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Development of Pre-set Counter-rotating Streamwise Vortices in Wavy Channel

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Abstract Development of counter-rotating streamwise vortices in a rectangular channel with one-sided wavy surface has been experimentally quantified using hot-wire anemometry. The wavy surface has fixed amplitude of 3.75 mm. The counter-rotating vortices are pre-set by means of a sawtooth pattern cut at the leading edge of the wavy surface. Variations of the central streamwise velocity U_c with a channel gap $H = 35$ mm and 50 mm (corresponding to a Reynolds number from 1600 to 4400) change the instability of the flow which can be distinguished from the velocity contours at a certain spanwise plane. The streamwise velocity contours and turbulence intensity for Reynolds number $Re = 3100$ and $H = 35$ mm show the disappearance of the mushroom-like vortices prior to turbulence near the second peak of the wavy surface, while for higher Re , this phenomenon occurs earlier. Under certain conditions, for example, for $Re = 4400$ and $H = 50$ mm, the splitting of the vortices can also be observed.

Keywords counter-rotating streamwise vortices, pre-set disturbance, wavy channel, hot-wire anemometry

1. INTRODUCTION

Instability of laminar flow in a wavy channel can manifest itself as streamwise vortices [1] or as traveling waves disturbances [2]. Various analyses on the instability mechanism have been reported since a century ago, such as by Rayleigh [3] in the case of rotating fluid, by Taylor [4] for the Taylor-Couette instability in parallel flow between concentric cylinders, by Dean [5] for fully developed flow in

curved pipe or duct, and by Görtler [6] for laminar boundary layer flow over a concave surface.

Counter-rotating streamwise vortices can be easily found in many fluid and thermal engineering applications, for instance, airfoils, turbine blades, and heat exchangers. A brief review of these vortices has been presented by Aider *et al.* [7]. Such streamwise vortices can be found naturally or be induced by using vortex generators [8] or other perturbation devices such as thin wires [9] and a zig-zag pattern cut on the leading edge of a plate or an airfoil [10, 11]. Naturally generated counter-rotating streamwise vortices usually have different spanwise wavelengths due to the “competition” of the disturbances with different amplification rates [12]. This might cause difficulties and bias in experimental studies of such vortices. Thus, a method to pre-set such vortices with uniform wavelength is required in order to characterize the development of these vortices.

The change of flow due to the presence of such vortices may cause heat and mass transfer improvements, for instance, to enhance mixing in heat exchangers or chemical reactors, but also some undesirable problems [7]. Therefore, it is important to understand the downstream development of these vortices in order to control them. A simple sinusoidal wavy channel can be used as a passive control for these vortices. The vortex instability in a wavy channel, which is caused by the centrifugal force field, is very similar to the so called Görtler instability [13]. Numerous experimental and analytical studies on flow over wavy surface, such as Nishimura *et al.* [14, 15], Gschwind *et al.* [16], and Cabal *et al.* [17] suggested stability criteria to control the vortices generated, while Floryan [18] suggested a neutral stability region as a function of the Reynolds number $Re (= U_c H / 2\nu)$ and the wavy surface geometry based on the linear stability analysis. However, almost all of the works mentioned earlier are for fully developed channel flow.

The appearance of such counter-rotating vortices makes the boundary layer flow over the wavy surface three-dimensional, which can be observed as a variation in boundary layer thickness in the spanwise direction. The thicker part of the boundary layer is called the “upwash” region where low momentum fluid is ejected from the surface, while the thinner part is called the “downwash” region where high momentum outer fluid move towards the wall [19]. An earlier visualization study on laminar boundary layer flow by Budiman *et al.* [20] showed that the presence of a wavy surface could delay the breakdown of such pre-set vortices until at least the first peak of corrugation, compared with the case for a flat plate.

