# SECONDARY FLOWS IN BOUNDARY LAYERS OVER STREAMWISE-ALIGNED WALL-ROUGHNESS

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*Abstract* The cause of recently observed spanwise-alternating low- and high-momentum pathways [1,2,3] to appear across the entire turbulent boundary layer formed over rough surfaces is experimentally investigated by measuring the flows over roughness elements with systematically varied spanwise spacing. We found that the secondary flows associated with these low- and high-momentum pathways only appeared when the spanwise spacing of roughness elements was roughly proportional to the boundary layer thickness, and did not appear for cases with spacing much less than the boundary layer height. This suggests that the ratio of the spanwise spacing to the boundary layer thickness, as opposed to the roughness height (or width), is the most important parameter to predict the occurrence of these secondary motions in turbulent boundary layers over rough walls.

## Introduction

Surface roughness can have a dramatic effect on the dynamics of turbulent boundary layers. Recently, it has been observed that large secondary vortices can form naturally over surfaces with irregular surfaces roughness [1]. These secondary motions are associated with low- and high-momentum pathways that extend across the entire thickness of the boundary layer, which can enhance mixing throughout the boundary layer [2]. Subsequent studies over idealised roughness patterns having spanwise transitions demonstrated that these secondary vortices can be attributed to the spanwise inhomogeneity in the surface topology and furthermore, that the secondary vortices were not particularly sensistive to the roughness height, but had some sensitivity to the width of the roughness elements. We intend to investigate the sensitivity of these secondary vortices on the spacing of the roughness strips, and hypothesize that these vortices only form when the spacing of roughness elements is comparable to the boundary layer thickness. To test this idea, we measured the flow field over five systematically defined surfaces having strips of roughness elements with increasing spacing.

## Experimental Procedures

Experiments were performed in the University of Southampton's 3'x2' windtunnel using LEGO pieces to form the roughness elements, similar to previous experiments in the same facility [4]. In this study, stripes of LEGO bricks having a width of $W = 15.8$ mm and height of $H = 9.6$ mm were aligned with the flow direction and extended over the full 4.5 m length of the windtunnel test section (see fig. 1). The spacing of the strips, S, was varied to have ratios of $S/W = 1, 2, 5, 7,$ and $11$. In all cases the freestream velocity was set to 15 m/s and the boundary layer that formed had a thickness of $\delta/H \approx 9.7 \pm 0.3$ and displacement thickness of $\delta^*/H \approx 2.7 \pm 0.1$.

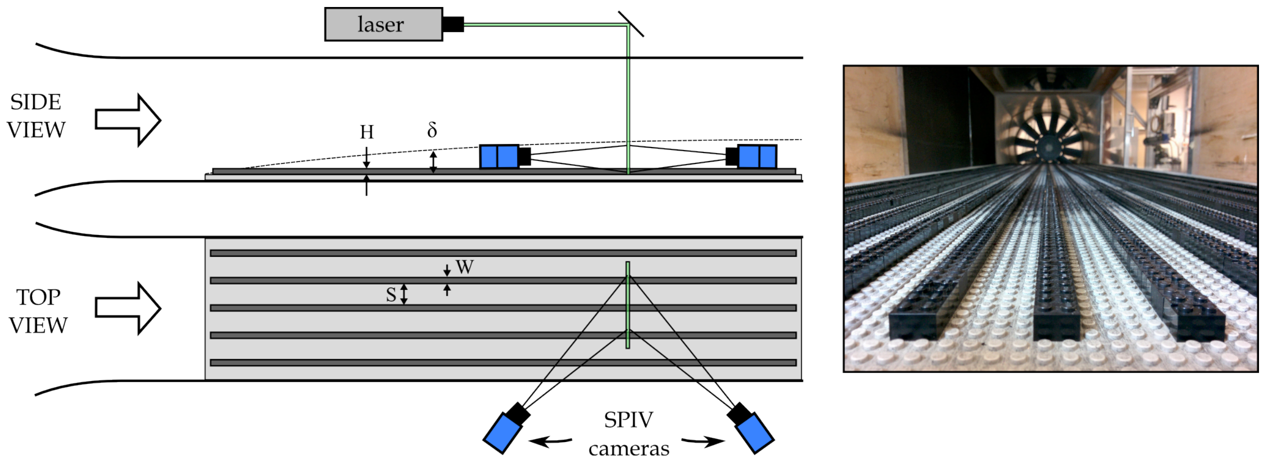


**Figure 1.** The spanwise cross-section of the flow over the roughness strips was measured using stereo-PIV in a wind-tunnel.

