The effects of flexible vortex generator on the wake structures for improving turbulence

Sharul Sham Dol1,*, Hiang Bin Chan2, Siaw Khur Wee2 and Kumar Perumal2

1Department of Mechanical Engineering, Abu Dhabi University, Abu Dhabi, United Arab Emirates
2Faculty of Engineering and Science, Curtin University Malaysia, Miri, Sarawak, Malaysia

*E-mail:sharulshambin.dol@adu.ac.ae

Abstract. Turbulence is a very useful flow characteristic that is used in many engineering devices to facilitate mixing, heat transfer in heat exchanger and improving aerodynamics in propeller. This paper has numerically studied the spatial characteristics of the wake behind a free-oscillating flexible vortex generator (FVG) in order to evaluate its turbulence generation ability. As the wake is playing as the effective turbulence region, the spatial characteristics can reflect the ability of the FVG in turbulence generation when a larger wake size indicates a greater turbulence region. Two VGs are considered in this study; circular and flat plate cantilever. Each VG was submerged individually in a subcritical flow ($10^2 < Re_D < 10^5$) and the generated wake was studied. The wake behind the FVG was visualized via the lambda2 vortex identification criterion and it was compared with its respective rigid counterpart. From the comparison, it is found that the FVG has a larger wake compared to its rigid counterpart. The result demonstrates that the FVG can generate a larger turbulence region. The cause of the increasing wake size was found to be the weakening of downwash behind the FVG when it bends. The downwash becomes weaker as the deflection of the FVG increases.

1. Introduction

Turbulence plays an important role in those devices in facilitating mixing, heat transfer process and improving aerodynamics. In engineering applications, such as a heat exchanger and lift generation devices, the implementation of vortex generators (VGs) guarantees a better turbulence generation that helps to improve the overall performance of the exchanger and improving aerodynamics in airfoils. The implementation of vortex generators in engineering devices is a common yet promising strategy to generate turbulence. VG is normally a static structure that can generate turbulence by disturbing the flow; it can be in any shape, including winglets, cylinders, blades, blocks and others. As long as the structure can interrupt the flow, it can be generalized as a VG.

This study proposes to manipulate the structural properties of a VG, in particular, the stiffness of the VG to achieve flexibility; hence creating a flexible vortex generator (FVG) that can oscillate depending on the surrounding flow dynamics. It is expected that the turbulence and the wake characteristics behind the oscillating FVG will be different compared to a rigid vortex generator (RVG). In this study, circular cantilevers and flat plate cantilevers, with different aspect ratio (AR), are used as the VG.
The study of flow dynamics behind an oscillating object, such as a cylinder or cantilever, have received relatively less attention than its structural dynamics. In the current understanding of flow past an oscillating object, the vortex pattern behind the object, either in 2-dimensional or 3-dimensional cases, has established a respectively comprehensive information compared its turbulence characteristics aspect. The vortex pattern has been studied by a number of researchers [1-4], and the results agree well with the vortex pattern map founded by [5].

However, there are limited studies on the turbulence characteristics behind an oscillating object. Griffin [6] conducted an experimental study on a forced-oscillating cylinder. This work resembles considerably to the current work except that the cylinder was forced-excited instead of oscillating passively. They measured the velocity field using hot-wire anemometry and the velocity fluctuation that represents the turbulent regime was computed. It was found that the velocity fluctuation behind the forced-oscillating cylinder was greater than a stationary one.

Yong et al. [7] experimentally studied the flow dynamics behind a flexible finite cylinder in a single-phase flow using a water tunnel via ultrasonic velocity profiler measurements. They found based on the turbulence production analysis, the flexible cylinder can generate turbulence at maximum 2.27 times of the amount generated by the rigid cylinder under the same flow condition.

The present study focuses on the turbulence characteristic behind an oscillating FVG via analyzing the spatial aspects of the wake. Since the wake behind a VG can be regarded as the region where turbulence activities take place, the size of the wake should be considered as one of the aspects of the VG’s turbulence generation ability. The work was done via the Fluid-Structural Interaction (FSI) simulation, which integrates both CFD and FEA. The model was validated with published data (e.g. [8]).

