From natural to forced counter-rotating streamwise vortices in boundary layers

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Abstract. Counter-rotating streamwise vortices (CRSVs) are ubiquitous in Fluid Mechanics, and especially in boundary layer and shear layer flows. A short review is presented showing how the CRSVs are naturally generated in boundary layer flows and how they can be artificially generated in the purpose of efficient flow control experiments.

1. Introduction
CRSVs are very common in many different types of flow and especially in boundary layer flows. They can occur naturally as the result of an instability mechanism. It will be the case of various manifestation of the centrifugal instability, for instance. It can also be seen in turbulent boundary layers as turbulent ”streaks”. This ”natural” CRSVs will be the subject of the first section.

Another way to create CRSVs is to use artificial devices in the boundary layer like, for instance, classic vortex generators (VGs) or wall-mounted bluff-bodies. Through different mechanisms, both types of devices lead to the creation of counter-rotating longitudinal vortices that, ultimately, can be used to control the physical properties of a boundary layer. It can be an objective in itself for heat transfer applications for instance [8]. This will be the subject of sections 2 and 3. Through these different examples, the objective of this paper is to give a short overview of the many different situations in which CRSVs can be encountered, even when unexpected.

2. Counter-rotating streamwise vortices naturally occurring in unforced flows
As mentioned earlier, the CRSVs can be encountered in many natural unforced flows and can then be seen as one of the most natural way for a flow to dissipate energy or to balance some external forces. From a general point of view, this 3D spatial organization of the flow seems to occur in the latest stage of non-linear saturation. The most well-known instability leading to CRSVs is the centrifugal instability which can occur when the centrifugal force overcomes the radial pressure gradient. From a general point of view, it can happen any time the flow exhibits curved streamlines. In the centrifugal instability family, one can distinguish three main configurations: the Taylor-Couette instability, the Dean instability and the Görtler instability (figure 1). The last one happens in an open-flow, within a boundary layer spatially growing over a concave wall, while the two firsts happen in confined flows. The Taylor-Couette instability
develops in the gap between two counter-rotating cylinders. The Taylor-Dean instability occurs in a curved pipe flow.

Figure 1. CRSVs generated by centrifugal instability: (a) the Taylor-Couette flow, (b) the Taylor-Dean Flow and (c) the Görtler instability.

In all cases, the onset of the instability depends on the curvature of the geometry. One of the consequences is an early transition to turbulence in the boundary layers growing over a concave wall compared to the flat-plate configuration. Depending on the situation, the occurrence of CRSVs in the boundary layers will be a problem (loss of efficiency of air cooling over hot rotating blades for instance) or, on the contrary, welcome (better mixing properties for instance). This is illustrated on figure 2 where the scalar concentration field is compared to the longitudinal velocity field [10]. One can see the typical "mushroom-like" structures observed in every visualizations of centrifugal instabilities. The centrifugal instability can lead to an early transition to turbulence. The CRSVs are still present in the boundary layer as intermittent structures whose signatures can be found in the statistics of time-series of fluctuation of concentration for instance [13].

Figure 2. Comparison between the contour of scalar concentration (a) and longitudinal velocity (b) in the cross-section of a spatially growing boundary layer over a concave wall (Görtler flow). One can see the "mushroom-like" structures typical of the Görtler CRSVs associated to the low-velocity (outflow) regions [10].
As mentioned earlier, the centrifugal instability can occur any time the curvature of the streamlines is high enough which is the reason why it is probably a much more common and universal phenomenon than expected. An example illustrating this idea is a recent observation made for the backward-facing step flow [5]. Indeed, an experimental investigation of the transitions of the flow downstream a backward-facing step revealed the existence of CRSVs (figure 3), at very low Reynolds number \( Re = U h / \nu = 100 \) when the flow is stationary and 2D, i.e. before the critical Reynolds number for the shear layer instability. In this case, the authors could relate the creation of CRSVs to a local Görler number calculated on the local curvature of the streamlines of the 2D flow obtained through a 2D CFD computation.

![Figure 3](image)

**Figure 3.** Visualization in a cross-section of the flow downstream a backward-facing step in the reattachment region (a). The Reynolds number \( Re = U h / \nu = 100 \) is below the critical Reynolds number of the shear layer instability so that the flow is stationary and 2D. One can clearly see (b) the mushroom-like structures characteristic of Görler type CRSVs [5].

Another example of CRSVs can be found in large Reynolds number flows like turbulent boundary layers. As a matter of fact, many experimental and numerical studies show that a turbulent boundary layer exhibits the so-called "turbulent streaks" which are essentially patches of counter-rotating longitudinal vortices. This is illustrated on figure 4, with a cross-section of a turbulent boundary layer artificially generated through a Large Eddy Simulation (LES) [2]. The figure (a) is a vector plot of transversal velocity field showing many longitudinal vortices in the boundary layer. The figure (b) is a contour plot of longitudinal velocity showing the low-velocity plumes which are the signatures of CRSVs that can also be observed in Görler instability, as shown on figure 2.

