

CRANFIELD UNIVERSITY

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Vortex formation downstream of an active vane vortex generator

School of Aerospace Transport and Manufacturing
PhD in Aerospace

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Academic Year: 2017 - 2022

Supervisor: Professor Kevin Garry
Associate Supervisor: Professor Simon Prince
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the degree of PhD

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ABSTRACT

A blended wing body aircraft, with embedded engine intakes near the wing trailing edge, requires aerodynamic optimisation under flight conditions to ensure satisfactory aerodynamic performance. In such a configuration, the wing surface upstream of the intake is a critical region within which active boundary layer flow control could provide significant benefits. The static vortex generator has additional drag under cruise conditions, but the active vortex generator not have the same issue. If the active vortex generator (VG) were to be utilised, the transient behavior of the flow downstream of the VG following its activation would need to be understood.

The active vortex generator concept adopted in the current study is a thin flat blade, inclined at a constant angle to the local flow direction, which can be deployed from its 'stowed' (fully retracted position), allowing it to project into the surface boundary layer and operate as a conventional blade vortex generator once fully extended. This study investigates the transient characteristics of the flow structure downstream of the blade during the deployment, using both up-scaled experimental and numerical simulations. The results contribute data to the development of an effective active flow control strategy, enhancing understanding of the flow control techniques.

The experimental approach is designed to examine the fundamental characteristics of the transient behaviour and is split into two work-phases. In Phase I, the study is focused on exploring the feasibility of the experimental approach to generate the vortex-forming transient. Phase II involves the use of a scaled-up experiment for a detailed study of the transient flow structure at Reynolds numbers in the range 1500 to 3500, based on local velocities in the boundary layer and the heights of the blade.

In the Phase II experiment, a multi-hole pressure probe is used to record the vortex formation and decay characteristics in a given downstream plane. The data show that the vortex development has a nonlinear response to the blade deflection during the blade deployment. This Phase II data is compared to both

RANS CFD steady-state simulations and analytical predictions using empirical models under steady conditions. The supplementary study indicates that the vortex-forming process is dependent on the transient nature of the VG blade deployment and cannot be adequately represented by the steady analysis.

A key outcome of this study relates to the practical application of vortex movement within the embedded boundary layer as a result of the VG blade deflection. The transient vortex position profile between the stowed (no vortex) and the deployed (steady-state or static vortex) location is very different from that predicted by steady-state modeling. The transient vortex vertical motion causes a smoother local circulation increase compared to the starting vortex, and the nonlinear circulation variations remain independent of blade size effects.

Furthermore, the findings presented in this thesis offer insight into active flow control. With continued study, the active blade vortex generator can increase the aircraft's efficiency and performance.

Keywords:

Vortex movements, initial vortex, active vortex generator, vortex forming

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LIST OF ABBREVIATIONS

ω	Vorticity (rad/s)
V_x	Velocity on X (m/s)
ω_{max}	Maximum vorticity (rad/s)
h_{vg}	Height of vortex generator (mm)
l_{vg}	Length of vortex generator (mm)
δ	Velocity boundary layer thickness (mm)
δ^*	Displacement thickness (mm)
S	Space between two blades (mm)
Re	Reynolds number
U	streamwise velocity (m/s)
U_{ref}	The streamwise velocity of incoming air (m/s)
y	Vertical distance in the boundary layer (mm)
τ_w	Shear stress in the boundary layer (Pa)
μ	Viscosity (kg/(m·s))
ρ	Air density (kg/m ³)
θ	Momentum thickness (mm)
p	Pressure (pa)
ξ	vorticity in X (rad/s)
ζ	vorticity in Y (rad/s)
η	vorticity in Z (rad/s)
r	volume fraction
r_i	volume fraction at phase i

u_i	velocity in phase i
t	Time (s)
$\vec{V}$	the velocity vector of V (m/s)
$\dot{m}$	mass per unit volume entering the phase
k	direction
u_{ki}	Velocity (m/s)
B_{ik}	body force per unit volume in phase i , direction k .
$\vec{k}$	Body force per unit vector
F_{ik}	Friction in direction k outside phase i .
l_{ik}	Interaction forces in direction k outside phase i .
H_i	energy transfer in the volume, phase i
Q_i	energy transfer to the volume from the surroundings, phase i
j_i	energy interacted with others, phase i
h_i	total enthalpy in the volume, phase i
$\bar{\phi}$	mean value of the steady condition (bar above, $\bar{u}_i$)
ϕ'	random variation of flow, (dot on upright, u'_i)
$\overline{\phi'}$	time average of variation, (bar above and dot on upright($\overline{u'}$)
ϕ	total quantity of flow at the current time (u)
t_1	time scale
ν	Kinetic viscosity (m ² /s)
ν_t	eddy viscosity or turbulence viscosity (m ² /s)
$\overline{u'_i u'_j}$	Reynolds stress tensor
τ_{ij}	Reynolds stress tensor (equal to $\overline{u'_i u'_j}$)
k	kinetic energy of turbulence (m ² /s ²)

L_t	characteristic length (m)
f_μ	damping function
ε	rate of the turbulence energy dissipation (only for $k - \varepsilon$ model)
ω	dissipation per unit turbulence kinetic energy (only for $k - \omega$)
SA	Spalart Allmaras turbulence mode
AVG	Active vortex generator
AOA	Angle of attack
ABLWT	Atmospheric boundary layer wind tunnel
TSFC	thrust-specific fuel consumption
NLFC	natural laminar flow control
HLFC	hybrid laminar flow control
RPM	Revolutions per minute
CFD	Computational fluid dynamics
VG	Vortex generator
SBVG	Submerged vortex generator
Δ	The changes
ESDU	Engineering Sciences Data Unit
BWB	blended wing body
AR	aspect ratio
RPM	Revolutions per minute

