TURBULENT DRAG REDUCTION USING WALL JETS AT FLIGHT SCALE REYNOLDS NUMBER

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Abstract Numerical experiments have been performed for modelling turbulent drag reduction due to active-control of wall jets using a linearised Navier-Stokes model in a turbulent boundary layer formed over a flat plate at $Re_\tau = 905$ corresponding to flight scale $Re_x = 10^6$. Its effect have been seen on transient growth of near-wall streaks and production of turbulent kinetic energy (TKE).Two sets, one corresponding to span wise slot and other corresponding to wall jets along the whole plate have been performed. Simulations are performed by varying magnitude of wall jets, its angle & locations and based on a measure of TKE, reduction in stream wise turbulent kinetic energy is recorded.

GOVERNING EQUATIONS AND MODELLING OF CONTROL

Numerical experiments have been performed to investigate, the effect of wall jets on the transient growth of near-wall turbulent streaks & stream wise turbulent kinetic energy,using a linearised Navier-Stokes (LNS) model. Governing equations in non-dimensionalized form of LNS equations, are expressed as:

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial u_i}{\partial t} + \bar{U}_j \frac{\partial u_i}{\partial x_j} + u_j \frac{\partial \bar{U}_i}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{1}{Re_\tau}(\frac{\partial^2 u_i}{\partial x_j \partial x_j}) + \tilde{f}_i \tag{2}$$

where, $\tilde{f}_i$ $(= f_i\hat{i} + f_j\hat{j} + f_k\hat{k})$ represents a forcing term which actually models the non-linear terms of the Navier-Stokes equations. For modelling the non-linear source-term, Low-Order Model (LOM) approach proposed by Lockerby et al.[1] is used.The forcing term used in current study emulates a localised Gaussian vorticity source such that the different components of non-linear body force field are given by $\tilde{f}_x = 0, \tilde{f}_y = 0, \tilde{f}_z = Gz^2\cos(\beta y)e^{-a(x-x_f)^2-b(z-z_f)^2}$. The forcing term is applied with $\beta = 0.05Re_\tau$ at $x_f = 1.014$. In the current study the other parameters of forcing terms are chosen such, to yield 9 to 10 pairs of high and low-speed streaks that decay to 5% of the maximum u' as they reach the outflow boundary.As the wall jets generate both span wise and wall normal velocities, depending on the inclination angle (θ) of the jet, they create base flow field of both span wise $(\bar{V})$and wall normal $(\bar{W})$ velocities. The governing equations for the applied control, can be expressed as given below:

$$\frac{\partial \bar{V}}{\partial t} + \bar{U}\frac{\partial \bar{V}}{\partial x} + \bar{V}\frac{\partial \bar{V}}{\partial y} + \bar{W}\frac{\partial \bar{V}}{\partial z} = \frac{1}{Re_\tau}(\frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} + \frac{\partial \bar{V}}{\partial z^2}) \tag{3}$$

$$\frac{\partial \bar{W}}{\partial t} + \bar{U}\frac{\partial \bar{W}}{\partial x} + \bar{V}\frac{\partial \bar{W}}{\partial y} + \bar{W}\frac{\partial \bar{W}}{\partial z} = \frac{1}{Re_\tau}(\frac{\partial^2 W}{\partial x^2} + \frac{\partial^2 W}{\partial y^2} + \frac{\partial \bar{W}}{\partial z^2}) \tag{4}$$

which is subject to farfield at the top-wall while at the bottom-wall it is subject to $\bar{V} = V_{abs}\cos\theta$, $\bar{W} = V_{abs}\sin\theta$. At inlet all perturbations are zero and at outflow the second derivatives are made zero. The governing equations of the mean velocities of the applied control were solved simultaneously with LNS equations. For LNS equations, at inlet $u_i = 0$, at Outflow $\frac{\partial^2 u_i}{\partial x^2} = 0$, at flat plate no-slip and for top farfield Boundary conditions($\frac{\partial^2 u_i}{\partial z^2} = 0$) are taken. Modified SMAC scheme is used which is a two-step semi-implicit pressure-correction based algorithm on collocated mesh. A rectangular domain of $4\pi\delta$ in stream-wise, $0.4\pi\delta$ in span-wise, and 5δ in wall-normal direction with 201 grid points in stream-wise 81 grid points in span-wise direction and non-uniform grid points in wall-normal direction.

