AN EXPERIMENTAL STUDY OF UNSTEADY VORTEX / TURBULENT BOUNDARY LAYER INTERACTIONS

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by

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LIST OF ABBREVIATIONS

1D	One Dimensional
2D	Two Dimensional
3D	Three Dimensional
AoA	Angle of Attack
AR	Aspect ratio
CCD	Charged Couple Device
CFD	Computational Fluid Dynamic
CoR	Co-Rotating
CtR	Counter-Rotating
Hp	Horse Power
HWA	Hot Wire Anemometry
LDA	Laser Doppler Anemometry
MVG	Micro Vortex Generator
OLWT	Open Loop Wind Tunnel
PC	Personal Computer
PDA	Phase Doppler Anemometer
PIV	Particle Image Velocimetry
RPM	Revolution per Minute
SBVG	Sub Boundary Layer Vortex Generator
TBL	Turbulent Boundary Layer
VG	Vortex Generator

LIST OF SYMBOLS

β	Vortex Generator Angle of Incidence
$\delta(x)$	Boundary Layer Thickness
ρ	Density
μ	Dynamic Viscosity
c	Vortex Generator Chord Length
c/h	VG chord length to VG height ratio
d	Vortex Generator Spacing Between Trailing Edge to Trailing Edge
d/h	VG trailing edge spacing VG height ratio
D	Vortex Generator Spacing in the Spanwise Location
f	Frequency
h	Vortex Generator Height
h/δ	VG height to boundary layer thickness ratio
k	Reduced Frequency
$\mathcal{R}e_x$	Reynolds Number
U_∞	Free Stream Velocity

KAJIAN EKSPERIMEN TENTANG INTERAKSI DI ANTARA VORTEKS TIDAK MANTAP DENGAN LAPISAN SEMPADAN GELORA

ABSTRAK

Tujuan utama kajian ini adalah untuk menyiasat kebolehan penjana vortek sub lapisan sempadan berayun melalui kaedah eksperimen. Kerja penyelidikan sekarang tertumpu kepada interaksi antara lapisan sempadan gelora dan penjana vortek sub lapisan sempadan. Tinggi penjana vortek adalah bersamaan dengan 20% ketebalan lapisan gelora. Kerja terbahagi kepada dua iaitu penjana vortek sub lapisan sempadan mantap (pasif) dan penjana vortek sub lapisan sempadan bergerak (aktif). Vortek mantap di hasilkan oleh penjana vortek sub lapisan sempadan statik dengan sudut tuju 18° untuk panjang perentas penjana vortek, tinggi dan ruang diantara penjana vortek yang berlainan. Untuk menghasilkan vortek tidak mantap, penjana vortek sub lapisan gelora di gerakkan pada beberapa frekuensi. Penjana vortek sub lapisan sempadan bergerak di gerakkan antara sudut tuju -18° dan 18°. Pergerakan ini dilaksanakan pada frekuensi terturun 0.03, 0.08, dan 0.16. Penjana vortek sub lapisan sempadan statik menunjukan nisbah bidang memainkan peranan penting untuk menipiskan lapisan sempadan gelora dan pemulihan pemisahan aliran. Frekuensi terturun terendah penjana vortek bawah lapisan sempadan bergerak menunjukan perkembangan baik vortek tidak mantap. Selain daripada itu, penggunaan penjana vortek sub lapisan sempadan bergerak terbukti efektif dalam pemisahan aliran.

AN EXPERIMENTAL STUDY OF UNSTEADY VORTEX / TURBULENT BOUNDARY LAYER INTERACTIONS

ABSTRACT

The main aim of the present study is to investigate the performance of an oscillating sub boundary layer vortex generator (SBVG) through experimental approach. The current research work will focus on the interaction between turbulent boundary layer and SBVG. The vortex generator height, h is approximately equal to 20% of the boundary layer thickness, δ. The work is divided into two parts i.e. steady (passive) SBVG and oscillating (active) SBVG. The steady vortex was created by the static SBVG with angle of incidence, β of 18° with different vortex generator chord length, height, and spacing between vortex generators. In order to create unsteady vortex, the SBVG was oscillated at a number of frequencies. The oscillating SBVG was oscillated between range of -18° and 18° angle of incidence. This motion was executed at reduced frequencies, k of 0.03, 0.08 and 0.16. The static SBVGs show that the AR plays an important role for TBL thinning and flow separation recovery. The lowest reduced frequency of the oscillating SBVGs show a good development of unsteady vortices. In addition, the oscillating SBVG employment is proven to be effective in removing the flow separation.

CHAPTER 1

INTRODUCTION

1.1 General Introduction

The art of flow control is as old as prehistoric man, whose sheer perseverance resulted in the invention of streamlined spears, sickle-shape boomerangs, and fin stabilized arrows. The German engineer Ludwig Prantl pioneered the science of flow control at the beginning of the twentieth century. The Second World War, and the Oil Crisis, motivated vigorous progress on flow control so as to achieve minimum dependence on oil usage with maximum control of the flows on aircraft. Spiralling oil prices and the concerns over global warming have further enhanced this motivation [1].