1 Introduction

Since the aircraft was produced, the interaction between the airflow and the aircraft has been discussed widely to improve the efficiency of aerodynamics. As a result, the blended wing body (BWB) aircraft has been developed. However, the new configuration also challenges flow control, especially for the flow separation at the front of the engine when the aircraft is under high-angle attack conditions. The separation is due to the high angle of attack, the fuselage's flat-plate-like upper surface increasing the adverse pressure gradient, and the flow separation causes the lift to reduce. Because of the unique placement of the engine, the separation draws the boundary layer into the engine, reducing thrust. The combination of lift and thrust reduction led to a significant risk to the BWB aircraft.

Blended-wing-body aircraft have special requirements for flow control. The conventional flow control methods on the upper section of the fuselage, such as static vortex generators, are not favored. These methods can introduce additional drag during cruise conditions. As a solution, real-time control methods for flow control have become imperative. These methods aim to delay separation under high-angle attack conditions while avoiding penalties during cruise conditions, ensuring optimal BWB aircraft performance. The project is for civil aircraft, so energy consumption also needs to be considered; high energy requirements may increase operation costs. Therefore, the choice of flow control methods is constrained by the need for active flow control techniques that are both effective and energy-efficient.

The active flow control method has been proven beneficial for real-time boundary layer separation situations. In this method, control devices work when necessary and switch off to avoid penalties under cruise conditions, as demonstrated by the active vane vortex generator. The previous studies mainly focused on the continual deflection-restoration devices and the dynamics of the coherent vortex structure for the vortex forming of the active vortex generator. The study shows the high-frequency active vortex generator has a short control range but a stronger control vortex.

The starting vortex generated by high-frequency devices provides powerful short-range control abilities but also demands a complex device structure and high energy requirements to achieve this level of effectiveness. The active vane vortex generator in the current study generates a vortex like a passive vortex generator, but the blade is retractable under the requirements. The blade deflects only once, potentially resulting in lower energy consumption, a longer control range, and lower device complexity compared to the high-frequency active vortex generator, making it function more like a passive vortex generator. Before applying the active vane vortex generator, exploring the downstream response to blade deflection is crucial to developing an effective flow control strategy. This study delves into the flow response downstream of the active vortex generator, aiming to enhance understanding of flow control techniques and refine the existing control strategy. This flow response study focuses on comprehending variations in key parameters, including vortex descriptors such as circulation, vortex location, and peak vorticity. Additionally, an in-depth analysis of flow physics is conducted to gain valuable insights into the control mechanisms.

The active vortex generator effectively manages flow separation by interacting with the static vortex. Understanding the transition from clear air to the formation of the static vortex holds vital significance for design guidelines and the current study. The flow response to blade movements is analyzed by examining circulation, vortex movements, and other flow properties. This comprehensive approach aims to uncover the underlying flow mechanism behind the vortex response, highlighting differences from previous studies, such as how the dynamics vortex formed without the starting vortex.

The effectiveness of control measures is closely linked to both the circulation and movement of the vortex at the static location. Uncovering the underlying flow physics through experimental results has clarified the relationship between blade movement and flow dynamics. This understanding serves as a valuable guide for designing more efficient flow control devices.

This thorough understanding provides the way for the application of active vane vortex generators in blended wing body aircraft and other vehicles, offering valuable insights for future designs and innovations in aerodynamics. The structure of the thesis is shown in Figure 1.1.