In order to quantify the spatio-temporal response of the LNS equations on application of control, we computed the stream wise turbulent kinetic energy of the near-wall streaks E_v, which is similar to the method proposed by Chernyshenko and Baig [2].

$$E_v(x, y, z = a, t) = \int_0^{L_x}\int_0^{L_y} u^2(t)|_{z^+=a}dxdy \tag{5}$$

where L_x and L_y denote the maximum domain lengths of the channel in x and y directions, respectively, while $z^+ = a$ denotes the respective wall-normal plane at which the E_v has been computed. A measure $\mu = \int E_v dt$ was then

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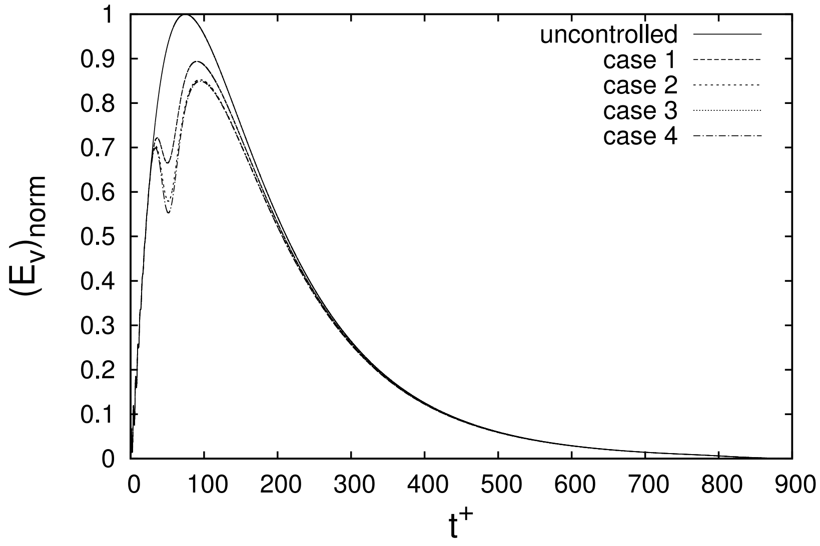

Figure 1. Variation of E_v, for controlled and uncontrolled cases, with t^+.

Case	Wall-jets	V_{abs}	ϵ
1	Constant Amplitude	2	6.72
2	Constant Amplitude	4	9.61
3	Random Amplitude	2-4	6.72
4	Oscillatory Amplitude	0-4	10.03

Table 1. ϵ for all cases of set 1

Case	θ (in degrees)	ϵ
1	10	38.88
2	30	65.96
3	50	72.92
4	80	75.71

Table 2. ϵ for all cases of set 2

evaluated by numerical integration using trapezoidal-integration scheme in order to find the growth/reduction of stream-wise TKE vis-a-vis uncontrolled flow. A percentage change of μ was computed at different wall-normal planes using the mathematical expression:

$$\epsilon|_{z^+=a} = \frac{\mu_{uncontrolled} - \mu_{controlled}}{\mu_{uncontrolled}} \times 100\% \tag{6}$$

ϵ is,therefore a measure of percent amplification of stream-wise TKE due to the application of control in comparison to the uncontrolled flow.

RESULTS AND DISCUSSIONS

Two sets of simulations were performed. In first set, a span-wise slot was taken from which jets were issued. We have run simulations by varying the Amplitude (V_{abs}) and angle of jets (θ). In second set, wall jets were issued from the whole bottom plate. In set one, four cases were run. In case 1, constant $V_{abs} = 2$ is used, for case 2 constant $V_{abs} = 4$ is used, for case 3, V_{abs} is randomly varied between 2-4 while in case 4, Oscillatory V_{abs} ($\omega = 50$), varying between 0-4 is considered. For all cases $\theta = 50°$ & $x_c = 1.5$ kept fixed. Figure 1 shows the temporal response of $(E_v)_{z^+=5}$, where E_v is normalized with the maximum kinetic energy for the uncontrolled case. From this figure, we see that decrease is recorded in the E_v. ϵ for all cases of set 1 are reported in Table 1 and it is seen that a maximum of 10% reduction in TKE vis-a-vis uncontrolled case is recorded for case 4.

In set two, we have run cases by changing θ from $10°$ to $80°$, for wall jets issuing all along the flat plate. For all cases V_{abs} have been random, varying between 2 to 4. Table 2 shows much higher reduction in TKE as we changed angle of jets from $10°$ to $80°$.

References

[1] D.A Lockerby, P.W Carpenter, & C Davies. Control of sublayer streaks using microjet actuators. *AIAAJ* **43**: 1878-1836,2005.

[2] S.I Chernyshenko & M.F Baig. The mechanism of streak formation in near-wall formation in near-wall turbulence. *Journal of Fluid Mechanics* **544**: 99-131, 2005