NUMERICAL INVESTIGATION OF THE EFFECT OF APPROACHING WIND DIRECTION ON SPEED-UP IN TURBULENT FLOW OVER A FORWARD-FACING RAMP

Xie Delia Fang, Blackburn Hugh & Sheridan John
Department of Mechanical & Aerospace Engineering, Monash University, Victoria, Australia

Abstract Turbulent flows over a forward-facing ramp (FFR) were investigated using numerical methods. The present direct numerical simulations (DNS) were conducted under conditions with approaching wind directions from 0° to 45° in order to examine the effect of approaching wind direction on speed-up. A spatially developed turbulent inflow was generated by applying a *recycled boundary condition*. Reynolds number is 2000, based on ramp height and bulk streamwise velocity of the oncoming flow, and the ramp is assumed to be infinitely extended in the spanwise direction. DNS results show quantitative turbulent statistics and structures of boundary layers over a FFR.

BACKGROUND

One of the key features of flow over complex terrain is local "speed-up". Despite significant efforts made in the past to understand turbulent flow over a complex terrain [2, 1, 6, 3, 4], few investigations have dealt with a yawed flow. There are two main reasons for this: first, until very recently, the nature of separated turbulent flow in general is complicated enough to be fully understood; second, though the current speed-up models could be extended to include wind direction effects, wind tunnel tests failed accurately predicting the speed-up owing to influence of end effects. Therefore, this research proposed an investigation of turbulent flow over a two-dimensional FFR using numerical methods. The motivation of this paper was to access a better understanding of flow features by topographical effect. An equally important aspect was to investigate yaw effects on speed-up feature.

METHODS

The governing equations used in the DNS are the incompressible Navier–Stokes equation without buoyancy terms. Body force per unit mass is introduced so that flow rate will be constant or oscillate around the defined level. By prescribing a spanwise body force we could introduce a spanwise flow, thus achieve a yawed inflow.

The present DNS based on the spectral element method is carried out under conditions of constant Reynolds numbers based on the free stream component normal to the ramp, U_∞ and the height of the ramp, H. The detailed computational conditions are indicated in Table 1, which includes the Reynolds numbers and domain information. Figure 1 presents the two-dimensional outline of the element mesh and the close-up on the area near the ramp along with a schematic of the *recycled boundary condition*. Non-uniform grids around the ramp are arranged in streamwise and wall-normal directions so as to adequately capture turbulent motions. The boundary conditions for the velocity field are the non-slip conditions on the walls, and free stream on the upper boundary. A special kind of boundary condition is prescribed at the inlet of the domain to generate a spatially developed turbulent inflow without the need for a separate development section. It is a variation of the method for generation of turbulent inflows proposed by Lund [5], here is referred to as a *recycled boundary condition*. Periodicity is assumed in the spanwise direction.

Re_τ	10000
Re_H	2000
ramp slope	45°
domain size ($x \times y \times z$)	$40H \times 5H \times 2\pi H$
yaw angles(α)	0°, 15°, 30°, 45°

Table 1. Computational conditions.

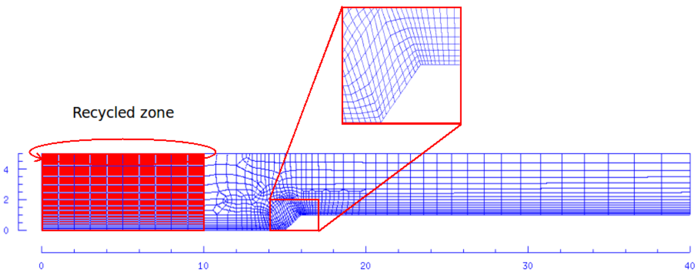


Figure 1. Two-dimensional FFR quadrilateral element mesh with recycling zone.