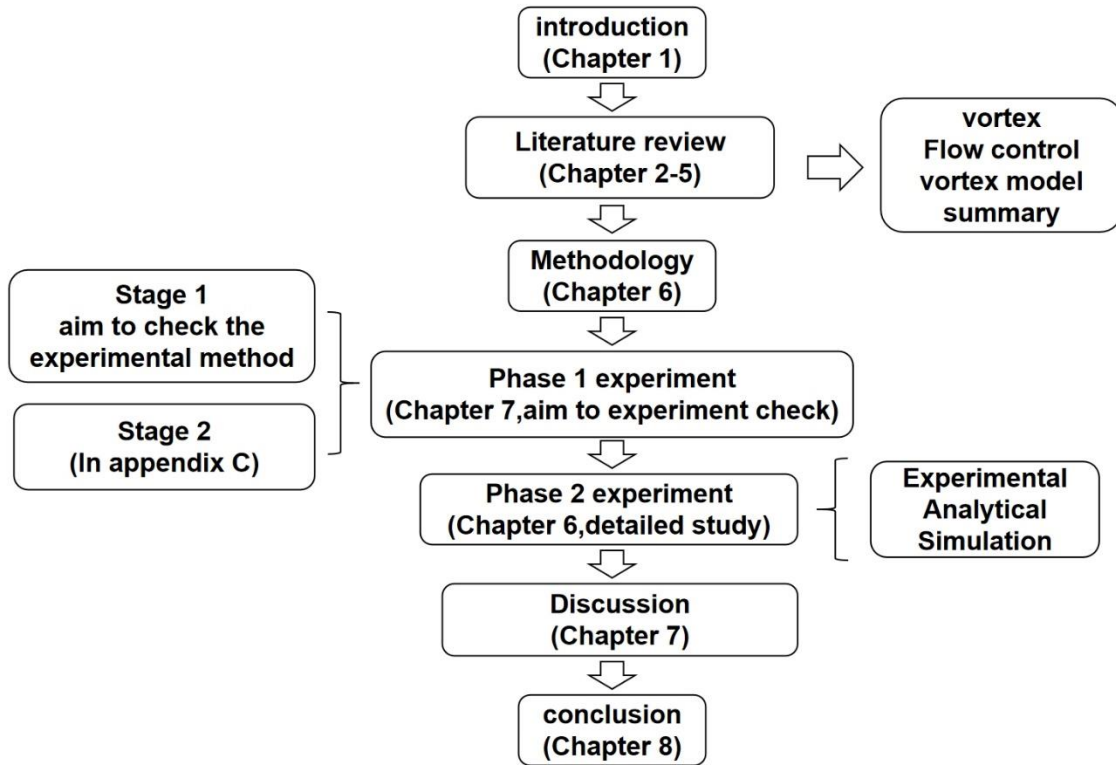


Figure 1.1 The structure of the thesis

The structure of the thesis contains three parts in 9 chapters. The first part is Chapters 2 – 5, referred to as the literature review. Chapter 2 discusses the flow physics of the vortex. In Chapter 3, the mathematical and empirical models of the vortex are listed and evaluated. Chapter 4 introduces modern flow control methods for analyzing passive and active vortex generators. This chapter examines the vortex-forming process of the active vane blade vortex generator in detail. Chapter 5 summarizes the literature review and points out the knowledge gap. Chapter 6 is the methodology, which introduces the study process, including the experiments, simulations, and data analysis methods.

The secondary part is comprised of the Phase I and Phase II study in Chapters 7 - 8. The Phase I study examined the experimental method for the vortex-forming

study. Phase II scaled up the experiment from Phase I and studied the vortex-forming more precisely. The experiment presented in Chapter 8 simulated static conditions as the reference.

The results are discussed and compared with other studies in Chapter 9 in the third part. The conclusions and outlooks of the vortex forming are presented in Chapter 10. Further works are detailed in Chapter 11.

2 Literature review of vortex

The current study is focused on the vortex forming using the active vortex generators, and the study involves the vortex forming, traveling, and vortex decay due to the relative distance changes. This chapter discusses the basic theory and concept of the vortex, mainly focusing on the pure vortex or the single vortex within the flow.

2.1 Vorticity

The air particles can rotate around and move in three coordinates (x, y, z). The translation along the coordinates can be represented by V_x, V_y, V_z . The velocities can be divided into mean velocity and fluctuations; the mean velocities are represented by U, V, W , and the fluctuations are represented by u, v, w . The motion of particles spinning around the axes creates vorticity ω , with three different axes, the vorticities are represented by ξ, ζ, η , or $\omega_x, \omega_y, \omega_z$, respectively. Both movements are shown in Figure 2.1.

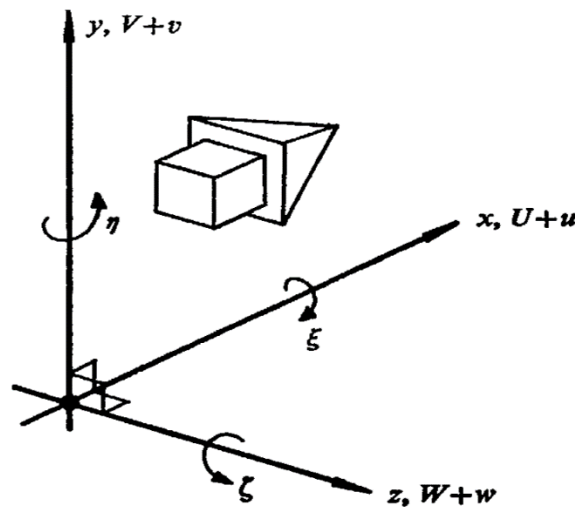


Figure 2.1 Two movements of the air particle [1]

The velocities on different axes are mean velocity U, V, W , and fluctuations u, v, w . The rotating of the particle around the axes are ξ, ζ, η .

The surrounding particles have different velocities, and the velocity difference causes the rotation of the air particles. Twice the angular velocity of the particle

can also represent the vorticity. It is shown below in Equation 1.1, Equation 1.2, and Equation 1.3.

$$\omega_x = \frac{\partial w}{\partial y} - \frac{\partial u}{\partial z} \quad (1.1)$$

$$\omega_y = \frac{\partial u}{\partial z} - \frac{\partial w}{\partial x} \quad (1.2)$$

$$\omega_z = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \quad (1.3)$$

The vorticity inside the vortex is caused by the velocity difference directly related to the tangential velocity. The peak vorticity is in the center of the vortex and also indicates the concentration of the vortex. The vorticity gradually decreases as the radius of the vortex increases.

2.2 Circulation

A vortex is formed by reorganizing the vorticity of particles. The vorticity within the vortex means the tangential velocity gradients change with radius variations. The integral of the vorticity in the vortex cross-section area is the vortex strength or circulation Γ , shown in Equation 1.4. The vortex can be described by three parameters: the “descriptors” [2]. Circulation Γ , peak vorticity, and location of the vortex core.

$$\Gamma = \int \omega \, da \quad (1.4)$$

The flow rotating around the moving axis is the secondary flow in the direction; the secondary flow affects the vortex's strength. Based on the rotation of molecules in the vortex, there are two types: the rotational vortex and the irrotational vortex. The irrotational vortex is also called the free vortex, which is the vortex without external force. The velocity increases to unlimited levels as it gets near the core, which means the irrotational vortex only exists in theory.