The flow field around wing, fuselage, empennage, and engine nacelle contribute to the value of lift and drag. The ability to manipulate the flow field actively or passively could potentially save millions of dollar in annual fuel costs. The challenge however is to achieve the ability using a simple device which is inexpensive and uncomplicated as possible to manufacture, operate and generate minimum adverse side effect. There are two main strategies which is the flow control device can be passive, requiring no auxiliary power and no control feedback, or it can be active requiring energy expenditure.

Passive methods could be slots on airfoils or turbulators which is surface protrusions used to trigger transition and utilize the fact that turbulent boundary layers are more resistant to separation than laminar boundary layers [1]. One of the most popular forms of passive separation control is the use of the vortex generators. Vortex generators are a surprisingly simple method of delaying flow separation. They consist of small lifting surfaces mounted normal to the surface. This results in the generation of streamwise vortices that cause an overturning of the flow thereby increasing the flow momentum near the wall. On the other hand, active methods may consist of jets used to energize to near wall flow, suction points used to control the local flow or moveable component which generate the oscillating vortices.

The concept of vortex generators was introduced by Taylor in 1948 [2], and has been applied in large variety of cases of internal and external flows, such as diffusers, compressor blades and airfoils. The successful use of vortex generators has result a 100% increase in the lift-to-drag ratio for a high-lift airfoil and significant reductions of the pressure loss in diffusers [2].

Control of turbulent flows, turbulent boundary layers in particular, has been a subject of much interest owing to the high potential benefits. Skin friction drag, for example, constitutes a large fraction of the total drag on commercial aircraft and cargo ships, and any reduction entails substantial saving of the operational cost for commercial airlines and cargo-shipping industries. Successful control, however, requires both a thorough understanding of the underlying physics of turbulent flow and an efficient control algorithm.

In the current study, the author investigates the effects of 2 types flow control device namely passive and active device. Both devices consist of low-profile or sub-boundary layer half delta wing shape vortex generators applied on the backward facing ramp surface. Backward-facing ramp is chosen as the test bed because it's generating a fully separated flow. It's hypothesized that both devices will be able to reduce the flow separation region significantly. In numerical investigation, Ahmad et al.[3] has studied the flow separation control of the diffuser using the oscillating sub boundary layer vortex generator. Therefore, experimental investigation of the effect of the oscillating sub boundary layer vortex generator to delay the flow separation carried out with different low range reduced frequency and the interaction of the unsteady vortex generated by the oscillating sub boundary layer vortex generator toward the turbulent boundary layer was studied.

1.2 Investigative Techniques

Most previous work related to flow control are based on an experimental approach. An experimental approach is preferable to develop the fundamental principles of the complex flow physics of vortex/boundary layer interaction. Experiments are also the most reliable method of investigation and provide the most accurate results.

Experimental approach come in many ways such as the particle image velocimetry (PIV), laser doppler anemometry (LDA), hot wire anemometry (HWA), flow visualization and others. For this experimental work, a particle image velocimetry (PIV) measurement technique was used. PIV has been used to measured velocity fields successfully for experimental conditions ranging from creeping flow in micro channels to supersonic flow in wind tunnels. PIV is a special technique which able to visualize large regions of the flow field and with the possibility to extract fluid flow information such as velocity, vorticity and turbulence patterns. PIV is also a non-intrusive technique because it is an optical technique and there is no disturbance introduced into the flow, as experience in other methods such as hot wire anemometry and pressure probe testing. PIV requires four basic components which is an optically transparent test section containing the flow seeded with tracer particles, a laser sheet to illuminate the region of interest, recording hardware consisting of either a CCD camera, or film, or holographic plates, and a software to process the recorded image to extract the velocity vector from the tracer particle.

1.3 Aim and Objectives

The aims for this research are to explore the performance of a sub boundary layer vortex generator (SBVG) by mean of passive and active devices embedded in the turbulent boundary layer. The aims include the following objectives:

- To provide the experimental database for the flow field induced by an oscillating sub boundary layer vortex generator (SBVG)
- To map, understand and analyse the flow field produced by the unsteady vortices and the turbulent boundary layer
- To investigate the effects of parameters involves in the mechanics of this flow interaction, such as the device reduced frequency

1.4 Thesis Organization

This thesis consists of 6 chapters. The present chapter has provided a general introduction and the aims and objectives of the current project. A brief review of previous work related to the project is described in Chapter 2. In Chapter 3, the experimental method and apparatus are briefly explained. Chapter 4 present results obtained from the static vortex generator. The oscillating vortex generator applied to separation flow is presented in Chapter 5. Finally, Chapter 6 concludes the present work.

