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DIRECT NUMERICAL SIMULATIONS OF A TRANSONIC AIRFOIL WITH SPANWISE FORCING FOR DRAG REDUCTION

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ABSTRACT

Spanwise forcing at the wall in the form of streamwise-travelling waves is applied to the suction side of a transonic wing to reduce its aerodynamic drag. The study, carried out with direct numerical simulations (DNS), extends our previous results [2], also presented at the last EDRFCM in Paris, and shows that shifting the shock wave downstream is key to enhancing the global aerodynamic efficiency and to reducing the overall drag. An extensive parameter study discusses analogies and differences with the incompressible plane case, provides quantitative metrics for the effectiveness of the forcing, and for the first time describes how the interaction between the shock wave and the turbulent boundary layer is modified by the control. It is found that, when the suction-side shock is delayed, the size of the ensuing separation correlates well with the reduction in skin friction. Moreover, the observation of the transient after the sudden application of control brings to light the key physical effects of the control.

BACKGROUND

The potential of spanwise forcing for reducing turbulent skin-friction drag in aeronautical application has received so far little attention: despite the large drag reduction rates predicted by DNS in plane incompressible plane channel and pipe flow [5], so far few studies explored realistic flows featuring non-planar geometries and compressibility effects. At EDRFCM 2022 we presented [3, 2] the first DNS of spanwise forcing via streamwise-travelling waves (StTW) of spanwise velocity [4] applied on a transonic wing with a shock on the suction side. Changes in position and intensity of the shock alters the aerodynamic performances of the wing significantly. In particular, the aerodynamic efficiency of the profile was improved. We estimated a 9% net reduction of the total aerodynamic drag on an entire aircraft when the angle of attack is reduced to retrieve the original lift. This seminal work only tested two quite similar configurations, whose control parameters were deduced from incompressible information; the extent and position of the surface area where the forcing is applied were just guessed. Moreover, an in-depth analysis of the physics behind the control-induced changes to the flow was lacking. The present work extends our previous study by addressing two goals. The first one is to explore the parameter space of the forcing variables together with the position and extent of the controlled region, such that analogies with the incompressible plane channel flow can be identified and discussed in terms of drag reduction and power budget. The second goal, instead, lies in understanding the link between control parameters and flow physics, to arrive at the description of how the streamwise-travelling waves, and the forcing in general, affect the complex physics of the shock/turbulent boundary layer interaction.

NUMERICAL METHODS

This work consists in DNS of the airflow around a transonic wing slab. The section profile is a supercritical airfoil, and the flow field is discretized with a mesh consisting of 536×10^6 grid points and complying with the requirements for fully-resolved turbulent scales. The compressible Navier–Stokes equations for a calorically perfect gas are solved with a second-order, energy-consistent finite-volumes numerical code [1]; the inflow is laminar, and turbulence is tripped numerically at 10% of the chord downstream of the leading edge on both sides of the wing. The flow features steady conditions of Mach number $Ma_\infty = 0.7$, chord-based Reynolds number $Re_\infty = 3 \times 10^5$, and angle of attack $\alpha = 4^\circ$, the latter corresponding to the angle of maximum aerodynamic efficiency of the wing. Flow control is applied on a portion of the suction side of the wing, and is achieved via StTW, an active technique in which the spanwise velocity component at the wall evolves according to:

$$W_w(x,t) = A \sin\left(\kappa_x x - \omega t\right)$$

where A is the forcing amplitude, and κ_x, ω are the spatial and temporal frequencies of the forcing, respectively. Two additional control parameters are represented by the beginning and end position of the actuated surface on the suction side of the wing (x_b, x_e, respectively). One simulation reproduces the reference uncontrolled scenario, while the space of the parameters is explored via 26 DNS in which all the control variables are modified at a constant angle of attack. Two additional simulations reproduce a controlled and an uncontrolled scenario at a reduced angle of attack ($\alpha = 3.45°$).

RESULTS

The aerodynamic coefficients of the airfoil are modified as a consequence of the changes in the wall stresses induced by the application of StTW. The aerodynamic efficiency is defined as $E = C_L/C_D$, where C_L, C_D are the lift and drag coefficients, respectively. The percentage changes of these variables, together with the one of the pitching moment $C_{m,TE}$ at the trailing edge, are plotted in Figure 1. E generally increases by approximately 10%, with the exception of one case, where StTW cause drag increase and efficiency decrease. Interestingly, the drag coefficient of the wing changes little as a consequence of the friction-reducing control, and sometimes even increases ($\Delta C_D > 0$). Clearly, changes in the efficiency are primarily related to enhanced values of C_L; the same can be observed for the pitching moment with respect to the trailing edge ($C_{m,TE}$), which is mostly built on normal stresses.