The vortex can be separated into three different parts based on the tangential velocity. The inner part is the solid vortex core, and the velocity gradients are

constant as the radius increases. The middle part is the viscous core, the velocity slopes increases then drop with the radius increase. The outer part is the inviscid outer region, and the gradient decreases with the increase in radius. The three parts are shown in Figure 2.2.

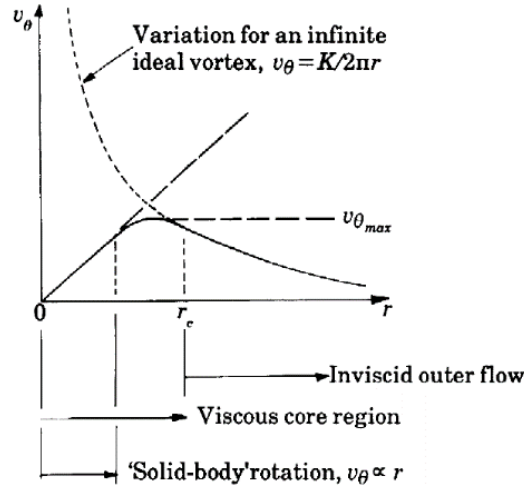


Figure 2.2 The structure of the vortex [3]

The X-axis is the radius of the vortex. r and r_c are the radius of the vortex and the radius of the viscous core, respectively. The Y-axis is the tangential velocity, v_θ and $v_{\theta max}$ are the radius velocity and maximum radius velocity. The K is the circulation around the vortex core outside the viscous region.

Based on the streamwise velocity in the vortex core, the vortex can be separated into a jet-like core and a wake-like core. The streamwise velocity in the jet core is higher than the free stream velocity and lower than the free stream velocity in the wake-like core. In the current study, the VG is vane blade VG, which usually produces a strong vortex (jet core) [4]. The streamwise velocity of two types of vortex as shown in Figure 2.3.

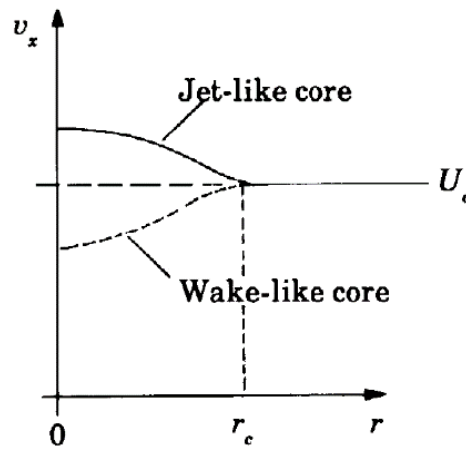


Figure 2.3 The streamwise velocity in two types of vortex core [3]

The r and r_c are the radius of the vortex and the radius of the viscous core, respectively. The X-axis is the velocity, where the v_x denotes the free stream velocity.

2.3 Vortex forming

The majority of the vortex on the aircraft's surface is the longitudinal vortex, which is generated by the pressure difference between two surfaces of the blade or wing. The thin wing theory is one of the classical methods to connect the vorticity with the lift. The method can be applied to the two-dimensional airfoil. With the Kutta condition, the circulation of the total wing Γ_1 and circulation of shedding vortex Γ_2 were connected. The circulation in the shedding vortex equals the circulation on the wing from the Kutta condition [5].

2.4 Vortex decay

The vortex traveled downstream with the strength decreasing, but the size is growing. Distance is one of the most important features of vortex decay. In a free stream or supersonic condition, the vortex can travel a longer distance than the vortex near the solid surface. Wendt shows that the interaction between vortices and solid surfaces strongly affects vortex decay [2]. In the experiment, the height of the vortex generator was similar to the thickness of the boundary layer. The result showed the single vortex on the flat plate could travel to 50 height of the initial vortex (h_i) with the huge strength decreases and vortex core growth. Due

to the large vortex core, the interaction goes higher than before, leading to a higher decay rate. The decay rates caused by the viscous vortex and surface interaction were more significant even than the vortex pair with a large space in between.

In the application, the VG blades are working in arrays. As the number of VG increases, the space between two vortices decreases, leading to a stronger interaction and faster decay than single-blade conditions. From the study, the interaction between two vortex cores or the flat plate surface was the key reason for the accelerated decline of the vortex. At the $76h_i$ distance downstream, the interaction accelerates the decay of the vortex, with only 30% strength left [3].

The interactions between the vortices and surfaces generate the force in the opposite direction of the vortex rotating. The force was generated in the high turbulence stress gradient area, which is the viscous core. The interactions happen when vortex cores are close to each other, but with the study given by Wendt [2], even the space between the neighbor vortex or solid surface was huge, but the decay speed was still faster than the isolating vortex condition.

The interaction between a vortex and the surroundings was not only the other vortex or solid surface [2,6]. The other factors that may affect the vortex are the secondary vortex, boundary layer, pressure gradient from the outer stream, dissipation in the vortex core, and the initial vortex forming processing, which also affects the core turbulence. Those parameters are shown in Figure 2.4.