3. **Counter-rotating streamwise vortices artificially generated in the flow**

It is also possible to force the creation of CRSVs through geometric artifacts. There are mainly two ways to generate streamwise vortices: through specifically designed Vortex Generators (figure 5) or through junction flows (figure 7).

VGs are usually designed and used to modify the physical properties of a boundary layer. One can distinguish the "mechanical" VGs from the "fluidic" VGs, or Jet Vortex Generators (JVGs). There are many different types of geometry for the mechanical VGs, as illustrated on figure 5. In particular there are many variations of the vane-type VGs [3, 4] (figure 5(b) and (c)) that are used to control separated flow (typically over an airfoil for aeronautics applications) or to improve the mixing in the boundary layers in heat exchanger [15] or chemical reactors.
Figure 4. CRSVs generated in a turbulent boundary layer: contours of streamwise velocity (a) and velocity vectors (b) in a cross-section of the flow obtained by LES simulation [2].

The non-conventional geometry presented on figure 5(a) has been used to increase the mixing in static chemical reactors [11], in the framework of a JouleII European Project. It was also used more recently to reduce both drag and lift of a 3D bluff-body as well as a real car [1]. The interest of such a geometry is that the angle between the blade and the wall can be varied, making it an active VG. This has mainly two advantages: one can control the angle as a function of a given control parameter (freestream velocity for instance) to ensure an optimal efficiency of the system in a closed-loop experiment [6]; the blade can be integrated in the wall when it is not used. Flow visualizations downstream of a row of BVGs revealed mushroom-like structures (figure 6) typical of CRSVs, and very similar to the one observed in centrifugal instabilities.

Figure 5. Examples of VGs: non-conventional BVGs (Blade Vortex Generators) (a) and classic vane types VGs generating inflow (b) or outflow (c) CRSVs.

Figure 6. Visualization of CRSVs downstream a set of BVGs. One can clearly see the typical visualization of mushroom-like structures as observed with Görtler vortices [10].
Junction Flows are created at the base of any wall-mounted bluff-bodies facing an incoming boundary layer [12]. A typical example is shown on figure 7(a) for a wall-mounted cylinder in a boundary layer [14]. One can see clearly the creation at the base of the cylinder of a horse-shoe vortex. The two arms of the horse-shoe vortex stretches around the bluff-body and finally create a pair of CRSVs further downstream (figure 7(b)). This kind of flow can be encountered in many different situations, like at the base of buildings in atmospheric boundary layer or in standard boundary layers flowing over an obstacle. As this kind of geometry generates strong CRSVs, it can be used collectively as VGs. Their efficiency will then depend on many parameters, like the spacing between the VGs. This point is the subject of the following section.

Figure 7. (a) Visualization of junction flow and horse-shoe vortex around the base of a cylinder mounted on a wall [14]. (b) Sketch of the pair of CRSVs created downstream of a cylinder mounted on a wall. The inflow and outflow regions are also shown.

4. Counter-rotating streamwise vortices as a tool for Flow Control

Once the ubiquitous nature of CRLVs in boundary layer flows is established, one can think of using them as a tool to control the flow. Generating CRSVs can strongly modify the properties of a flat plate boundary layer. This is what has been studied using four cylinders as VGs (also called CVG for Cylindrical Vortex Generators) which are defined by their diameter \( d = 8mm \) and their height \( h = 6mm \) [7]. The spacing between the VGs, or wavelength \( \lambda \), is fixed and equal to \( 3d \) (figure 8(a)).

The experiments are carried out in a low-speed water tunnel made of plexiglas to allow optical measurements from any direction including downstream. The flow is driven by gravity using a water reservoir kept to a constant height. The rectangular cross section of the tunnel is 100mm high and 150mm wide. The test-section is 800mm long. The four VGs are located 100mm downstream from the beginning of the test section. As shown in figure 8(a), the origin is taken at the lower wall, at the symmetry point of the VG line. \( x, y, z \) are respectively the longitudinal, the vertical and the spanwise directions. The mean freestream velocity is \( U_\infty = 4cms^{-1} \). The typical boundary layer thickness at the beginning of the test section is about 10mm.