CHAPTER 2

LITERATURE REVIEW

2.1 Flow Control

2.1.1 Introduction

Flow control is defined as a positive manipulation of fluid flow. Typically the aim is to control the transition and separation, to reduce the drag, to enhance the lift, to augment the mixing mass, momentum or energy, to suppress the flow induced noise, or a combination of these to meet any of these targets, for wall bounded flow, involves either the delay or advance of transition from laminar to turbulent flow, the prevention or provocation of flow separation, or the suppression or enhancement of turbulence levels. In the next sub-chapter, only separation control and mixing enhancement flow control methodology will be discussed.

2.1.2 Separation Control

Flow separation is generally accepted to be the breakaway or detachment of fluid from a solid surface. Separation is generally accompanied by significant thickening of the rotational flow region adjacent to the surface with a marked increase in the velocity component that is normal to the surface. Separation is almost always associated with losses of some kind, including loss of lift, drag increase, and pressure recovery losses. Flow separation control can be met by placing vortex generator on the wings [4, 5, 6, 7, 8], placing the blown flap, leading edge extension or strakes and using passive bleed in the inlets of supersonic engines.

Jirasek [4] has carried out a computational fluid dynamic (CFD) simulation for three element high lift airfoil with vortex generators. They found that the flow separation was eliminated by using vortex generators. Lin et al. [6] experiment showed that the attenuating flap resulted in significant narrowing of the wake of the three element airfoil as shown in the Fig. 2.1. Flow separation on the flap (without VG) covered approximately 0.5c in the vertical direction, whereas when VG was applied it covered only 0.2c.

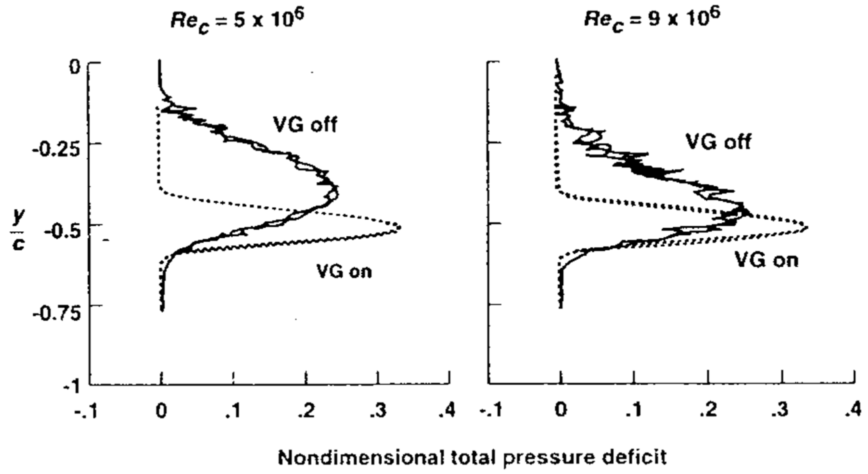

Fig. 2.1 Effect of vortex generators on wake profiles ***(reproduced from Lin et al. [6] page 1320)***

Ashill et al. [5, 9] and Rae et al. [10] carried out an experimental work to visualise the effect of the vortex generator onto the flow separation on the bump flow, as the sub boundary layer vortex generator will reduce the length of separation region. They showed that the decay rate of the vortices downstream of the split vanes is lower than the joined vanes of the forwards wedges.

Jenkins et al. [7] has conducted an experimental investigation of flow separation for adverse pressure gradient test bed. They found out that the micro vortex generators are more effective than any of the other devices in recovering pressure in backward facing ramp. [see Fig. 2.2]

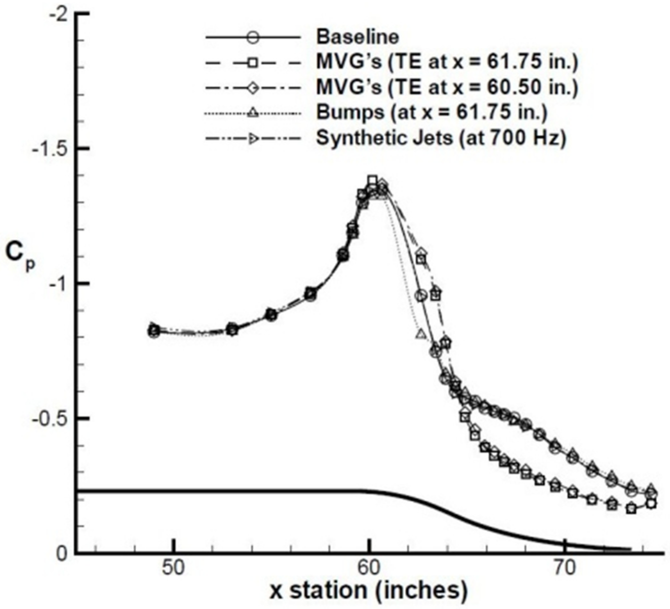

Fig. 2.2 Comparison of Pressure Distributions micro vortex generators, bumps, synthethic jet ***(reproduced from Jenkins et al.*** [7] ***page 10)***

Separation control effectiveness was evaluated in terms of lift enhancement and drag reduction [6]. Jirasek [4] simulations showed that the higher lift can be obtained by placing the vortex generators on the flap. Lin et al. [6] also installed the vortex generator on the flap. He concluded that the separation alleviation on the flap significantly improved both the lift and drag performances of the airfoil at approach condition.

