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AUTO-GENERATION BY INTERACTION OF WEAK EDDIES

Manu V Goudar*[1], Wim-Paul Breugem[2], Yoshifumi Jodai[3], and Gerrit E Elsinga[4]
[1,2,4]*Laboratory of Aero and Hydrodynamics, Delft University of Technology, Delft, The Netherlands*
[3]*National College of Technology, Kagawa College, Takamatsu, Kagawa, Japan*

Summary For channel flow, we explore how the interaction of weak eddies produces additional eddies by means of auto-generation. This is done by DNS of two eddies with different initial strengths, initial sizes and initial stream-wise spacing between them. The numerical procedure followed is similar to Zhou et al[1]. The two eddies merge into a single stronger eddy when a larger upstream and a smaller downstream eddy are placed within a certain initial stream-wise separation distance. Subsequently, the resulting stronger eddy is observed to auto-generate new eddies. The non-merging cases with small initial stream-wise separation also auto-generate. The auto-generation is characterized by a rapid lift-up of an initial eddy, which blocks the incoming flow and leads to shear-layer roll-up and formation of a new eddy. The same sequence of events is observed in a fully developed turbulent boundary layer[2].

INTRODUCTION

To create energy-efficient designs by reducing drag, it is essential to understand the internal structure and dynamics of wall-bounded turbulent flows. One of the ways to describe the dynamics of boundary-layer flows is the hairpin eddy model[3], based on coherent structures. The hairpin-like vortices are observed to populate the outer layer over a range of Reynolds numbers [4]. They are organized in the direction of the mean flow and occur in packets[5, 6, 7]. This packet organization not only enhances the Reynolds shear stress[5], but also, while occupying only 4% of total area of the flow, it contributes to more than 25% of the Reynolds shear stress[8]. Hence, vortex organization in packets is considered important. The packet formation has been explained by the auto-generation mechanism or parent-offspring concept[3]. Zhou et al[1] reported that the hairpins above a threshold strength can auto-generate. However, such strong vortices do not frequently appear in actual turbulent flows. Hence, we consider scenarios involving weak eddies, which are frequent in actual wall-bounded turbulence. The effect of low-speed streak on auto-generation, which is located under the eddy, is also studied. Finally, we examine the critical aspects leading to the onset of auto-generation and present a modified interpretation of the auto-generation mechanism.

The interactions between two ideal non auto-generating eddies is studied numerically by Direct Numerical Simulation (DNS). We follow a similar procedure to [1] in extracting the eddy from fully developed turbulent channel flow and simulate them dynamically. A variety of scenarios are created based on different initial strengths, event location and initial stream-wise spacing between the aligned eddies. The two eddies merge (Fig. 1a-b), when an eddy conditioned at higher wall-normal location is placed upstream of the one conditioned at the lower wall-normal location. The eddy with higher wall-normal location moves faster due to higher local flow velocity and merges with the downstream eddy creating an above threshold strength eddy, which auto-generates (Fig. 1c). However, only the merging cases with lower stream-wise separation auto-generate. Because, as the initial distance between the eddies increases, merging takes longer time, during which the eddies weaken individually and hence the merged eddy is not strong enough to create new vortices. Also, a few non-merging cases generate new structures, when the initial stream-wise separation between initial eddies is lower. From these observations, it is inferred that merging can create stronger eddies, but is not the sole mechanism. The auto-generation may depend upon a sufficiently small initial stream-wise separation of the two eddies as it is common between all the auto-generation cases.

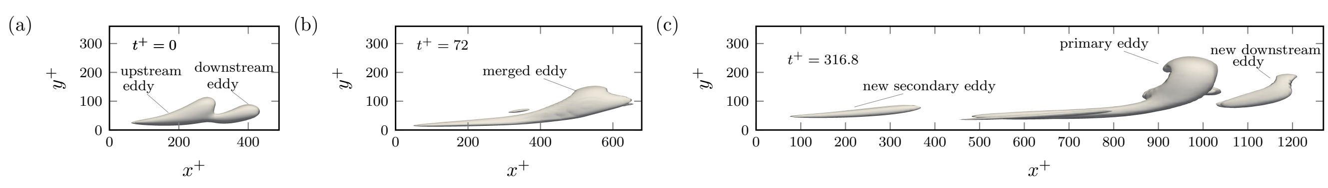

Figure 1: Iso-contours of swirling strength squared (10% of maximum) at time $t^+ = 0, 72$ and 316.8 for the two-eddy case with stream-wise separation $\Delta x^+ = 118$ (side view). Two eddies in (a) merge to form a single stronger eddy in (b). Merged eddy further auto-generates as shown in (c). x^+ and y^+ represent stream-wise and wall-normal directions, respectively, normalized by wall units.