RESULTS

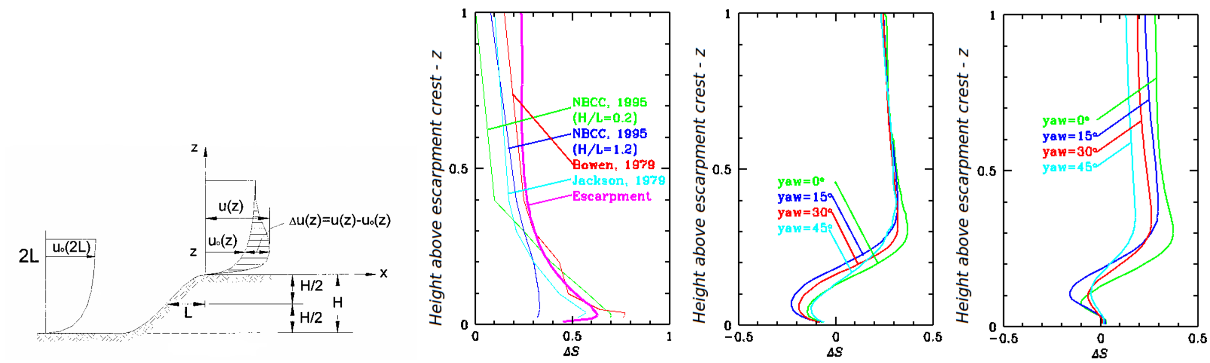
The averaged fields have been analyzed to identify the main flow features. The speed-up factor, ΔS, given by the equation of $\Delta S = [\Delta u(z)L]/[u_0(2L)H]$, enables us to compare our results to those in the literature [1]. In these expressions H

represents the height of the ramp, L represents the horizontal distance from the crest to where the ground elevation is half the height of the ramp, $\Delta u(z)$ represents increase in velocity, i.e., $u(z) - u_0(z)$ at height z above the local ramp surface, $u_0(2L)$ represent upstream reference velocity at the height $2L$ above the ground respectively, similarly $u_0(z)$ represent upstream reference velocity at height z above the ground respectively, Figure 2(a).

Figure 2(b) compares our results with typical results used in Bitsuamlak's review paper [1]. The mean velocities remarkable accelerate on the edge due to surface elevation. For different geometries of escarpments ($H/L = 0.2$ to 1.2), normalized speed-up factors from literature and our results are fairly similar. Note that speed-up factors from previous studies tend to neutralize further away the surface. However our results show minor decline due to the blockage ratio of 0.2 downstream.

Figure 2(c) represents normalized speed-up values normal to the edge at $1H$ downstream of the edge. By comparing four different yawed flows, we found that streamwise mean velocity of all cases have reverse flow regions, i.e. $\Delta S < 0$, indicating re-circulation zones. Velocity profiles at $y \geq 0.5$ are nearly identical for all yaw angles, indicating that the sweep-independence principle holds. Profiles for flow near the surface $y \leq 0.5$ begin to deviate, indicating that near-wall speed-up factor are influenced by the tangential wall frictions. We also found that flows without yaw angle give maximum speed-up ratio near the wall.

A comparison of speed-up factors along inflow direction is plotted in Figure 2(d). Again, speed-up factors without yaw angle are the highest($\Delta S = 0.37$ at $z = 0.31$)). However the sweep-independence principle no longer holds here as ΔS decreases with increasing yaw angles.



(a) (b) (c) (d)

Figure 2. (a) definitions of parameters for calculations of normalized speed-up ratio; (b) normalized speed-up ratio and typical results from literature [1]; (c) dimensionless velocity speed-up factors, normal to the edge, at $1H$ downstream with yaw angle $0°$, $15°$, $30°$ and $45°$; (d) dimensionless velocity speed-up factors, along the inflow, at $1H$ downstream with yaw angle $0°$, $15°$, $30°$ and $45°$;

CONCLUSIONS

We have investigated the yawed turbulent flow over a ramp at $Re_H = 2000$ with the emphasis on isolating influence of yaw. Flow in the ramp-normal direction shows decrease trends if profiles of speed-up are compared at the same normalized position with increasing yaw angle. Flows without yaw angle give maximum speed-up ratio near the wall. At a certain height above the ramp, the streamwise speed-up shows approximate collapse.

References

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