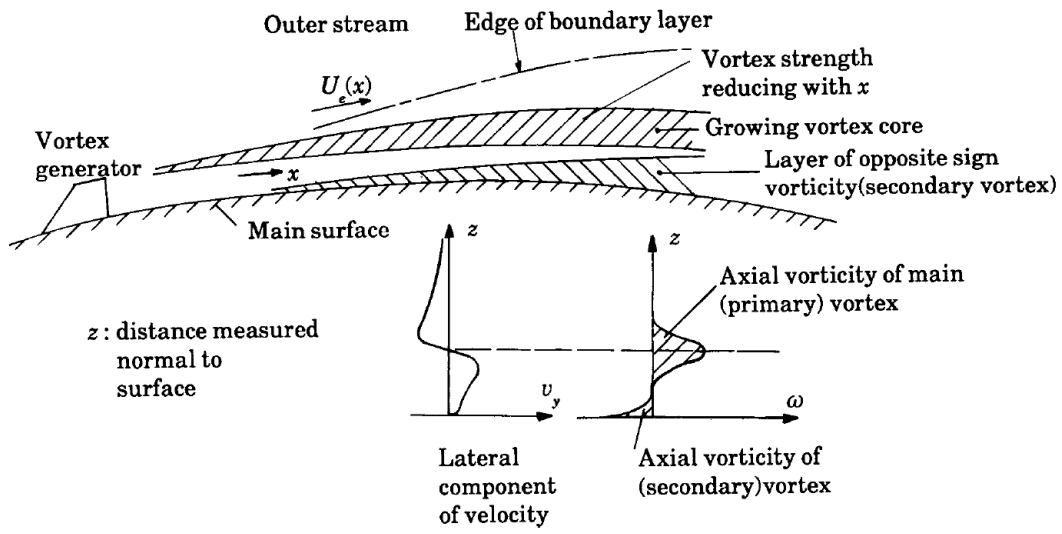


Figure 2.4 Parameters affecting vortex decay and core growing [3]

3 Literature Review of Theoretical Model of Vortex

This chapter introduces vortex models applied in the analytical study of Phase II, encompassing both theoretical and empirical models.

3.1 Single Vortex Generator with Theoretical Model

The theoretical model enables the determination of descriptors of a single vortex, including its locations, circulation, and peak vorticity. The foundational model is the Prandtl theory for airfoils, which computes lift through integral surface circulation under the Kutta-Joukowski condition. Equation 3.1 depicts surface circulation, and lift is derived from circulation, as illustrated in Equation 3.2.

$$\Gamma = \int \gamma ds \quad (3.1)$$

$$L = \rho_{\infty} V_{\infty} \Gamma \quad (3.2)$$

When an airfoil or vortex generator blade encounters oncoming flow at an angle of attack, Equation 3.4 incorporates the angle of attack and chord length. Here α in Equation 3.3 represents the angle of attack, and c signifies the airfoil chord length. This equation is applicable only to thin airfoils or blades, known as the thin wing theory. Circulation derived from the thin wing theory is depicted in Equation 3.4.

$$L = \rho_{\infty} V_{\infty} \Gamma = \pi \alpha c \rho_{\infty} V_{\infty}^2 \quad (3.3)$$

$$\Gamma = \pi \alpha c V_{\infty} \quad (3.4)$$

The physical shape of the wing or blade holds significance. The aspect ratio denotes the ratio between the blade's height and chord length. Equation 3.5 presents the equation encompassing the aspect ratio. In the study, the aspect ratio was utilized for both elliptical and rectangular platform wings, following Wendt's approach. Equation 3.6 outlines the equation for the aspect ratio.

$$\Gamma = \frac{\pi v_{\alpha} \alpha c}{1 + \frac{2}{AR}} \quad (3.5)$$

$$AR = \frac{8h}{\pi c} \quad (3.6)$$

The blade's relative height strongly influences its performance. Assuming the circulation generated by the wing section transitions into streamflow, Wendt [85] established a new expression for the shed circulation involving the relative height of the blade, as depicted in Equation 3.7.

$$\Gamma = \frac{k_1 v_\alpha \alpha c}{1 + \frac{k_2}{AR}} \tanh \left[k_3 \left(\frac{h}{\delta} \right)^{k_4} \right] \quad (3.7)$$

The hyperbolic tangent function represents the boundary layer effects. The values of k_1 to k_4 shown below were derived from experimental data using least-squares regression, Wendt [7].

$$k_1 = 1.61$$

$$k_2 = 0.48$$

$$k_3 = 1.41$$

$$k_4 = 1.00$$

3.1.1 Potential flow theory

The simplest theory to simulate the vortex is the inviscid theory, which has been applied to track and develop a single free vortex downstream. In Biot-Savart law, the vortex induces the secondary velocity, and the velocity strength depends on the radial distance from the vortex core to the local point. According to the theory, the strength of the vortex is Γ , and the radial distance between the local point and the vortex core is r . The tangential velocity at the local point can be represented by Equation 3.8.

$$V_\theta = \frac{\Gamma}{2\pi r} \quad (3.8)$$

The vortices were separated into Real and Image vortices to represent the vortex on a flat surface. The image vortex reflects the real vortex with the surface shown in Figure 3.1. The force between two vortices replaced the interaction between

the vortex and the solid surface. Both vortices have the same distance between vortex cores to the surface: the distances b .