The smaller stream-wise separation between eddies emulates the increasing threshold strength, as the velocity field of the two individually eddies gets superimposed and amplified. Hence, the role of the velocity field and specifically of the overlapping low-speed streak in the onset of auto-generation is explored. When the stream-wise separation is small, low-speed

*Corresponding author. Email: m.goudarvishwanathappa@tudelft.nl

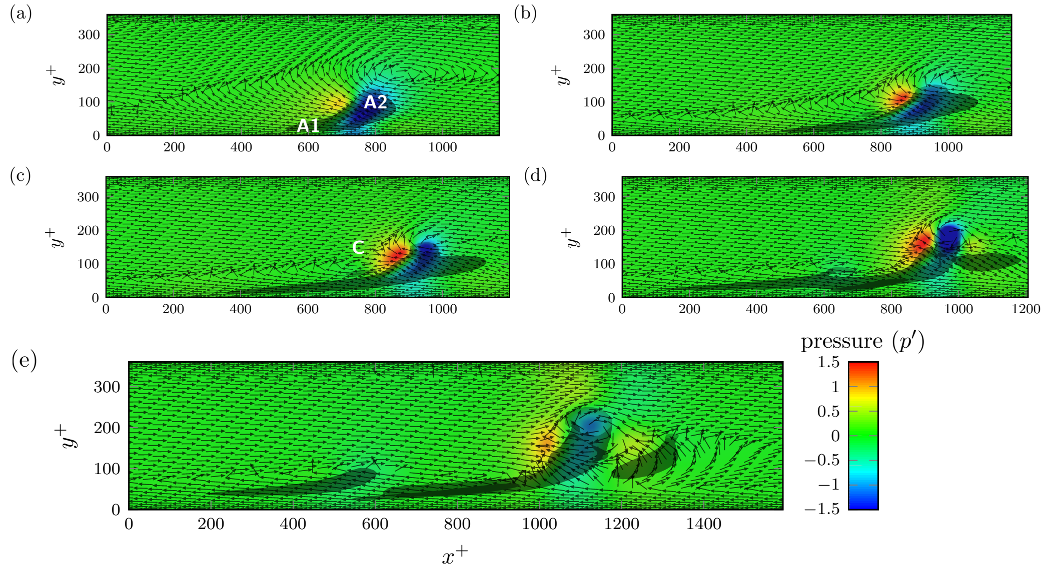

Figure 2: Auto-generation mechanism : Vector plots of velocity fluctuations (u'^{+}, v'^{+}) along with fluctuation pressure (p') contours in the symmetry plane which is between the two legs of an eddy. u'^{+} and v'^{+} are velocity fluctuations in stream-wise and wall-normal directions, respectively. All vectors are scaled by unit length, hence only indicate the flow direction. The iso-surfaces in the figures correspond the 10% of the initial maximum swirling strength. This is for two eddy case $(76, 51)$ at strength $\alpha = (1, 1)$ with $\Delta x^+ = 59$. Figures a-e represent the evolution of two eddies and vector plots in time at $t^+ = 28.8,\ 57.6,\ 86.4,\ 158.4$ and 244.8 respectively.

streaks from the two eddies overlap and get superimposed, which amplifies the strength of the resulting streak. A separate set of simulations has been performed by adding a divergence-free low-speed streak to a conditional eddy to understand the influence of vortex-streak interactions on auto-generation. However, these simulations do not show any auto-generation.

Finally, based on the above observations, the current picture of the auto-generation mechanism is modified. Analysis of the data suggests that the strong lift up of the initial hairpin head is due to the ejection event located at the hairpin head (Fig. 2a). Due to the lift up of the head, the in-rushing flow is blocked (Fig. 2b). This inrush of flow and the already existing ejection events cause the shear layer to deform and roll-up in the span-wise direction (z) just upstream of the vortex (Fig. 2c-d). As this span-wise roll-up becomes stronger, it connects to the leg/legs of the downstream vortex and becomes a new vortex by separating from the main vortex (Fig. 2d-e). When the ejection events are stronger in any of these two vortices, a third eddy will be formed in a similar way, else, the eddies are dissipated over time. The generation mechanism of new hairpin vortices is also observed in experiments by [2] within a fully turbulent boundary layer in a similar way.

This modified mechanism differs from the existing mechanism by [1] where induced vortex motions result in the formation of a kink in the legs of the initial eddy before a new hairpin head is created. In other words, kink formation in [1] is due to mutual and self induction of stream-wise legs, whereas in the present mechanism, it is the consequence of shear layer roll-up and ejection events. Also, the presence of two stream-wise vortex legs is not necessary to describe the onset of auto-generation as a single leg can lift up and block the incoming flow leading to the shear-layer roll up and further generation of a new eddy. The main implication of the present study is that commonly found weak eddies can also auto-generate, strengthening the existing hairpin eddy model[3].

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