2.1.3 Mixing Enhancement

The boundary layer thickening and flow separation will result to the reduction of the flow to proceed to regions of higher pressure. This can be avoided by increasing the rate of mixing of the fluid particles.

Jenkins et al. [7] has done experimental investigation of flow control for mixing augmentation on the adverse pressure gradient ramp. They used micro vortex generator (MVG) and synthetic jet vortex generator. Fig. 2.3 shows the flow visualization topology of the baseline flow, micro vortex generator and synthetic jet vortex generator. It can be seen in the baseline flow a formation of vertical structures.

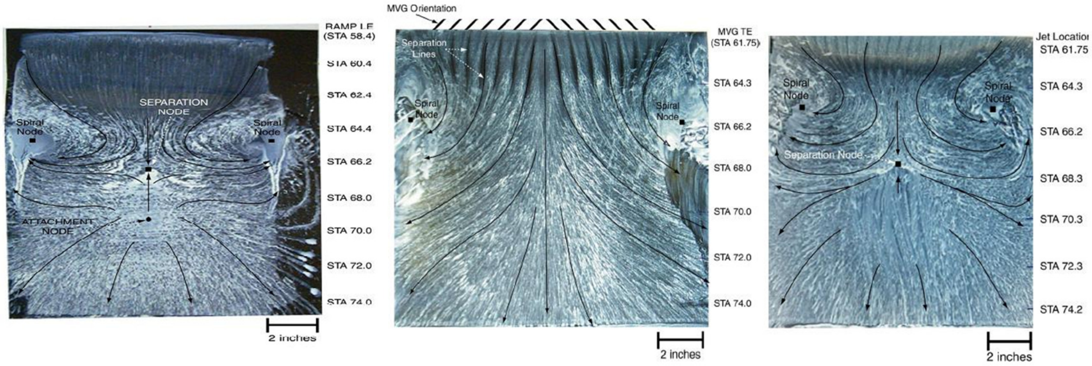

Fig. 2.3 Flow Visualisation for Adverse Pressure Gradient; from left to right: Baseline, MVG, Jet Vortex Generator ***(reproduced from Jenkins et al.*** [7] ***page 8 and 9)***

The micro vortex generator creates a series of strong vortices as indicated by the dark separation lines. These vortices reduce the influence of the sidewall vortices and allow the flow in the centre of the ramp to remain attached. As for the jet synthetic vortex generator, the vortices appear to be weaker and unable to overcome the influence of the sidewall vortices. Therefore, the micro vortex generator is more effective to re-energize the boundary layer.

Experimental investigation by Yao et al. [8] focused on the mixing generated by the low profile and conventional vortex generators in the boundary layer. The low profile vortex generator has shown a better mixing augmentation as the vortices of the conventional vortex generator tend to move apart from the wall as it moves downstream. Yao et al. [8] and Jenkins et al. [7] experimental works have shown that the potential of micro vortex generator which can enhance the mixing of the wall bounded flow.

Kerho et al. [11] has carried out experimental investigation on the vortex generator embedded in the boundary layer. Their investigation found that a vortex generator size with the height of half of local boundary layer thickness will produce a good combination of enhanced mixing with minimal device drag.

2.1.4 Flow Control Strategies

Gad el-Hak [1] categorized flow control strategies as ‘active’ and ‘passive’. These terms do not have any clear definitions, but nonetheless are commonly used. Typically, the classification is based either on energy addition, on whether the control is steady or unsteady, or on whether there are parameters (such as an oscillation frequency) that can be modified after the system is built. Unsteady flow control involves any time-varying effects, such as the addition of mass, momentum, energy, and vorticity. In addition to that, shape modification, including periodic or quasi-periodic approaches, at a time scale commensurate with the relevant dynamics of the flow. A passive control device does not require any auxiliary power, while the active control devices require energy to operate.

Passive control includes devices such as vortex generators, riblet, and steady suction or blowing. The primary advantage of passive control is simplicity. Passive control techniques tend to be lighter, less expensive to design and manufacture, and easier to maintain than active control thereby making passive control more likely to be used in real-world applications. On the downside, passive controls may only be effective over a limited range of operating conditions and there may even be conditions for which a passive control degrades system performance. Likewise, since most engineering flows contain complex unsteady motion (instabilities, turbulence) the ability of a passive (steady) device to control these unsteady motions is inherently limited.

Active control includes all types of unsteady actuators where oscillating momentum injection for separation control is a typical example. Active flow control requires a control loop and is divided into predetermined and reactive categories. Predetermined control includes the application of steady or unsteady energy input without regard to the particular state of the flow. Reactive control is a special class of active control in which the control input is continuously adjusted based on measurement (sensor).