The aim of this work is to quantitatively study the downstream development of pre-set counter-

rotating streamwise vortices in a boundary layer over a wavy surface by means of hot-wire anemometry. The channel is of rectangular cross-section with one-sided wavy surface, as sketched in Fig. 1. This study also covers some variations of the Reynolds number Re and channel gap H within the unstable zone of the vortex instability criterion as suggested by Floryan [18].

FIG. 1 Sketch of (a) the wavy channel, the flow direction, and the coordinate system; (b) sawtooth pattern at the wavy surface leading edge of the channel (all dimensions are in mm).

2. EXPERIMENTAL SET-UP

A rectangular acrylic transparent channel with one-sided wavy (sinusoidal) surface is used in this experimental study (Fig. 1). The wavy surface has a wavelength λ and an amplitude a of 76 mm and 3.75 mm, respectively. This wavy surface consists of four wavelengths and connected to a 150 mm long entrance flat plate. A sawtooth pattern with 6.3 mm depth and a spanwise wavelength of 15 mm was crafted on the leading edge of the entrance flat plate to induce or pre-set the counter-rotating streamwise vortices with spanwise wavelength equal to that of the sawtooth pattern. The spanwise wavelength value of 15 mm is adapted from the distance between perturbation wires used by Mitsudharmadi *et al.* [19] which could induce the Görtler vortices in a concave surface boundary layer with maximum amplification rate. This method was similar to that used by Hasheminejad *et al.* [11] and the initial channel normal gap H is 35 mm, which gives the non-dimensionalized parameter $S = a/H = 0.107$. The channel width is 160 mm, which is sufficient to avoid the near wall effect from the

side wall [20]. A Cartesian coordinates system is used to represent the streamwise (x) direction of the flow, normal (y) from the wavy surface, and spanwise (z) distance from the center of the channel. The channel is connected to a low speed, open-loop wind tunnel test section. The turbulence level in the test section is about 0.35% for a streamwise velocity range of 1.0–5.0 m/s.

A 5 μm diameter and 1 mm long tungsten wire single hot-wire probe DANTEC 55P15 designed for boundary layer measurements was inserted from a small hole on the flat surface of the channel ($y = 35$ mm) and used to measure the streamwise velocity component. The probe is mounted on a traversing mechanism and connected to a Constant Temperature Anemometer (CTA) system that coupled to a signal conditioner. The motors of the traversing mechanism can move in the y and z direction with accuracy of ± 0.01 mm. The top surface of the wind tunnel test section has been modified to support the hot-wire probe and its traversing mechanism. A narrow slit was made along the spanwise direction of the channel for the insertion of the hot-wire probe. Throughout the spanwise movement of the probe, the rest of the slit was covered by a plate that attached to the traversing mechanism to eliminate the possible suction effect due to this narrow opening. The measurements are taken at the central region of the channel, that is, -15 mm $\bullet$ z $\bullet$ $+15$ mm, with a spanwise step size of 0.1 mm, while the normal step size begins with 0.1 mm at the near wall region and gradually increased to 0.5 mm as the probe approaches the edge of the boundary layer. The $z = 0$ is aligned with the downwash region, as reported by Budiman *et al.* [20]. During the experiments, the measured data were low-pass filtered at 3 kHz and sampled at 6 kHz for duration of 21 seconds. Calibration checks were carried out frequently to maintain the measured data within the acceptable range of less than $\pm 2\%$ drift.

A Pitot-static tube that connected to a pressure transducer is fixed at the center of the channel near the leading edge. A T-type thermocouple connected to an Agilent 34970A data acquisition unit is also placed adjacent to the Pitot-static tube to measure the temperature at the center of the channel. These temperature data were used as compensation due to the change in ambient temperature throughout the experiment.