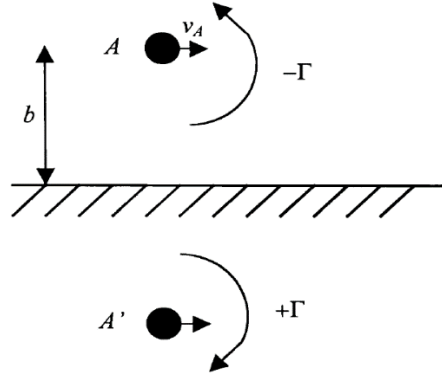


Figure 3.1 Real vortex and Image vortex by potential flow model [8]

The two vortices replaced the movement along the spanwise direction. The combined effects of two vortices can represent vorticity in the model, as shown in Equation 3.9.

$$\omega_z = \frac{i\Gamma}{2\pi} \ln(z - ib) + \frac{i\Gamma}{2\pi} \ln(z + ib) \quad (3.9)$$

To obtain the lateral motion of vortex A , velocities at the beginning are needed, which are u_A, v_A at location $x = 0, y = b, z = x + iy = ib$. The real vortex can not induce any velocity, so the velocities come from the image vortex. The velocities are shown in Equation 3.10 and Equation 3.11. The current equation ignores several effects, such as the boundary layer, and therefore the equation can only be applied to the single vortex in the free stream far from the forming process [8].

$$u_A = \frac{\Gamma}{4\pi b} \quad (3.10)$$

$$v_A = 0 \quad (3.11)$$

This induced velocity changes with increasing distance. At the vortex core, the velocity reaches infinity, which is impossible in a real situation. The vortex core is considered as a solid body in rotation, and the current potential model does not simulate the real vortex core.

3.1.2 Vorticity vortex model

In the viscous vortex model, the particle rotates around the axis and about its own axis. The vortex core also contains vorticity in the real case, and the vorticity in the vortex core is usually called peak vorticity.

Lamb theoretically studied the vortex with a viscosity core in the boundary layer. The Lamb model comes from the potential vortex and involves the time-dependent viscous decay of vortex parameters and the growth of the vortex core in size.

The vorticity of the vortex of a cross-section follows the Gaussian distribution; the closer to the vortex core, the higher the vorticity is. The distribution is shown in Equation 3.12. The velocity induced by the vortex is given by Equation 3.13.

$$\omega_x = \frac{\Gamma}{4\pi\nu t} e^{-r^2/4\nu t} \quad (3.12)$$

$$v_t = \frac{\Gamma}{2\pi r} \left(1 - e^{-r^2/4\nu t}\right) \quad (3.13)$$

The vorticity is related to circulation, shown in Equation 3.12; the peak vorticity is located at the center of the vortex, $r = 0$, as shown in Equation 3.14, and it is used to compute the peak vorticity in Chapter 7.

$$\omega_{peak} = \frac{\Gamma}{4\pi\nu t} \quad (3.14)$$

4 Literature Review of Flow Control

In the past decades, prior studies have shown that aircraft performance and maneuverability potentially increase through the high efficiency of flow control, such as range and payload, and the decrease in air pollution and noise. These beneficial results made flow control a major area of aerodynamic studies [9].

Several flow phenomena are suitable for flow control, including the turbulent and laminar boundary layer, transition, flow separation, and reattachment. Those controls have resulted in the lift and drag of the aircraft. The relationship between the flow controls and resultant forces are described in Figure 4.1.