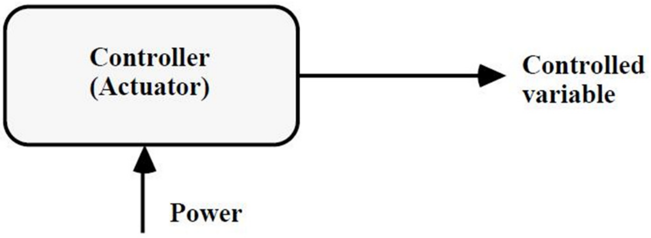

Fig. 2.4 Predetermined, open-loop control for active flow control ***(reproduced from Gal-el-Hak [1] page 29)***

The control loop for predetermined active flow control is open as shown in Fig. 2.4 which means no sensors are required. In open-loop control, the actuator parameters are set at the design stage and remain fixed regardless of changes in the state of the flow. As mentioned above, all passive controls are open-loop. Conversely, open-loop active control is clearly an under-utilization of the potential of active control to respond to changes in the flow.

2.2 Vortex Generator

2.2.1 Introduction

Vortex generators are highly efficient aerodynamic devices and cause the formation of longitudinal vortices giving rise to local mixing of the flow, energizing the boundary layer and consequently delaying or preventing separation or inducing secondary flow motion which restructures entire flow-field. Extremely simple in concept, they usually consist of tiny plates attached to the surface and protruding normal to it. They are set at an angle to the free stream and thus act as small lifting surface with each producing a strong axial vortex that trails downstream. These lifting surfaces or so called vortex generator generate streamwise vortices which trail after the vortex generator create overturning of the near wall flow. In this process high momentum fluid particles are swept on helical paths towards the surface resulting in an increase of near wall momentum. The vortex-wake behind a slender winglet-type obstacle described a complex flow structures. Fig. 2.5 shows a typical wake structure generated by a winglet. The main vortex is formed by the flow separation at the leading edge of the winglet, while the corner vortex is formed by the deformation of the near wall vortex line at the pressure side of the winglet.

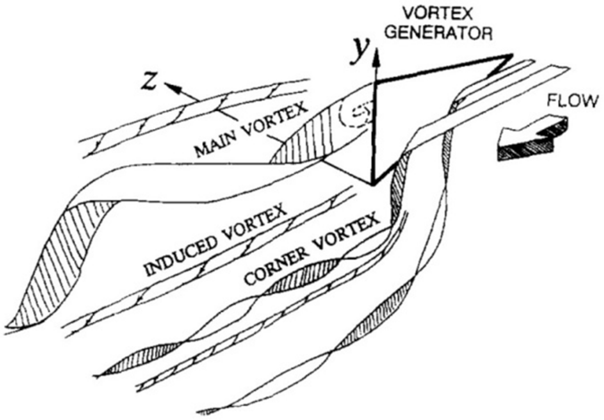

Fig. 2.5 The wake structure generated by a winglet ***(reproduced from Fiebig [12] page 112)***

The induced secondary motions produce an enhanced rate of mixing and consequent greater rate of momentum interchange between the outer inviscid flow and the retarded fluid in the boundary layer. Fluid particles with high momentum in the free stream direction are swept along helical paths towards the surface to replace the retarded air at the surface, which in turn is swept out away from the surface. This mechanism allows a larger pressure to be imposed without separation occurring. It also yields improvements in pressure recovery, which means that the chance of reattachment is improved although the flow is locally separated. Corresponding to the increase of the rate of mixing, the mean surface shear stress downstream of the vortex generators is also increase.

Velte et al. [13] experimental investigation of helical structure of longitudinal vortices embedded in turbulent wall bounded flow showed that the vortex radius (ε), the circulation (Γ), the helical pitch (l), and the advection motion of the vortex (or axial velocity at the vortex centre) (u_0) showed linear dependency with the device angle of incidence. The vortex radius showed a weak increase with increased device angle of incidence, while the circulation shows a large increase in magnitude. The vortex advection velocity decreased with increased device angle of incidence while the helical pitch did not change notably and considered close to constant.

2.2.2 Type of Vortex Generator

Vortex generators can be divided into two types, namely passive and active vortex generators.

2.2.2.1 Passive Vortex Generator

The usual and most effective devices are the vane-type vortex generators. There are many different type of vane vortex generator namely as rectangular vortex generator, triangular vane vortex generator, trapezoid vane vortex generator and others. Godard et al. [14] found out the triangular actuators produce a significant improvement (+20%) compared to rectangular ones and moreover the triangular shape is better in term of drag penalty.