3. RESULTS AND DISCUSSION

The velocity profile of the incoming flow to the channel is uniform. The preliminary test using Particle Image Velocimetry (PIV) at the inlet of the channel is plotted in Fig. 2(a), which demonstrates

a "flat top-hat" velocity profile. To obtain contours plot of mean velocity profiles as well as the turbulent intensity, the flow-field velocity data obtained from the hot-wire measurement were post-processed by using TECPLOT software. A repeatability test was carried out by repeating the experiment twice with a time span of two weeks to find out whether the vortex structures formed in the channel remain the same. Figure 2(b) shows the normalized velocity profile at the first peak, $z = 5$ mm. There is no significant difference between the two data sets, which suggests that the structures are steady and remain consistent for that particular operating condition.

FIG. 2 (a) Normalized velocity u/U_c at the entrance of the channel, as obtained by preliminary PIV measurement, shows a "flat top-hat" velocity profile. (b) Normalized velocity u/U_c at $z = 5$ mm from the hot-wire measurement shows the reproducibility of the data obtained from different date of experiment, which indicates that the structures remain consistent for a flow condition studied. (c) Velocity profiles at the first peak, taken from $2 \text{ mm} \leq z \leq 6 \text{ mm}$, $Re = 3400$ and $S = 0.107$. Due to the

similarity profile with $z = 0$, the spanwise location $z = 2$ mm could represent the downwash, while $z = 6$ mm represents the upwash region.

FIG. 3 Contours of normalized streamwise velocity u/U_c at the first peak for $S = 0.107$ and various Re : (a) 1600, (b) 2100, (c) 3100, and (d) 4400.

FIG. 4 Contours of normalized streamwise velocity u/U_c for $S = 0.107$ and $Re = 3100$ at various locations: (a) 40mm from the leading edge, (b) 75mm from the leading edge, (c) 1st peak, (d) 1st valley, (e) 2nd peak, and (f) 2nd valley

Various streamwise velocity plots at $2 \text{ mm} \leq z \leq 6 \text{ mm}$ are presented in Fig. 2(c). The u value is normalized by the streamwise velocity at the center of the channel near the leading edge U_c . At $z = 2 \text{ mm}$, the velocity profile is somewhat “fuller”, which may represent the downwash region. Although the downwash region was initially set at $z = 0$ (Fig. 1(b)), but there is no significant difference between the velocity profile at $z = 0, 1$, and 2 mm , thus the plot for $z = 0$ and $z = 1 \text{ mm}$ were omitted in Fig. 2(c). Within $1.23 \text{ mm} < y < 6.47 \text{ mm}$, the value of u/U_c is greater than 1. The maximum u/U_c is 1.03 at $y = 2.09 \text{ mm}$. At $z = 6 \text{ mm}$, the inflection point in the boundary layer velocity profile can be observed, which represents the characteristic of the upwash region. This inflection point indicates high shear layer that is formed near the edge of the boundary layer and might be referred to the onset of the nonlinear region, in which the growth of the disturbance is smaller than that in the earlier linear region [19, 21]. In the case of Görtler vortices, the nonlinear growth region, which is subjected to the occurrence of the varicose mode instability, is the location where the spanwise wavy shape due to the counter-rotating vortices transforms into “mushroom-like” structures [19].

As the Reynolds number Re increases, the flow becomes more unstable. The effect of Re towards the streamwise velocity is discernible in its normalized contour in Fig. 3. For $Re = 1600$, two prominent wavy structures appeared on the spanwise plane of the first peak of the wavy surface. These two structures were steady and nearly uniform due to the pre-set of spanwise wavelength caused by the leading edge pattern [11, 20]. As Re is increased to 2100, the boundary layer at the upwash region becomes thicker due to upward movement of the low momentum fluid from the near wall region, as indicated by “greener” area in the contour. For higher Re , the vortex structures are transformed into “mushroom-like” structures but might not be uniform anymore, which is due to a different growth rate of the induced disturbances amplitude. As shown in Fig. 3(c), at $Re = 3100$, two different size of mushroom-like structures are found. Finally at $Re = 4400$, the structures start to collapse prior to turbulence.