We make a 3D reconstruction of the boundary layer using two-components PIV measurements in different horizontal planes parallel to the wall. We show on figure 8(b) a typical longitudinal velocity contour downstream of the CVG for \( z = 3mm \). It clearly shows spanwise modulations with inflow (accelerated, in red) and outflow (decelerated, in light blue) regions which can be interpreted as nonlinear perturbations. When the inflow regions are large, the result is a global decrease of the boundary layer thickness and then a global increase of the boundary layer velocity gradient. This should induce a modification of the base flow. One should emphasize here the longitudinal persistence of the perturbations. Some preliminary measurements were carried out.
more than 40d downstream the VGs and the spanwise modulation of the longitudinal velocity field could still be observed. This observation confirms that the CRSVs is one of the most natural perturbations for a boundary layer. If it had not been the case, the perturbations would have decayed very quickly.

For this Reynolds number the flow is steady and can be separated in different linear and non-linear perturbations:

\[ U(x, y, z) = U_{\text{base}}(x, y) + u_L(x, y, z) + u_{nL}(x, y, z), \]  

(1)

where \( U_{\text{base}} \) is the base flow boundary layer, \( u_L \) is the first harmonic perturbation (wavelength \( \lambda \)), while \( u_{nL} \) is the nonlinear perturbation. We can write the different perturbations as Fourier decompositions, averaged along the \( z \) direction on only two wavelengths (between \( z = -24 \text{mm} \) and \( z = 24 \text{mm} \)) to avoid most of boundary effects:

\[ u_L(x, y, z) = u^*_1(x, y) \exp \left( i \frac{2\pi}{\lambda} z \right), \]  

(2)

\[ u_{nL}(x, y, z) = \sum_{k \geq 0, k \neq 1} u^*_k(x, y) \exp \left( i k \frac{2\pi}{\lambda} z \right), \]  

(3)

\[ \left< U(x, y) \right>_z = U_{\text{base}}(x, y) + u^*_0(x, y), \]  

(4)

where \( U(x, y, z) \) is the measured flow-field with the VGs while \( U_{\text{base}}(x, y) \) is the measured base flow without the VGs. The mean flow modification (or zeroth-mode [16, 9]) \( u^*_0(x, y) \) is then calculated, after \( z \)-averaging the flowfield with VGs on a multiple of the forcing wavelength and substracting the measured base flow. The vertical profiles \( u^*_0(x, y) \) computed for every \( x \) position can be integrated over the vertical direction \( y \) to give a global estimate of the zeroth mode along the \( x \) direction:

\[ E_o(x) = \int_0^\infty u^*_0(x, y) dy, \]  

(5)

From the longitudinal evolution of \( E_o \) we can evaluate different quantities which could help to choose some critical parameters in a VG experiment, like the minimum longitudinal distance from the separation the VG should be placed. As a matter of fact, \( E_o \) can be seen as a global measure of the balance between inflow and outflow regions: if \( E_o > 0 \), the flow is dominated by inflow regions, and respectively outflow regions for negative values. We call this value the
"inversion length" $L_{inv}$ and we show its evolution as a function of the spacing of the VG on figure 9. We see that the case $\lambda = 3d$ leads clearly to the shorter $L_{inv}$. For this spacing, we know that the flow will be dominated by the inflow regions and should lead to a delay of the separation.

![Figure 9](image1.png)

**Figure 9.** (a) Evaluation of the inversion length $L_{inv}$ from the longitudinal evolution of the energy of the zeroth mode $E_0(x)$. (b) Dependency on the spacing between VGs of the spatial growth rate $\beta$ of $E_0(x)$.

The configuration with four CVGs and a $3d$ spacing has been used on a separated flow over a smoothly-rounded ramp (figure 10). The CVGs are located $10d$ upstream from the beginning of the curved ramp so that the flow will be clearly dominated by the inflow regions when it reaches the separation line. We show the result on figure 11: the averaged separation is delayed by 20%, i.e. $5.5\text{mm}$ compared to the natural separation line. This result seems to confirm that the inversion length is a good parameter to choose the location of the VGs line.

![Figure 10](image2.png)

**Figure 10.** Description of the experimental set-up. The four CVGs are located $10d$ upstream of the contoured ramp and the spanwise spacing is $3d$.

From the analysis of the linear and non-linear perturbations induced by a set of VGs, one should be able to find other criteria relevant to choose the optimal parameters for a given flow control experiment. It also is associated to the search of the optimal perturbations for a spatially growing laminar, transitional or turbulent boundary layer.

5. Conclusion
In this short review it has been shown how the CRLVs are ubiquitous in many natural flows and especially in boundary layers in which they appear as one the most natural coherent structures.
Figure 11. Streamlines of time and space averaged flow over a smoothly contoured ramp in a vertical plane, without VG’s (a) and with VGs (b). The average separation line is delayed further downstream. The position of the separation is marked with the dotted lines.

This is also the reason why the CRLVs they seem to be the perfect tool for flow manipulation: one the perturbation has been injected, it grows spatially and a very long persistent length can be observed in the longitudinal velocity field.

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