Besides that, the arrangement of vortex generators can be divided to co-rotating (CoR) vortex generator or counter-rotating (CtR) vortex generator. The interaction between adjacent vortices of counter rotating vortex generator is rotating in opposite directions of each other and for the co-rotating vortex generator configuration the adjacent vortices rotating in the same direction. Fig. 2.6 shows two vortex generators configurations that produce co-rotating and counter-rotating longitudinal vortices arrays respectively. Streamwise vortices develop downstream of these devices and induce momentum transfer between the free stream and the near wall regions.

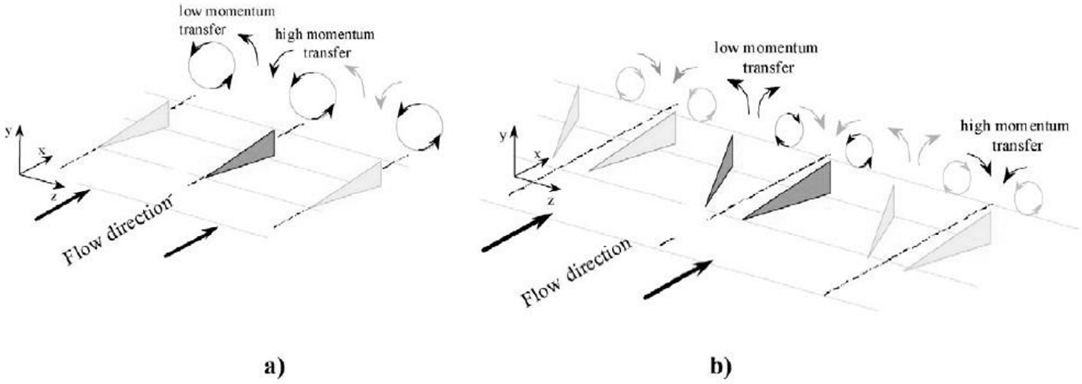

Fig. 2.6 Passive device configuration(a) Co-rotating, (b) Counter rotating

(reproduced from Godard et al. [14] page 183)

The co-rotating array transports low momentum fluid upward (away from the wall) and high momentum fluid downward between two adjacent streamwise vortices. For small values of the spanwise spacing, these opposite phenomena reduce the vortices effectiveness and persistence. Besides, a co-rotating array of vortices induces it own spanwise displacement by self induction while developing downstream. The major advantage of the co-rotating system is that, the vortices do not move away from the surface. The counter-rotating system dissociates the upward and downward momentum transport. The high momentum is transported downward to the wall around each vortex generators symmetry plane. The low momentum in transported upwards to the free stream between two different vortex generators.

Pauley et al. [15] work say that vortex pair with common flow down moves as it develops and resulted widening region of boundary layer thinning. The strength of the vortices generated was found to be independent with the half delta wing spacing and found out that delta wing spaced two generators heights or more apart produced the same strength vortices but closer spacing of generators slightly inhibits the ability of the delta wing to generate vortex. Pauley et al. [15] shows that as the spacing of the vortex generators was increased, the thickness of the boundary layer between the vortices also increases. Boundary layer thinning was surprisingly persistent. Wendt et al. [16] concluded that the large spacing produce vortices that travel along the wall to form array consisting a widely spaced upflow pairs. The vortices in these upflow pairs moves away from the wall region weaken the interactions between the vortex array and the boundary layer. The small spacing produce tight array of weak vortices that remain in close proximity to the wall and the resultant interaction with the boundary layer is strong.

The effect of different vortex generators angle of incidence which was investigated by Pauley et al. [15] showed that the boundary layer thinning at the common flow down region did not vary with the increased of the vortex generators angle of incidence and the width of the thinned region increase in proportion to the vortex strength. The boundary layer thinning at the centreline did not vary with increasing vortex generator angle of incidence and the width of the thinned region increased in proportion of the vortex strength as the angle of attack increases. The insensitivity of the boundary layer thickness to vortex strength is apparently due to offsetting effects; the stronger image flow of the stronger vortices carries them apart.

Pauley et al. [15] has investigated about the effect of angle of attack on the vortex strength of half delta wing vortex generators and found that for angle of attack less than 18 deg, the strength of the vortex pair produced increases linearly with angle of attack. For angle of attack greater than 18 deg the rate of increase decreases for delta wing vortex generators. Godards et al. [14] also agreed with the vortex generator angle of incidence value and proved that the optimal value of half delta wing vortex generators angle of incidence β is 18°.

One of the flow control pioneers, Schubauer et al. [17] applied wide range of mixing devices in order to investigate the mixing cause by the devices. Schubauer et al. [17] introduced vortex generator such as wedge, ramp, plow, scoop, dome, and others. The mixing on a coarse scale by relatively large, widely spaced devices was far more effective than fine scale mixing and multiple rows were less effective than a single row of devices properly spaced and properly stationed. Ashill et al. [5] performed experimental investigation on forwards wedge vortex generator, backwards wedge vortex generator, spaced counter rotating half delta wing vortex generator and single rotation half delta wing vortex generator. They found that the spaced counter rotating half delta wing vortex generator was the most effective in reducing the extent of the flow separation. They also showed that the lowest vortex decay rate compare to others type of vortex generator investigated.