Figure 4 shows the velocity contours for $Re = 3100$ and $S = 0.107$. At $x = 40 \text{ mm}$, the wavy variation of boundary layer thickness is very prominent, as shown in Fig. 4(a). The spanwise width of these wavy structures is decreased further downstream over the flat entrance plate, as depicted in Fig. 4(b). It is clear that the wavy surface helps the induced structures to preserve farther downstream, compared with the flat plate case where no distinguished vortex structure can be found after $x = 40 \text{ mm}$ downstream of the leading edge [11]. As the flow accelerates at the first peak, the

wavy structures evolve to form mushroom-like structures which could indicate the initiation of the varicose mode instability as previously reported by Mitsudharmadi *et al.* [19]. The structures remain unchanged at least until the first valley (Fig. 4(d)). Prior to the breakdown of the structures, the low streamwise velocity region near the wall widens. This could be attributed to laminar mixing enhancement, which has been visualized as vague structures [20]. At this condition, the spanwise undulation of the structures occurred, as depicted in Fig. 4(e). Finally at the second valley, the variation of boundary layer thickness is somewhat indistinct, which suggests that the mushroom-like structures have broken down prior to turbulence.

Figure 5 depicts the contours of turbulence intensity (Tu) and isoshear contours of $\bullet u/\bullet y$ and $\bullet u/\bullet z$ at various streamwise locations. The turbulence intensity is defined as

$$Tu = \frac{1}{\bar{u}} \sqrt{\frac{1}{n} \sum_{i=1}^n (\hat{u}_i - \bar{u})^2}, i = 1, 2, \dots, n \quad (1)$$

where $\hat{u}$ and $\bar{u}$ are respectively the instantaneous and mean local sampling velocity obtained from the hot-wire anemometry. At the first peak of the wavy surface (Fig. 5(a)), the concentration of the turbulence intensity in the core of the vortex pair is clearly indicated by the high values region denoted in red. This core becomes more diffused as it moves further downstream; indicated by its lower values in yellow in Fig. 5(b) which is relatively larger in size compared to that depicted in Fig. 5(a). The highest turbulence intensity region is beneath the structure, approximately at $y < 1.5$ mm, that is, the separation bubble as visualized by Budiman *et al.* [20]. At the second peak, the reattachment occurred and more chaotic structure is depicted in Fig. 5(c). The turbulence intensity contour suggests that the mushroom-like structures were diffused at the second peak. This is later supported by turbulence intensity contours in Fig. 5(d) which shows the large momentum and low turbulence intensity without any wavy pattern remaining at $y > 2$ mm.

FIG. 5 Contours of (left to right) turbulence intensity (Tu), normalized u/y and u/z of a vortex pair ($0.1 \leq y \leq 5$ mm; $0 \leq z \leq 10$ mm) for $S = 0.107$ and $Re = 3100$ at various locations: (a) 1st peak, (b) 1st valley, (c) 2nd peak, and (d) 2nd valley. Broken lines indicate negative values.

Contours of u/y and u/z from the first peak to the second valley locations that have been normalized with the local u/y and u/z at the wall are also presented in Fig. 5. The high magnitude positive shear can be found at the top center of the vortices (Fig. 5(a)), which is near to the boundary layer edge at the upwash region [22]. The negative u/y can be observed in the middle under the maximum turbulence intensity area and it disappears as the flow move further downstream. From the u/z contours in Fig. 5(a), it is found that the maximum magnitude of the u/z in the contour is somewhere around $1 \leq y \leq 2$ mm. These high u/z regions, which refers to the cores of the vortices, were lifted up to about $y = 3$ mm as the flow passed the first valley (Fig. 5(b)). Another yet smaller vortex pair can also be found at the bottom of the main vortices with opposite rotational directions, as depicted in the u/z contour in Fig. 5(b) and reported earlier by Saric and Benmalek [23]. This might be a result of the suction effect from the upwash region of the larger vortices. This particular vortex

pair is excluded from further discussion as it appears inside the separation bubble region ($y < 1.5$ mm), while for the current study, only 1D probe of the CTA was used to quantify the flow.

