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TURBULENT DRAG REDUCTION USING SPANWISE FORCING IN COMPRESSIBLE REGIME

F. Gattere, A. Chiarini, M. Zanolini
Dip. Scienze e Tecnologie Aerospaziali, Politecnico di Milano, 20156 Milano, Italy

D. Gatti
Institute for Fluid Mechanics, Karlsruhe Institute of Technology, 76131 Karlsruhe, Germany

M. Bernardini
Dip. di Ingegneria Meccanica e Aerospaziale, Roma La Sapienza Univ, 00184 Roma, Italy

M. Quadrio
Dip. Scienze e Tecnologie Aerospaziali, Politecnico di Milano, 20156 Milano, Italy

ABSTRACT

This work addresses the natural extension of streamwise travelling waves of spanwise velocity to the compressible subsonic and supersonic regime. Three values of the bulk Mach number $M_b = 0.3, 0.8$ and 1.5 are investigated with a set of 252 direct numerical simulations (DNS) at friction Reynolds number of $Re_\tau = 200$ and $Re_\tau = 400$. The maximum drag reduction is found to increase with the Mach number. For a supersonic flow the maximum drag reduction occurs at larger frequencies and larger wavenumbers compared to the incompressible data. In the limit of oscillating wall, however, the opposite trend is observed, with the peak moving towards lower frequencies as the Mach number increases, confirming the results of other authors.

BACKGROUND

Drag reduction strategies can be classified into two categories, namely passive and active. The former usually needs a deformation of the surface of the wall without the need for energy supply. Among passive technologies, riblets are the closest to be implemented in practical applications. Laboratory tests showed that they can reduce drag up to 8%, but they have the main drawback of needing continuous maintenance. Among active strategies, the ones concerning the motion of the walls are the most promising. This work focuses on the technique of the streamwise travelling waves of spanwise velocity [5] defined by the spanwise velocity forcing at the wall $w_w(x,t) = A\sin(\kappa_x x - \omega t)$, where A is the amplitude, κ_x is the wavenumber and ω is the frequency, which define the wavelength $\lambda_x = 2\pi/\kappa_x$ and the period of the oscillation $T = 2\pi/\omega$. The spanwise oscillating wall [3] and the stationary wave [6] can be considered as two limit cases of these travelling waves when $\kappa_x = 0$ and $\omega = 0$, respectively. The numerical experiments of [5] in an incompressible turbulent channel flow at $Re_\tau = 200$ showed a maximum drag reduction of 48% in correspondence of a net power saving of 17% for $A^+ = 12$; the + superscript indicates wall units.

To estimate the real potential of skin friction drag reduction via spanwise wall oscillation in real applications it is of paramount importance to take into account the effects of compressibility. Recently, [7] carried out a DNS study of a compressible channel flow subjected to spanwise oscillating walls ($\kappa_x = 0$) at Mach number $M_b = 0.3, 0.8$ and 1.5, $Re_\tau = 200$, $A^+ = 12$ and $T^+ = 25 - 300$. The drag reduction rate was found to increase with the Mach number and the optimum period to shift toward higher values with respect to incompressible data. The higher Mach simulations, however, led to an anomalous monotonic increase of DR with frequency, which required further investigations for different Reynolds numbers and domain sizes. This particular behaviour was found to depend on low Reynolds effect and relaminarization problems, which can be produced by a too small domain for a given value of Re_τ, or to an excessive value of Re_τ for a given domain.

The present work is the first comprehensive extension of the streamwise travelling waves drag reduction technique to the compressible regime for both $\kappa_x \neq 0$ and $\omega \neq 0$. [4] already performed a direct numerical simulation of streamwise travelling waves on the surface of an airfoil in transonic regime, investigating the effect of the actuation on the aerodynamic forces. However, a parametric study to assess the dependence of the Mach number on the drag reduction performances still lacks. In this work we aim to fully characterise the dependence of both the drag reduction rate and the power budgets on the Mach number varying the parameters of the travelling wave applied to the wall of a fully developed turbulent channel flow.

METHODS

A database of direct numerical simulations is computed for this analysis using STREAmS (Supersonic TuRbulEnt Accelerated Navier–Stokes Solver), a high-fidelity solver for large-scale simulations of compressible turbulent wall-bounded flows developed by [1]. Three sets of simulations at different values of the bulk Mach number $M_b = 0.3, 0.8$ and 1.5 are performed to assess the effects of the compressibility on the behaviour of a fully developed turbulent channel flow subjected to streamwise travelling waves of spanwise oscillation. For all cases the Prandtl number is set to $Pr = 0.72$. For each value of the imposed bulk Mach number, two sets of direct numerical simulations are performed, with initial friction Reynolds numbers $Re_\tau = u_\tau h/\nu$ set at $Re_\tau = 200$ and $Re_\tau = 400$; here u_τ is the friction velocity, h is the channel semi-height and ν is the kinematic viscosity. For each one of the six sets of simulations described above, a single uncontrolled and 42 controlled simulations have been performed. The wave amplitude

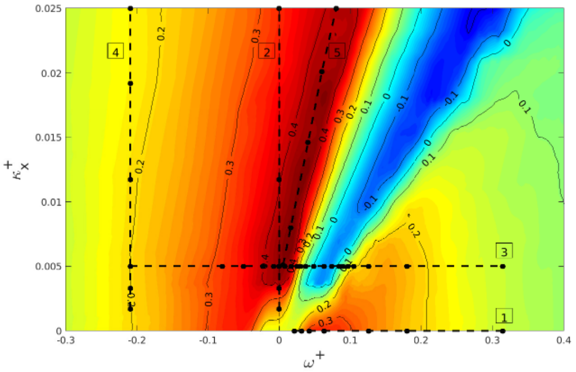

Figure 1: Control map of the drag reduction rate DR (adapted from [5]). The dashed lines are the investigated regions and the black dots correspond to the actual simulations.