The conventional vortex generator may produce excess residual drag through conversion of aircraft forward momentum into uncoverable turbulence in the aircraft wake. Therefore, a more efficient vortex generator could be achieved if the strength of the induced vortices is reduced, to an extent where it is just enough to delay the flow separation. This concept led to the development of the low-profile vortex generator. Low-profile vortex generator which is also known as sub boundary layer vortex generators employments to suppress boundary layer separation is not a new concept in flow control technologies. Reducing the height of conventional vortex generators to only a fraction of boundary layer thickness, δ provide effective momentum transfer toward wall several times their own height [18]. The sub boundary layer vortex generator will reenergize the boundary layer through flow mixing. Embedded vortices in array become more complicated as they not only interact with the wall and the turbulent boundary layer, but also with each other.

The sub boundary layer vortex generator is defined as a device with height, h approximately equal to 20% of the boundary layer thickness, δ and the conventional vortex generator is with the height of $h \approx \delta$ [8]. The sub boundary layer vortex generator [5, 9, 10] also refer as embedded vortex generator [15, 16, 19], micro-vortex generators [2, 6, 7] and low profile vortex generator [8, 57].

Lin [2] has conducted an experiment to differentiate the effect between conventional vortex generator and sub boundary layer vortex generator and found out that both vortex generators provide mostly attach flow directly downstream the ramp trailing edge. However the conventional vortex generator resulted to highly three-dimensional and pocket of recirculation flow. The sub boundary layer vortex generator has weaker vortices that produce just strong enough streamwise vortices to overcome the separation. In addition, Jenkins et al. [7] concluded that sub boundary layer vortex generator is very effective in controlling the flow environment for an adverse pressure gradient, even in the presence of secondary vertical flow.

Lin [2] concluded that the sub boundary layer vortex generator is more effective than the conventional vortex generator as the variant of the pressure between the plane positions for sub boundary layer vortex generator did not shown big gap as the conventional vortex generator. However, the sub boundary layer vortex generator will loss it effectiveness when the ratio of vortex generator height to boundary layer thickness, h/δ is less than 0.1, corresponding to $y^{+} < 300$ at the inner (log) regions ends and the outer (log) begins [2].

Rae et al. [10] experimental work showed the effectiveness of sub boundary layer vortex generators to delay trailing edge flap separations. The sub boundary layer vortex generators also managed to eliminate large areas of separated flap flow at all Reynolds numbers.

Yao et al [57] has concluded that the maximum vorticity magnitude increases as angle of attack increases for the low-profile vortex generator, but the trend is reversed for the conventional vortex generator. The phenomenon is probably due to the flow being partially stalled or stalled around the larger vortex generator at higher angles of attack.

2.2.2.2 Active Vortex Generator

Active vortex generator is a vortex generator that requiring energy expenditure in order to generate the vortices. The active vortex generator can be divided into two parts namely jet vortex generator [7, 20, 21], and vibrated vortex generator [3, 22-33].

Vortex generator jet is a jet of air pass through wall into a crossflow to create a dominant streamwise vortex. The vortex generator jets outlet can be in rectangular shape [20] or in round shape [7, 21]. For rectangular shape jet vortex generator, Godard et al. [20] found out that when the slot thickness increases the skin friction will be decreases. As for the round shape jet vortex generator, Jenkins et al. [7] wrote that when the hole diameter was increases, there was little effect on the pressure recovery. Round shape vortex generator jets did not have significant influence of the skin friction variation for the skew angle [21]. Godard et al. [21] concluded that the co-rotating arrangement of the round shape vortex generator jet result a significant increase of the skin friction.

Westphal et al. [22] performed experimental investigation on the oscillated vortex generator with the reduced frequency of oscillation, k of 0.14. The vortex generator was oscillated with the scotch yoke mechanism. Shizawa et al. [24] conducted experimental investigation to study the longitudinal vortices downstream of active vortex generators pairs and used the circular wing lip type of active vortex generator. The active vortex generator was actuated up and down by changing it height periodically at $\omega = 21.6$ rad/sec in angular velocity and they found out that the peak velocity at the core of the longitudinal vortices maintains constant from up-phase to down-phase.

Littell et al. [23] has conducted experimental investigation of the unsteady flowfield behind a vortex generator rapidly pitched to angle of attack using the half delta wing vortex generator and oscillated about z-axis at the $1/3$ of the chord length. The vane's motion is completed in a nondimensional time, $\tau \approx 2$. The interesting features of the rapidly pitched vortex generator can attributed to the motion of the vane giving rise to an effective angle of attack that varies along the flat plate.

