the vortices on both sides of the ejection and sweep, reducing the strength of the vortices with a considerable drag reduction. With regard to the exciting effect on the drag reduction, various control schemes were proposed[6-8]. However, this kind of control is unpractical in real applications since the information of the flow field is required, which is hard to be measured. With the opposition control in mind, Lee et al.[9] developed a so called suboptimal control scheme by optimizing a cost function in a single time step based on the wall pressure and the spanwise wall friction. Many other control schemes were also developed, as reviewed by Kim[4] and Kasagi et al.[10].

In recent years, the development of the microelectromechanical systems (MEMS) technology provides us with the possibility for the practical application of the active turbulence control[10]. Using the technology of MEMS, the "smart skin" for drag reduction shows very good prospects[11,12]. As an excellent candidate for the shape of MEMS, the flow over dimples/pimples has drawn more and more attentions in the flow controls in recent years[13,14]. But most of studies only focus on the heat exchange enhancement and the flow structures induced by static dimples. Through experimental measurements of turbulent flows over surfaces with a regular arrangement of static shallow dimples, Alekseev el al.[15] pointed out that the shallow dimples can lead to a decrease of the skin-friction up to 20% apart from the heat-transfer enhancement. However, a reverse conclusion was made by Lienhart et al.[16] through the investigation via both simulation and experiment for the same arrangement as that employed by Alekseev et al.. With complementary evidence, they pointed out that the shallow dimples on a flat surface does not lead to drag reduction but rather to a slight total drag increase. After that, the flow structures over a static dimple were studied by Ge et al.[13] in detail via direct numerical simulations and a slight total drag increase was observed by Lienhart et al.[16]. The active dimples on the wall were first used for drag reduction in the incompressible flow by Yang et al.[17] based on both the opposition control and the suboptimal control scheme, achieving drag reductions of about 12% and 11.4%, respectively. However, the result seems a little encouraging since the deformation of the dimple is approximately represented by a disturbing velocity. To clarify the effectiveness of the active pimples/dimples for the turbulence drag reduction, the direct numerical simulation is carried out to study the turbulent flow over the active dimples/pimples in the present paper. Different arrangements of the dimples/pimples are studied by the opposition control to find the suitable diameter of the dimples/pimples to achieve better drag reduction. Then, the suboptimal control scheme based on small active dimples is investigated in detail.

## 1. Numerical method

As many previous studies in the field of turbulent drag reduction, the turbulent channel flow is adopted as a research objective in the present study. The Navier-Stokes equation and the continuity equation for the incompressible Newtonian fluid are taken as the governing equations:

$$\frac{\partial u_i}{\partial t} = F_i - \frac{\partial \Pi}{\partial x_i} + \frac{1}{Re}\frac{\partial^2 u_i}{\partial x_j \partial x_j} \tag{1}$$

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{2}$$

where $F_i$ is the $i$-th component of the Lamb vector, $\Pi$ is the total pressure. The equations are non-dimensionalized by the half channel width $H$ and the bulk mean velocity $U_m$. Hence the Reynolds number can be expressed as $Re = U_m H / \nu$, where $\nu$ is the kinetic viscosity of the fluids. All variables below are scaled by $\rho$, $U_m$ and $H$. Hence, the drag, the time and other parameters in the following discussions are all nondimensionalized quantities. In the streamwise ($x$ or $x_1$) and spanwise ($z$ or $x_3$) directions, the flow is assumed periodic. In the wall normal direction ($y$ or $x_2$), the no-slip condition is imposed at the walls.

For a channel with active dimples/pimples on the wall, the wall geometry is time-dependent and complex. Let the upper and lower walls are located at $y = 1+\eta_u$ and $y = -1+\eta_d$, where $\eta_u = \eta_u(x,z,t)$ and $\eta_d = \eta_d(x,z,t)$ represent the amount of deformation at the corresponding walls, respectively. The computational coordinate system $\xi_i$ and $\tau$ is defined as:

$$t = \tau,\quad x_1 = \xi_1,\quad x_2 = \xi_2(1+\eta) + \eta_0,\quad x_3 = \xi_3 \tag{3}$$

in which $\eta = (\eta_u - \eta_d)/2$, and $\eta_0 = (\eta_u + \eta_d)/2$. Using the above equation, the physical space with complex and time-dependent walls is then transformed to a time-independent rectangular computational space. In the computational space, the upper and lower walls are located at $\xi_2 = 1$ and $\xi_2 = -1$, and the no-slip conditions at the walls can be written as

$$\xi_2 = -1:\quad u = 0,\quad v = \frac{\partial \eta_d}{\partial t},\quad w = 0 \tag{4}$$

$$\xi_2 = 1:\quad u = 0,\quad v = \frac{\partial \eta_u}{\partial t},\quad w = 0 \tag{5}$$

By the above coordinate transform, the temporal and spatial derivatives can be represented by