2. Numerical model

After reviewing some related studies, it is found that the RANS model is one of the popular fluid flow models that is used in simulating the FSI (e.g. [9]). In all of the mentioned papers, the classical equation of motion is used as the structural model.

Unsteady Reynolds-Averaged Navier-Stokes (URANS) equation is used to compute the fluid flow. SST k-ω turbulence model is used to model the turbulence. Details of the URANS equation, energy equation and (SST) k-ω turbulence model can be found and described extensively in [10, 11]. The typical (3 degree-of-freedom) equation of motion, Eq. (1) is used to model the structural motion:

\[ m\ddot{x} + q\dot{x} + kx = \sum F_x \]  

where \( F_x \) is the force in \( i \)-direction, \( m \) is the mass, \( q \) is the damping coefficient and \( k \) is the spring constant.

An important aspect of the numerical model is the method that couples the structural model with the fluid flow model. In the present work, a strong two-way FSI coupling method is used. Besides, an implicit coupling scheme is used during data transfer. This implies that the data is transferred iteratively within the two models until the pre-determined termination criteria are satisfied [10].

![Figure 1. Schematic of the fluid domain (not to scale).](image)

Figure 1 represents the simulation domain used in this study. Uniform flow was applied in the inlet of the domain. The boundary conditions of the flow domain are provided in [10]. In this study, the
circular and flat plate cantilever are used as the VG. The fluid, flow and structural properties of the simulated cases are given in [10].

A mesh independency study was carried out to obtain the best mesh for the study. The $y^+$ value was constantly monitored to ensure that it falls below 5 – a threshold or criteria from the Law of the Wall that allows the near wall mesh to model the boundary layer correctly. Unstructured polyhedral meshes are used in this study. The meshes that were used in this independency study is tabulated in [10]. Note that the mesh size is defined based on the diameter of the cantilever – the characteristic length of the present study. This allows the mesh to be universally applicable in any cases with the same configuration but with a different cantilever size.

The drag coefficient, pressure profile and velocity profile were monitored to get the optimal mesh size, as shown in figure 2. From the study, Mesh 4 is selected as the optimum mesh based on the analyses. The selection criteria are based on the convergences of each data monitored as the mesh size changes. The monitored results were converged at Mesh 4 and further refinement to Mesh 5 does not cause significant differences in the results (e.g. $C_D$). A structured hexahedral mesh is used on the VGs.

![Figure 2](image)

**Figure 2.** The mesh independency study: (i) drag coefficient, (ii) pressure profile at $x/D=0.75$ downstream and (iii) velocity profile $x/D=0.75$ downstream.

**3. Results and discussion**

The wake is visualized using Lambda2 criterion, a mathematical scheme developed by [12] to define vortex boundary. The Lambda2 criterion defines the boundary of a vortex only when the second eigenvalue of $S^2+Ω^2$ is negative. This method has been used in other studies defining vortices (for example, in [13, 14]) and good results are obtained. In the following section, the Lambda2 iso-surfaces are presented. In other words, it is a 3-dimensional visualization. An abbreviation is introduced to facilitate the following discussion. With this abbreviation, the lengthy “AR=8 circular FVG” can be written as 8CF; where the “8” denotes the aspect ratio, the “C” denotes “circular” (it will be “P” for flat plate), and the “F” denotes “FVG” (it will be “R” for RVG). Using this concept, “AR=5 flat plate RVG” can be written as 5PR.