McEwan [29] carried out experimental investigation to study the periodic actuation of vortex generator on a flat plate and used the half delta wing vortex generator as suggested by Westphal and Mehta [22]. The half delta wing vortex generator was oscillated using a stepper motor with range of reduced frequencies, k of 0.1 – 6.3 and the half delta wing vortex generator was oscillated about z-axis at the trailing edge of the vortex generator at the range of $5^\circ \leftrightarrow 32^\circ$. He found out that the dynamically oscillated vortex generator generate a lower level of peak vorticity compared to the static vortex generator and he suggested that the oscillating vortex generator should be perform at the lower range of reduced frequency.

Ahmad et al. [3] conducted numerical investigation of the oscillated vane vortex generator to control the diffuser flow separation. The half delta wing vortex generator was oscillated with reduced frequency of 0.5 and the vortex generator angle of incidence varied from $0^\circ \leftrightarrow 10^\circ$, $0^\circ \leftrightarrow 20^\circ$, and $10^\circ \leftrightarrow 20^\circ$. The effect of lateral spacing also studied in the investigation and they found out that the oscillating sub boundary layer vortex generators are sensitive to the angle of incidence and the lateral spacing.

Hattori et al. [32] performed experimental investigation of longitudinal vortex pair generated by active vortex generator. They investigated the behaviour of half delta wing vortex generator which is oscillated at the $0.5c$ of the vortex generator chord. The vortex generator was oscillate at a range of angle of incidence about $-18^{\circ} \leftrightarrow 18^{\circ}$ using two stepping motors at frequency of $5Hz$. For the co-rotating case, they found out that the behaviour between the right and left of vortex is different.

2.3 Interaction between Vortex and Turbulent Boundary Layer

2.3.1 Introduction

Longitudinal vortices generated in, or merging with boundary layers are found in many flows of practical importance. Longitudinal vortices in turbulent boundary layers belong to the class of ‘slender’ turbulent flows, in which velocity gradients in the y and z directions are much larger than longitudinal (x-wise) gradient. Once formed, the angular momentum of single longitudinal embedded vortex is reduced only by the span wise component of surface shear stress, which is usually very small. Therefore, isolated vortices in boundary layers tends to persist for very long distances downstream and the ratio of vortex size to boundary-layer thickness remains almost constant because the turbulence diffuses both.

Steady vortex could be produced by placing the vortex generator (e.g. half delta wing) upstream of the test bed [2, 5, 9, 14, 15, 17, 19, 34, 35]. As for unsteady flow, some active movement of the generator [22, 23, 29, 30, 32, 33] or injection jet flow [7, 20, 21] to generate the unsteady vortex.

2.3.2 Interaction between Steady Vortex and Turbulent Boundary Layer

Based on the benefits of the embedded vortices inside the boundary layer, many researchers pursued experimental [15-17, 19, 34-37] and numerical investigations for the interaction between a steady vortex with the boundary layer, for better understanding of the physics of flow.

Experimental investigation of mixing in turbulent boundary layers in a region of adverse pressure gradient has been carried out as earliest as 1960s by Schubauer et al. [17]. A variety of mixing schemes was tested and all of the involving fixed devices (passive vortex generator) arranged in a row on the surface in the region of rising pressure. The experiment explored the mechanics of boundary layer re-generation through the comparison of artificial turbulence injection, by auxiliary devices, to the relaxation of natural adverse pressure gradient to provide a more gradual pressure recovery and enable natural turbulent mixing to keep the flow from stagnating.

Shabaka et al. [19] conducted an experimental study of the relatively weak longitudinal vortices embedded in a turbulent boundary layer. They found that the behaviour of the various components of eddy viscosity, deduced from measured Reynolds stresses, suggests that the simple empirical correlations for these quantities used in a common turbulence models are not likely to yield accurate flow predictions. It was expected that the skin friction would be high near places where the v-component of velocity near the surface is negative, bringing high-speed fluid down from above and low when the flow is away from the surface. It should be noted here that the engineering use of vortex generators relies on an overall increase in skin friction.

Cutler et al. [36] has conducted an experimental investigation of the interaction between a strong longitudinal vortex and a turbulent boundary layer. They used a pair of trailing vortices which generated by a delta wing mounted ahead of a flat plate so that the trailing vortices merge with the turbulent boundary layer on the upper surface of the flat plate and they found that the secondary vorticity does indeed roll up into a weak secondary vortex before being entrained into the primary vortex. Their explanation was that each vortex in the pair causes strong cross flows in the boundary layer underneath the core and as a consequence of the no-slip condition, longitudinal vorticity is generated which is opposite in sign to that in the vortex. After passing under the vortex the boundary layer fluid breaks away from the surface at a separation point and subsequently tends to roll up into a weak secondary vortex.

Pauley et al. [15] has carried out an experiment to indicate the effect of the arrangement of the vortex generator towards the interaction with turbulent boundary layer. Pauley et al. [15] shows that vorticity is diffused much more rapidly from a vortex embedded in a turbulent boundary layer than from a free turbulent vortex as a vortex can only lose circulation by interaction with the wall. Skin friction measurements show that the skin friction perturbation is much larger in the common