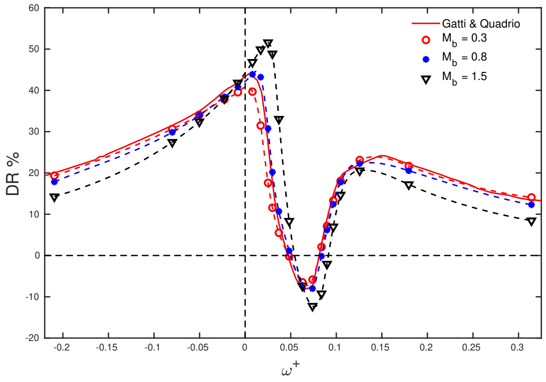

Figure 2: Percentage of DR versus frequency ω^+ for the streamwise-travelling waves at $A^+ = 12$ and $\kappa_x^+ = 0.005$ (line 3) for $Re_\tau = 400$. The red solid line represents the incompressible reference data [2].

is fixed at $A^+ = A/u_\tau = 12$, while different combinations of the (ω, κ_x) values are selected. Figure 1 reports the DR map for the incompressible regime, where the control parameters of each simulations (black dots) are chosen. The dashed line 1 refers to the oscillating wall case with $\kappa_x = 0$, while the dashed line 2 to the steady wave with $\omega = 0$. Line 3 considers a constant wavelength and sets $\kappa_x^+ = 0.005$. Line 4 investigates the area of low drag reduction and fixes the oscillating frequency at $\omega^+ = -0.21$. Finally, line 5 analyses the optimum ridge for drag reduction. The size of the computational domain is $(L_x, L_y, L_z) = (6\pi h, 2h, 2\pi h)$ in the streamwise, wall-normal and spanwise directions. For the $Re_\tau = 400$ cases the number of mesh points in the three directions is $N_x = 768$, $N_y = 258$, $N_z = 528$ for the subsonic regime and $N_x = 1024$, $Ny = 258$, $Nz = 512$ for the supersonic regime. For $Re_\tau = 200$, instead, half the number of points is used in each direction. In wall units this corresponds to a mesh spacing of $\Delta x^+ = 9.8$, $\Delta y^+ = 0.51 - 6.35$, $\Delta z^+ = 4.8$ and $\Delta x^+ = 7.4$, $\Delta y^+ = 0.50 - 6.19$, $\Delta z^+ = 4.9$.

RESULTS

As an example figure 2 shows of the effect of the M_b numbers along line 3 in figure 1 for $Re_\tau = 400$ and investigates the effect of compressibility in regions of the (κ_x, ω) map where both drag reduction (DR) and drag increase (DI) may occur.

The DR trend for low compressible regime is in good agreement with [2], with a non-negligible mismatch only for $\omega^+ \approx 0$. Compressibility shows two main positive effects on the drag reduction performance of the travelling waves. First, the DR increases between slightly small negative value of ω and $\omega^+ \approx 0.05$, whereas decreases elsewhere. This is a promising result since it outlines an improvement in the drag reduction for increasing M_b precisely in the region of interest of the control map, i.e. near the peak, while the performance worsens in the regions of minor interest. Second, the global peak shifts at larger ω^+, whereas the second positive peak shifts at smaller ω^+, shrinking the DI zone and consequently, widening the values of frequency for which the control is effective. However, the DI peak also shows increasing negative values with increasing M_b and it shifts towards larger ω^+. Overall, for the low and moderate Mach number, the drag reduction peak occurs for an oscillation frequency of $\omega^+ = 0.008$ and reads $DR_{max} = 40\%$ and $DR_{max} = 44\%$ for $M_b = 0.3$ and $M_b = 0.8$ respectively. For the supersonic regime, instead, the peak occurs at higher frequency, i.e. $\omega^+ = 0.025$ and for $M_b = 1.5$ reaches the large value of $DR_{max} = 52\%$.

In the case of active control, information about the drag reduction is not sufficient to fully assess the efficiency of a technique, being also the energy expenditure to control the flow a parameter to be considered. Therefore, the balance between the cost, i.e. the energy injected to the system to move the walls, and the benefits, i.e. the reduction of the skin friction drag, has to be examined. Generally the cost to control the flow $|P_{in}|$ decreases with increasing values of the Mach number, thus compressibility shows a positive effect also on the energy expenditure and this effect is larger for increasing values of the control frequency.

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