At the second peak, the vortices are diffused even more, as shown in Fig. 5(c). From the middle picture, no concentration of high $\bullet u/\bullet y$ shear can be found anymore, while from the $\bullet u/\bullet z$ contours, the downstream evolution shows that the two cores tend to widen before it collapses. From Fig. 5(d), it can be concluded that the vortex structures were almost totally breakdown prior to turbulence at the second valley.

The variation of streamwise velocity at the downwash and upwash region can be referred to measure the growth of disturbance amplitude. This information will be useful to quantify and understand the development and decay of the mushroom-like structures along the streamwise direction. The dimensionless amplitude is defined as

$$\kappa_u = \frac{u_{dw} - u_{uw}}{2U_c} \quad (2)$$

as suggested by Winoto and Crane [24]. The theoretical analysis of this parameter is presented by Finnis and Brown [25]. At the first peak of the wavy surface, the value of κ_u increases as Re increases from 1600 to 2100, while for higher Re , κ_u decreases, as depicted in Fig. 6(a). This is also similar with the linear variation of velocity presented by Bippes and Görtler [26]. The maximum disturbance amplitude $\kappa_{u,max}$ is 0.086, 0.165, 0.111, and 0.071 for $Re = 1600, 2100, 3100$, and 4400, respectively. This κ_u profile suggests that the saturation point of the growth of disturbance amplitude lies at the range $1600 < Re < 3100$, where the finite amplitude of the disturbance has been reached, the mushroom-like structures dominate the boundary layer flow, and the main flow transforms into another possibly condition in which secondary instability may intensify [27].

For the constant Re and S (Fig. 6(b)), it is found that there is a notable increase of κ_u as the flow moves to the first peak. At the second peak, more inflection point is found, that is, at approximately $y = 0.6$ mm. The more inflection points seem to trigger the breakdown of vortex structures [28]. Figure 6(c) shows that the maximum growth of disturbance amplitude $\kappa_{u,max}$ decreases at the flat entrance plate before slightly increases towards the first peak and decreases once more as the flow moves further downstream. The latter decrease is associated to the decay of the mushroom-like structures prior to breakdown to turbulence.

FIG. 6 Behavior of disturbance amplitude κ_u plotted in the normal direction of the flow (a) as a function of the Reynolds number for a fixed $S = 0.107$ at the first peak of the wavy surface, (b) at various streamwise locations for $S = 0.107$ and $Re = 3100$, and (c) plot of maximum disturbance amplitude $\kappa_{u,max}$ at various streamwise locations for $S = 0.107$ and $Re = 3100$

The contours of the normalized streamwise velocity u/U_c for a channel gap of 50 mm at various Reynolds numbers are shown in Figure 7 in order to look at the effect of the channel gap H on the counter-rotating streamwise vortex structures. By changing the normal gap H from 35 mm to 50 mm and comparing to Fig. 3 at the same Reynolds number, it is found that as S decreases, the structure size gets relatively larger. This is indicated by the isocontour line of 0.95 at the center of the vortices, which is approximately at $y = 6$ mm for $Re = 2100$ and $S = 0.075$ (Fig. 7(a)), while in Fig. 3(b), the

average height of the structure is not more than 5 mm. However, the average ratio between the boundary layer thicknesses at the upwash region over the channel gap almost remains constant, that is, about 12 to 14% of the channel gap. It is also interesting to notice the appearance of smaller wavy patterns in between the counter-rotating vortices in Fig. 7(c). These wavy patterns might indicate the splitting of the vortices which occurred naturally at certain flow conditions, similarly with the case of Görtler vortices which has been reported by Mitsudharmadi *et al.* [29]. Compared with Fig. 3(d), with the same $Re = 4400$, the vortex structures were still relatively more apparent. This indicates that as S is decreased to 0.075, the flow generally becomes more stable.

