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Effect of length of two-dimensional obstacles on characteristics of separation and reattachment

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ABSTRACT

The flow over a forward-facing step (FFS) and a backward-facing step (BFS) have been extensively studied separately, but the interaction between both obstacles has received little attention. It is believed the distance between the two faces of the step is a critical parameter governing the overall behaviour of the flow. This could have implication on the effect an obstacle would have on its surroundings, such as wind disturbance, or spread of pollution. Consequently, we investigate in detail the flow over a two-dimensional obstacle (also referred to as a rib), that consists of a FFS followed by a BFS. The flow field in such configuration is a result of the interaction between the multiple separation regions that appear upstream, above and downstream of the ribs. Our experimental model is submerged in a fully turbulent boundary layer ($\delta/H = 1.37$, where δ and H are respectively incoming boundary layer thickness and rib height), and the Reynolds number based on rib height is $Re_H = 20,000$. Rib length (distance between the two vertical faces) varied between $L/H = 0.1$ and $L/H = 8$. In order to describe the general features of such a flow, we carried out flow field velocity and surface pressure measurements. Results show that two trends exist according to the length of the rib. Short ribs ($L/H \leq 4$) produce one large recirculation region from the leading edge which results in higher levels of large scale turbulence which propagate far downstream. On the contrary, the FFS portion of long ribs ($L/H \geq 4$) is decoupled from the BFS portion. Two separate shear layers are formed which decay quicker resulting in lower levels of turbulence propagating downstream.

1. Introduction

Surface-mounted obstacles in industrial, aeronautical, or civil engineering produce unsteady flows with strong turbulence. These situations may improve flow-mixing properties, stabilize a combustion process, or jeopardize the integrity of buildings and their surroundings. Most previous studies have focussed on the separation and reattachment for forward-facing or backward-facing step flows (FFS and BFS). A two-dimensional backward-facing step flow is perhaps the most studied canonical separated flow (Armaly et al., 1983; Lee and Mateescu, 1998; Lee et al., 2004), primarily because it is a major source of drag in automotive and aerospace applications. It contains a separated shear layer which interacts with both the free-stream and a region of reverse flow. This produces a complex feedback mechanism that is a source of pressure loss and noise (Chun and Sung, 1996; Le et al., 1997). In comparison, the forward-facing step flow has been a subject of fewer studies (Sherry et al., 2010; Pearson et al., 2013). This type of configuration has been examined more recently in the context of wind resource assessment near escarpments and cliffs for normal flow as well as yawed flow configurations (Rowcroft et al., 2016).

Despite being very common in nature and engineering applications, the flow field past a two-dimensional rib, which is a combination of forward-facing step followed by a backward-facing step, remains a subject with little documentation. Depending on the distance between the upstream and downstream edges of a rib, the separated flow of the forward-facing step may reattach on top of the rib or merge to different degrees with that of the backward-facing steps. Consequently up to three regions may interact together: upstream, on top, and downstream of the rib (see Fig. 1). As described by authors studying these types of obstacles, instrumentation was a limitation, thus a thorough description of recirculation regions was also limited (Counihan et al., 1974; Arie et al. 1975a, 1975b; Castro, 1979; Moss and Baker, 1980; Bergeles and Athanassiadis, 1983; Castro and Dianat, 1983; Dianat and Castro, 1984; Castro and Haque, 1987; Antoniou and Bergeles, 1988).

In flow past ribs, there is a difference between flow past ribs with a reattached flow on the top surface (long ribs), and ribs too short for

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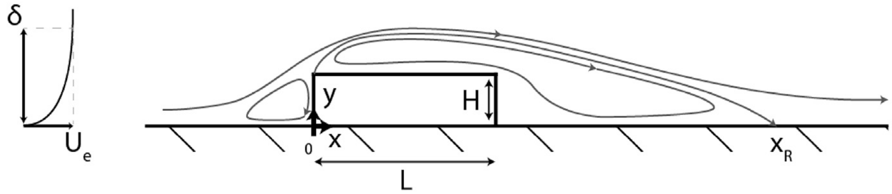

Fig. 1. General configuration of the flow over ribs illustrating the main parameters of the study.

reattachment to take place on the top surface (short ribs). This type of flow has been examined in the context of an elongated bluff body, where the flow separates at the leading edge and reattaches along the chord of the body before separating once again at the trailing edge. Cherry et al. (1984) examined the flow over an infinite plate with a blunt leading edge and found that large vortices are shed from the leading edge separation bubble, however, there was not associated periodicity. Nakamura and Nakashima (1986) have shown that these vortices will form a staggered vortex-street-like arrangement in the wake of blunt-nosed elongated bodies even with a splitter plate because of the presence of the trailing edge. In these type of flows, the elongation ratio (which is the ratio between length of the body to its thickness) is analogous to the length (L) to height (H) ratio of wall-mounted ribs. Parker and Welsh (1983) performed a detailed study for rectangular cylinders over a wide range of elongation ratios and found that there is no dominant frequency in the wake at high Reynolds numbers. Taylor et al. (2011) showed that larger leading edge separation-reattachment increases the role of the turbulent stresses in the recirculation region. Taylor et al. (2013) found that the changes in the leading edge separation-reattachment create markedly different levels of turbulent kinetic energy and near wake structure. Although there are similarities between elongated bodies and ribs, the presence of a wall that bounds the flow in the wake as well the turbulence in the incoming boundary layer will alter the characteristics of separation and reattachment at the leading edge and the wake of wall-mounted obstacles.