These changes descend from the shift of the shock towards the trailing edge; a second effect is its intensification, which consequently affects the shock/turbulent boundary layer interaction. This has major consequences on the flow. Figure 2 shows a detail of the friction coefficient C_f in the region of its local minimum. When StTW are effective, a major decrease of C_f is observed before the shock. The increased adverse longitudinal pressure gradient is however transmitted without changes across the boundary layer, and the slower near-wall flow becomes more prone to separation. The curves are colored according to the skin-friction drag reduction $\Delta C_f = 1 - C_f/C_{f,0}$ extracted at $x/c = 0.4$ on the suction side of the wing (the '0' subscript denoting the reference uncontrolled simulation), and show that cases with small ΔC_f have minimal or no separation. One drag-increasing case, instead, presents a globally increased friction coefficient. A comparison with data from the incompressible channel flow confirms that StTW yield analogous effects on C_f on the transonic wing. We found that, when present, the size of the separated region correlates well with ΔC_f. Furthermore, from the analysis of the temporal transients ensuing after the activation of control, we deduced that the presence of recirculation is a consequence of the modified position of the shock, and not a direct effect of the application of StTW.

Deciding position and extent of the actuated portion of the suction side represents a non-trivial problem, where the increase in aerodynamic efficiency should be maximized by limiting as much as possible the power consumption of the forcing. We tested different configurations changing x_b, x_e, and found that withdrawing the control from the post-shock region has positive consequences, while delaying the beginning of the actuation has detrimental effects on the performances of the wing.

With the two simulations performed at $\alpha = 3.45°$, a reduced incidence chosen for the controlled wing to produce the same lift of the reference wing, we estimated a total reduction in the aerodynamic drag of a full aircraft equal to 12.5%. This is a huge figure, and its value has to be appreciated also in view of the negligible power cost when compared to the power required for cruise fight.

At the Meeting, we will also compare StTW as applied to the plane channel flow and to the transonic wing, as a function of the control input. We will provide a first description of how the classical transonic shock wave/turbulent boundary layer interaction is altered by the control, and how the topology of the shock system is affected by the reduced levels of friction brought about by the spanwise forcing.

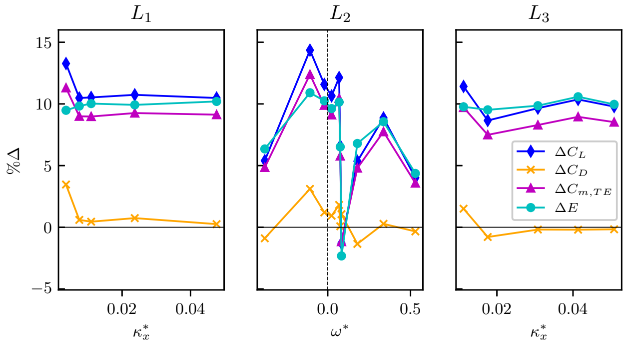

Figure 1: Percentage changes of lift, drag, trailing edge pitching moment and aerodynamic efficiency.

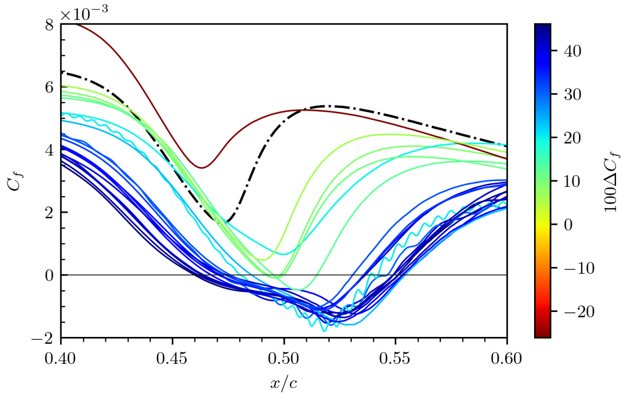

Figure 2: Friction coefficient C_f: zoom at its local minimum on the suction side. The dashed line is the reference uncontrolled case. The value of ΔC_f is encoded in the line color.

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