Velocity measurements were acquired using stereo-PIV in a cross-section normal to the flow direction 4 m downstream of the leading edge. Measurements were recorded using two LaVision Imager-LX 29MP cameras, fitted with lenses having a focal length of 200 mm and an aperture of f5.6, at 2 Hz with an image pair separation time of 15 μs. A 200-15PIV Nd:YAG laser by Litron Lasers illuminated the measurements plane and the flow was seeded using a Magnum 1200 fog machine. Vectors were determined with Lavision's DaVis 8.2.2 software, using window sizes of 32x32 pixels with 50% overlap, resulting in a resolution of one vector per 0.9 mm. Mean vector maps were determined from sets of 2000 independent measurements.

## Results

The mean velocity maps measured over the representative cases of S/W = 1 and 5 are plotted in fig. 2. For the cases with coarse spacing (S/W ≥ 5), large secondary vortices were observed in the mean velocity maps. In these cases, the spacing was comparable to the boundary layer thickness (0.8 ≤ S/δ ≤ 1.8). The secondary vortices flanked the LEGO strips and were associated with boundaries of regions of strong upwelling over the LEGO pieces and wide downdrafts in the valleys. The downdrafts carried with them high velocity from the outer boundary layer and are consistent with the descriptions of high-momentum pathways; similarly the regions over the LEGO pieces correspond with low-momentum pathways. This is consistent with previous observations in the literature. These regions create spanwise inhomogeneities in the mean velocity reaching the outer edges of the boundary layer.

The cases with fine spacing (S/W ≤ 2; S/δ ≤ 1/3), on the other hand, did not feature large coherent vortices or zones of low- and high-momentum in the mean velocity maps. Rather, very small pairs of counter-rotating vortices appear directly above the LEGO pieces, but are limited to the roughness sub-layer (between 3-5H) and do not extend across the boundary layer. Furthermore, the mean velocity above the roughness elements do not have significant spanwise inhomogeneity, indicating that low- and high-momentum zones are in fact not present for the fine spacing cases.

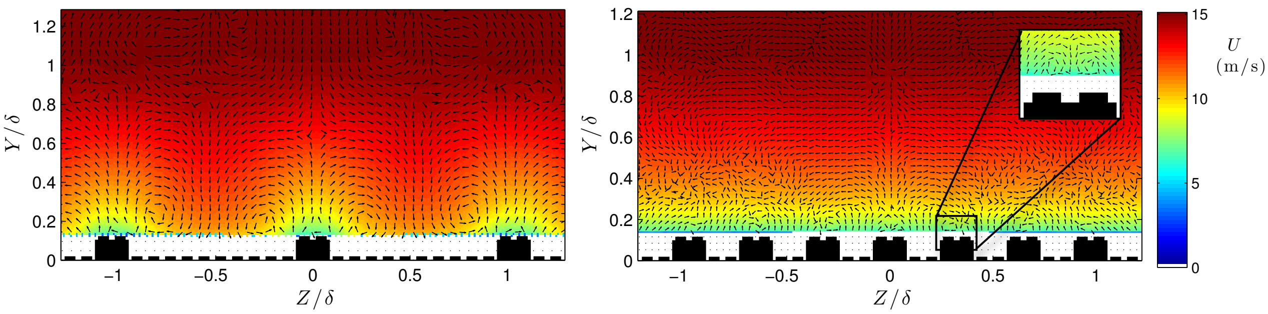


**Figure 2.** Large secondary vortices appear in the cross-section of the the velocity field over the coarsely-spaced case with S/W = 5 (left) but not over the finely-spaced case with S/W = 1 (right).

## Conclusions

This study shows that the presence of low- and high-momentum secondary flows is directly related to the sparsity of the large roughness elements. When the roughness is closely packed, there is no room for generating and sustaining these secondary flows and when the spacing becomes comparable to boundary layer thickness (i.e. sparse), the secondary flows appear to be sustained.

## References


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