Figure 8 shows the turbulence intensity at $Re = 3100$ and $S = 0.075$. The pattern of turbulence intensity is very similar to the previous one obtained at the same Reynolds for a larger $S = 0.107$ obtained in Fig. 5(a). However the magnitude at the core is about 1.5 times greater. From the isoshear u/z contour in Fig. 8, it can be seen that there are two strong negative shear areas, indicated by the dark blue regions. This suggests that basically there are two pairs of high u/z shear in every counter-rotating vortices structure. One pair near the wall is responsible to the formation of the stem of the mushroom-like structures, while the other pair belongs to the formation of the mushroom head. However, it is not clearly depicted in the positive region in Fig. 8 and in Fig. 5(a), as to show these regions, the measurements need to be done in very fine spatial resolutions. When the

FIG. 7 Contours of normalized streamwise velocity u/U_c at the first peak for $S = 0.075$ and various Re : (a) 2100, (b) 3100, and (c) 4400.

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structures collapse prior to turbulence, the pair at the mushroom head will disappear earlier than the other pair, similar to that shown in Fig. 5(d).

It is found that by keeping other parameters constant, the change of amplitude of the wavy surface affects the formation of the counter-rotating streamwise vortices. By doubling the amplitude of the wavy surface and the channel gap, it is understandable that the curvature on the wavy channel becomes stronger. As a result, from Figs. 9 and 10, it can be seen that the mushroom “stems” become shorter but the “hats” are much wider. In this case, the induced disturbance and centrifugal force field on the wavy surface are less strong to eject the low momentum fluid from the wall. From Fig. 9 it is also interesting to note that the maximum velocity is not at the center of the channel, but at the downwash region, something that is hardly noticeable from Figs. 3 and 4. By normalizing the streamwise velocity u with the central velocity U_c , at the downwash of this larger wavy surface amplitude, the fluid is accelerated by a factor of 1.2.

4. CONCLUSIONS

The development of pre-set counter-rotating streamwise vortices in a laminar boundary layer flow in a rectangular cross-section channel with one-sided wavy surface has been investigated by means of hot-wire anemometry. It has been experimentally shown that the pre-set disturbance from the sawtooth cut on the leading edge would create a variation in boundary layer thicknesses in the spanwise direction, which corresponds to the upwash and downwash region. Such variation of boundary layer thickness is sensitive to the flow instability, which depends on the Reynolds number Re and the ratio of the amplitude of the wavy surface to the channel gap S . The presence of wavy surface in a channel prevents the pre-set vortices to breakdown earlier, thus might improve the mixing due to the three dimensional movements of the fluid induced by the appearance of such vortices.

As the flow becomes more unstable, the disappearance of the mushroom-like structure prior to turbulence occurs earlier. The variation of the velocity profile at the upwash and downwash region is associated to the growth of disturbance amplitude, which could explain the downstream development and decay of the counter-rotating streamwise vortices. Under certain conditions, the splitting of the vortices prior to their breakdown can also be observed.

NOMENCLATURE

a	amplitude of wavy surface
H	channel gap, measured at the leading edge
Re	Reynolds number ($=U_c H / 2\nu$)
S	ratio of amplitude of wavy surface to channel gap
Tu	turbulence intensity
$\hat{u}$	instantaneous (sampling) velocity
$\bar{u}$	mean (sampling) velocity
u	local streamwise velocity
u_{dw}	local streamwise velocity at downwash region
u_{uw}	local streamwise velocity at upwash region
U_c	central streamwise velocity
x, y, z	Cartesian coordinates system
κ_u	dimensionless disturbance amplitude
$\kappa_{u,max}$	maximum dimensionless disturbance amplitude
λ	wavelength of the wavy surface
ν	fluid kinematic viscosity

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Highlights:

- Pre-set counter-rotating streamwise vortices have been successfully quantified
- Various size and shape of vortices as Re , channel gap, and amplitude changes
- Disappearance of the mushroom-like structures near the second peak