In the context of wall-mounted obstacles, Castro (1979) asserts that here is a possibility of a reattachment point on the top if there is sufficient amount of turbulence in the incoming boundary layer, and if the rib is long enough. Bergeles and Athanassiadis (1983) and Arie et al. (1975b) agree and find that the threshold between the presence and absence of a reattachment point on top of the rib is near $L/H = 3$. Bergeles and Athanassiadis (1983) show that the FFS portion is consistent with an isolated FFS in similar flow conditions without discussing potential effects of Reynolds number and incoming flow. Bergeles and Athanassiadis (1983) describe the presence of two trends in the mean recirculation length (L_R) of the wake region. L_R decreases linearly with rib length for short ribs ($L/H < 4$) from over $11.5H$–$2.8H$ and is nearly constant for long ribs ($L/H \geq 4$) at approximately $3H$. The authors note that L_R in the wake of long ribs is less than what is commonly found in simple backward-facing steps. Adams and Johnston (1988) quote a typical L_R between four and ten times the step height in backward-facing steps, whereas Bergeles and Athanassiadis (1983) quote values of L_R in the region of three times the height in the case of ribs. Leclercq et al. (2001) find similar results for a rib with $L/H = 10$. The argument of strong turbulent flow mixing at the trailing edge of the rib is used to justify the discrepancy between ribs and isolated BFS. Finally, the recirculation region upstream of the rib receives the least amount of attention from aforementioned studies, but it seems to display a nearly constant mean recirculation length (Bergeles and Athanassiadis, 1983).

The surface pressure distribution, which defines the largest aerodynamic load on a rib-like structure, was addressed by Arie et al. (1975a). The study provides an overview of the behaviour of ribs immersed in a turbulent boundary layer by investigating the mean pressure drag generated at different inflow conditions, but less emphasis is placed on the effect of rib length. For rib lengths up to $L/H = 5$, within a range of rib height to boundary layer thickness ratio comparable to Bergeles and Athanassiadis (1983), it is reported that pressure drag coefficient decreases with rib length, and δ/H. For longer ribs, it is reported that the drag coefficient remains relatively unchanged. It can be assumed that for very long ribs, skin friction on the top surface increases viscous drag which is not accounted for in pressure drag. Arie et al. (1975b) supports the first experiment and adds a more detailed overview of surface pressure distribution for two rib lengths ($L/H = 2$ and $L/H = 4$). Some trends are highlighted: the pressure drop after the leading edge of the rib is stronger as δ/H decreases, and the pressure on the downstream face is constant at all heights whereas it is not on the upstream face.

Finally, the turbulent fluctuations induced by ribs is studied by Arie et al. (1975b) and Antoniou and Bergeles (1988). The mixing process in the wake between the uniform flow above, and the still region downstream of the rib is compared by Arie et al. (1975b) to Görtler's theory on a uniform flow mixing with static fluid. The authors quote maximum turbulence intensity being generated at lowest δ/H, and above the top surface of the rib. The exact height of maximum turbulence intensity varies with rib length ($y/H = 1.13$ for short ribs and $y/H = 2.5$ for a fence). The deviation is associated with Coandă effects along the top surface. In addition, the authors observe that the disruption caused by ribs requires a long time or distance to return to unperturbed boundary layer characteristics. Indeed, it is still not recovered at $25H$ downstream of the ribs. Similar findings were made by Castro (1979). Antoniou and Bergeles (1988) studied the far wake of short and long ribs and found the lifespan of perturbations caused by long ribs is comparatively shorter than those caused by short ribs. However, the near-field flow characteristics that could lead to this far field effect remains unresolved.

In the current study, the aim is to develop further understanding of the flow over ribs of different lengths. The analysis is focussed on three main topics: the length of each recirculation region as rib length varies, the average surface pressure distribution these ribs yield, and finally the turbulent flow fields in the near-wake of the rib. We investigate the effect of rib length on the fluctuations of these quantities, and identify the causes of established trends.

2. Experimental arrangement

2.1. Test cases and flow conditions

The experiment was carried out at the University of Southampton in an open return wind tunnel with a rectangular test section of 0.9 m × 0.6 m × 4.35 m. The arrangement is depicted in Fig. 2. Speed in the test section (U_e) was set to 10 m/s and verified with a pair of Pitot tubes. The experiment was mounted on a smooth false floor to control the incoming boundary layer. It extended 2.35 m upstream of the two-dimensional obstacle, and 1.35 m downstream. The leading edge of the false floor was a thin wedge with a strip of zig-zag tape to trip the boundary layer. In order to control circulation around the floor, a flap was mounted at the trailing edge. It was set at an angle that would suppress separation at the leading edge of the floor. This was verified with surface oil flow visualisation near the leading edge. A synthetic smoke generator was used to seed the flow.

The obstacles (referred hereafter as ribs) extended along the entire span of the wind tunnel, thus generating a “two-dimensional” obstacle.