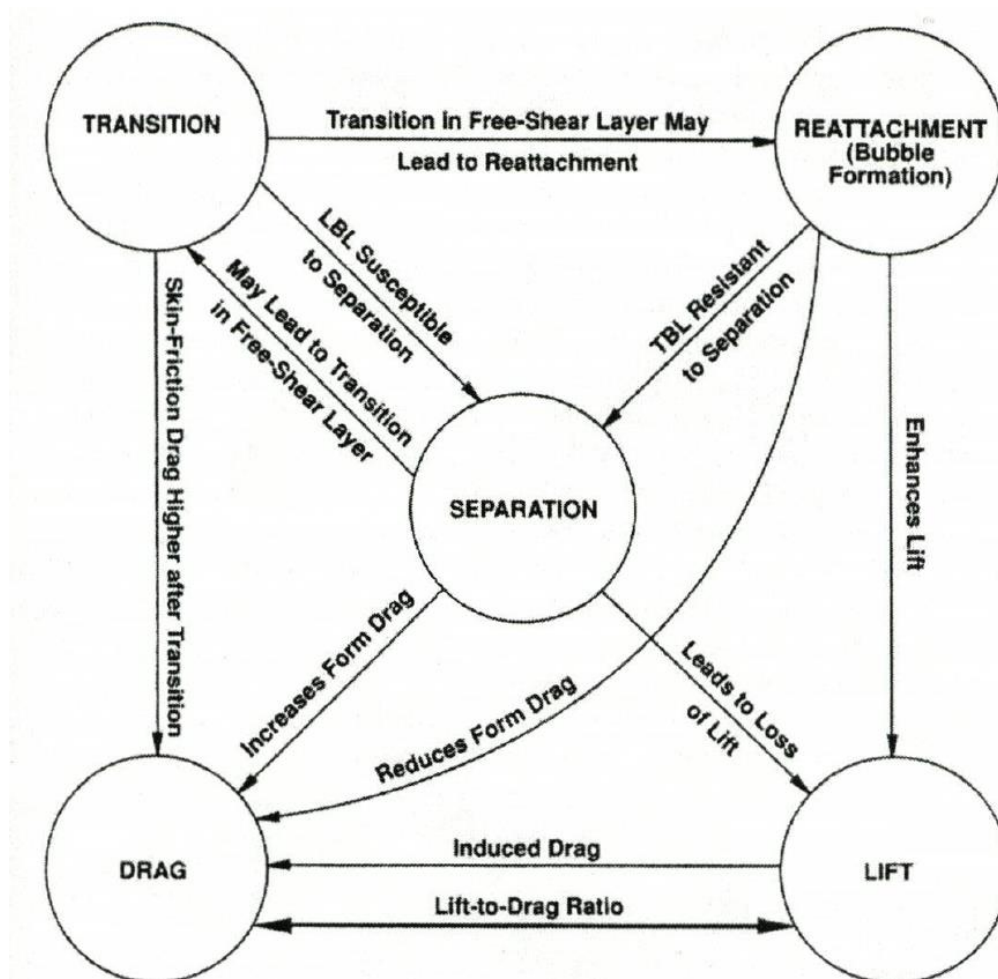


Figure 4.1 Interrelation between flow control goals [10]

Figure 4.1 shows several phenomena. It presents the relationships among the flow control, the drag, and the lift. The core of the flow control is recognized as separation.

To control the different flow phenomena, Ashill [11] summarised the three main flow control approaches. First, it is designed to avoid separation or other conditions (like lifting surface), such as the supercritical wing [12]. Second, it ensures smooth separations from sharp edges [13]. Finally, devices such as the vortex generator are applied to stop or delay the flow separation. This project focused on controlling the flow by devices.

The device control methods can be categorised into passive and active flow control. The active techniques accomplish real-time control by switching on when necessary. It also eliminates the penalty drag when switched off. The active flow control could adjust the performance by different parameters. These are the functions that differ from passive flow control. However, adjusting parameters requires extra energy to supply an additional feedback system. The system of the two control methods is shown in Figure 4.2.

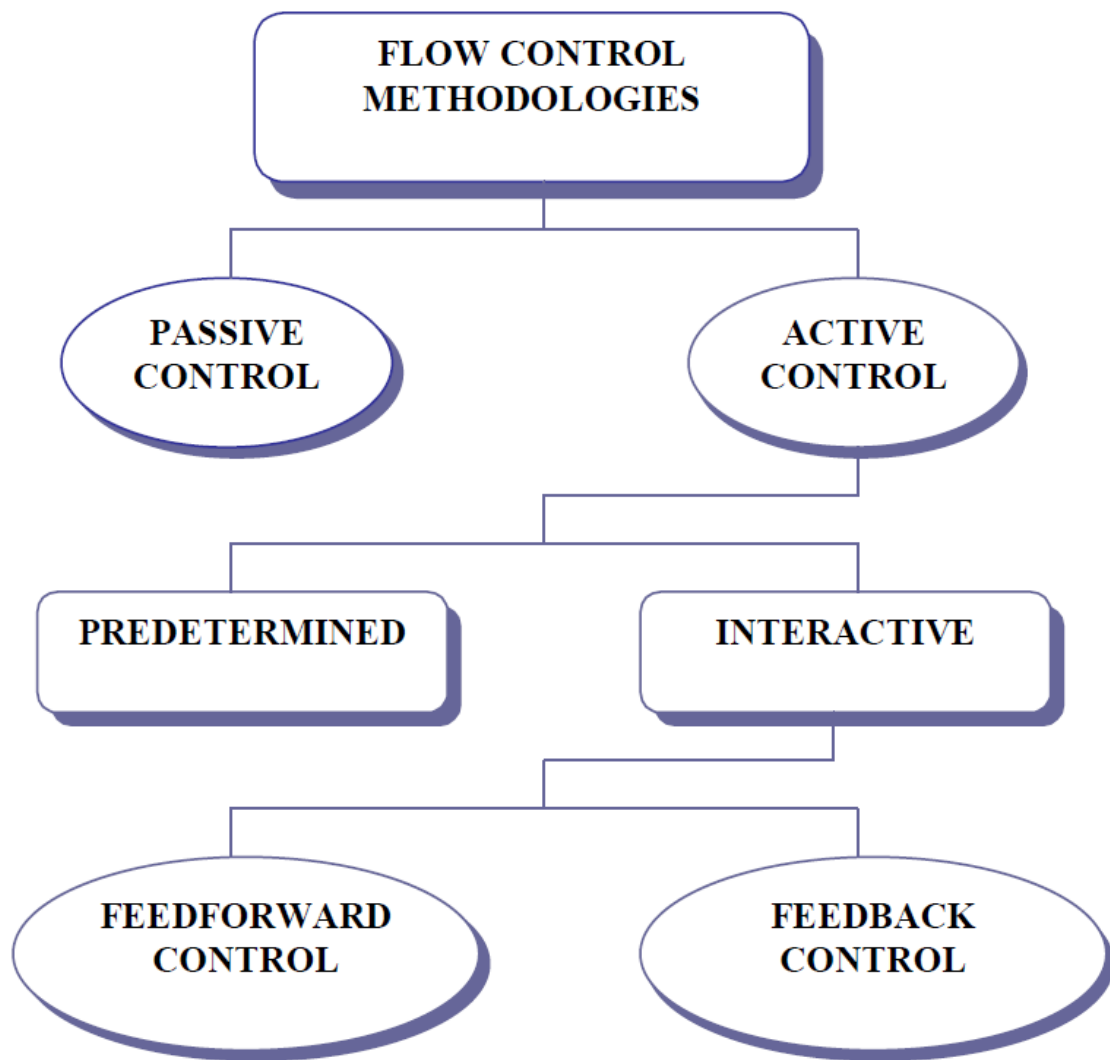


Figure 4.2 The methodologies of passive and active flow control [14]

The flow control methodologies have been categorised into different types, and then the active flow control has also been categorised into forwarding control and feedback control.