Firstly, the height of the wake is examined. In this discussion, the presented figures focus on the Lambda2 iso-surface in the $x$-$z$ plane (side view). The wake behind the rigid and flexible circular RVG and FVG are presented. Figure 3 clearly shows that the wake of the circular FVG has greater height compared to the wake of circular RVG, regardless of AR. The wake of the FVG has increased 62.2%, 25% and 25% for AR=6, 8 and 10 cases respectively. Next, the wake of flat plate RVG and FVG are presented, in figure 4. Unlike the circular FVGs, the wake of flat plate FVG does not show significant height difference at lower AR. The height difference only becomes observable at greater AR; where the wake of the 6PF is greater than that of the 6PR by ~21.3%. As mentioned before, the wake represents the effective region where turbulence activities take place. Hence, a larger wake generated by the FVGs denotes a spatially greater turbulence compared to the RVGs.
The cause of the wake height increment will be discussed in the following discussion. It is known that the transportation of vortex depends on the velocity field of the flow, therefore, in order to examine the cause of the wake height increment, the mean streamlines behind the VGs are computed. The mean streamlines plot of the circular cases are shown in figure 5. Based on the mean streamline plots of the RVG case, a downwash (a downward fluid flowing motion) is present behind the circular RVG. The downwash is a common flow feature behind a cantilever, which is reported by all works that have studied the flow past a cantilever. By comparing the streamlines of the RVG case with its respective Lambda2 iso-surface, it is clear that the vortex structure is downwashed towards the ground plate by this unique flow feature and eventually it causes the wake height to be shorter than the total length of the RVG. On the other hand, the downwash is not present behind the circular FVG. As a result, the vortex structure is transported to the downstream without experiencing any downward motion. Thus, the wake of circular FVG has an equivalent height irrespective of its aspect ratio.

Figure 6 shows the streamline plots of the flat plate cases. In contrast to the circular case, the downwash behind the flat plate FVG does not vanish completely. It is weakened only at higher AR, which has explained the insignificant wake height difference between FVG and RVG at low AR. Now, it is clear that the weakening or vanishing of the downwash plays an important role in the wake height increment, but it raises another question: what governs the weakening or vanishing downwash? To answer this question, the evolution (time series) of the streamlines plot is examined. Note that the streamlines of the circular case do not possess significant changes with time. Therefore, the streamlines plot of the flat plate case is used to identify the relationship, as shown in figure 7. From the figure, it can be observed that the weakest downwash is obtained when the flat plate FVG is attaining a larger deflection. Conversely, the strongest downwash is attained when the flat plate FVG is at its smallest deflection. This observation suggests that the strength or scale of downwash is scaled with the degree of deflection of the FVG; the greater the deflection, the weaker the downwash.

![Figure 3. The lambda2 iso-surface at the z-x plane-of-symmetry (y/D=0), of the circular (i) RVG and (ii) FVG, with (a) AR=6, (b) AR=8 and (c) AR=10.](image)

![Figure 4. The lambda2 iso-surface at the z-x plane-of-symmetry (y/D=0), of the flat plate (i) RVG and (ii) FVG, with (a) AR=4, (b) AR=5 and (c) AR=6.](image)
Figure 5. The streamlines of the normalized mean velocity magnitude at the plane-of-symmetry \((y/D=0)\) of the circular (i) RVG and (ii) FVG, with (a) \(AR=6\), (b) \(AR=8\) and (c) \(AR=10\).

Figure 6. The streamlines of the normalized mean velocity magnitude at the plane-of-symmetry \((y/D=0)\) of the flat plate (i) RVG and (ii) FVG, with (a) \(AR=4\), (b) \(AR=5\) and (c) \(AR=6\).

Figure 7. The streamlines plot at the plane-of-symmetry \((y/D=0)\) of 6PF at (top) \(t=3.63s\) and (bottom) \(t=3.83s\).

4. Conclusion
In general, the FVG can generate wake with greater height compared to the RVG. In the current study, the circular FVGs have generated wake with 25.0–62.2% taller wake than the wake of the RVG; and the wake of the flat plate FVGs is at most ~21.3% taller than the wake of the RVG. The wake height increment is caused by the weakening or vanishing of downwash behind the FVG. The weakening or vanishing of downwash is scaled with the degree of deflection; the greater the deflection, the weaker the downwash. The width of the wake does not differ significantly despite a large transverse motion of the FVG. Since the wake represents the effective region where turbulence activities can take place, a larger wake generated by the FVGs denotes a spatially greater turbulence compared to the RVGs. Besides, this present study has demonstrated a different viewpoint to study turbulence generation ability other than the classical statistical study. The spatial analysis shed light on the possibility to actively control the spatial scale of turbulence, without compromising the turbulence strength, by simply altering the deflection of a VG in the system.
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