Two methodologies can be applied in the active flow control – predetermined and interactive. The predetermined method controls the flow without considering the current situation of the flowfield, while the interactive one requires the current state of the flowfield to be measured by a sensor to adjust the devices through a forward or backward control system.

There are three parts to the flow phenomena in active flow control. The first is boundary layer control, the second is vortex control, and the third is jet, wakes, and mixing control, as shown in Figure 4.3. This paper focused on boundary layer separation control. The boundary layer separation control enhances safety performance by delaying or stopping the flow separation and reduces drag and operating costs.

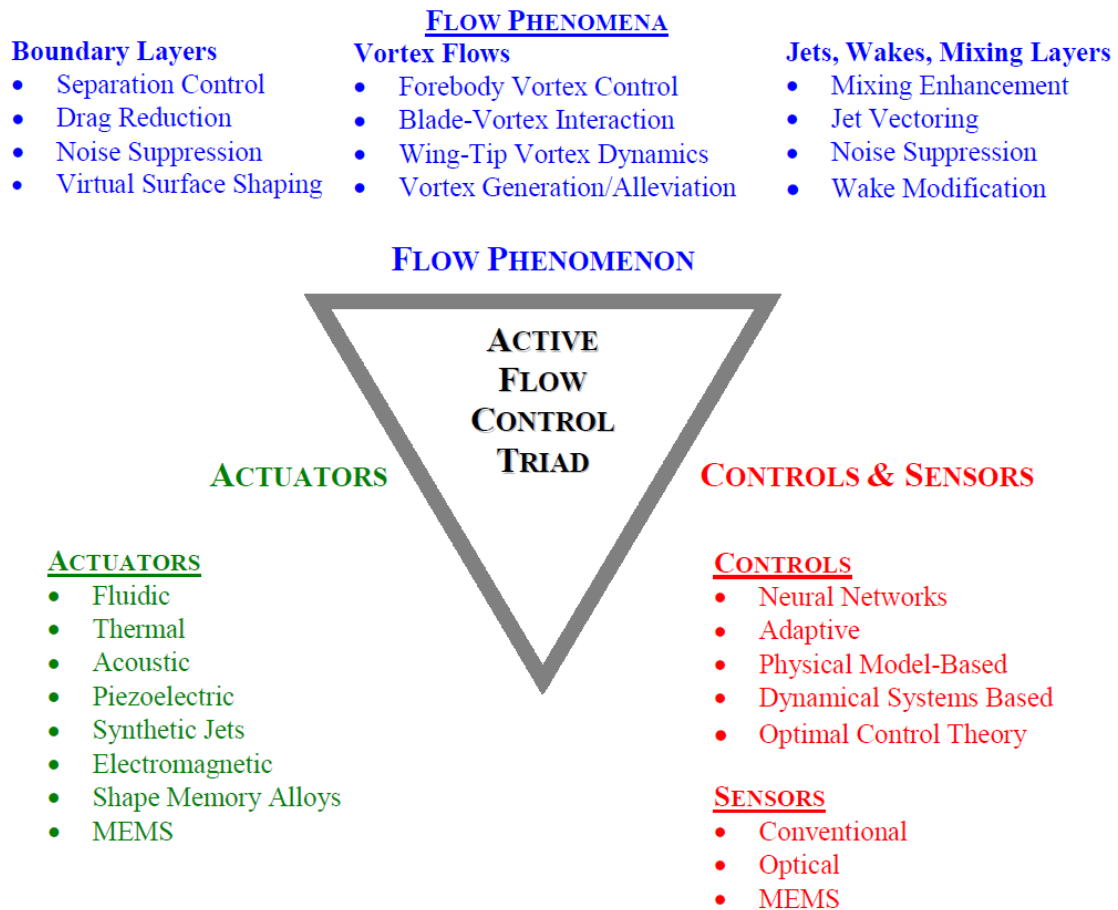


Figure 4.3 The triad of the active flow control [14]

The phenomena need to be controlled, and the active control devices and the sensors are summarized.

The focus of this paper is the boundary layer separation active control. The typical active devices used for separation control include the active blade vortex generator, air-jet vortex generators, synthetic jets, and plasma jets. Those devices will be introduced and compared in the rest of the current chapter.

4.1 Modern flow control application

The aircraft development leads to complicated flow control. Multiple flow control methods have been developed and applied to the aircraft. The typical aircraft applications are fuel-air mixing, noise reduction, drag reduction, and separation control.

4.1.1 Fuel-air Mixing

Fuel-air mixing often occurs in the combustion chamber of the gas turbine engine. Proper fuel-air mixing can reduce air pollution, such as nitrogen oxides (NO_x), which will lead the engine to meet the new emissions control requirements. The mixing also reduces the aircraft's thrust-specific fuel consumption (TSFC), leading to lower operating costs. The mixing quality can be increased by the flow control devices, such as synthetic jets [15–18] and vortex generators [19–23].

4.1.2 Noise control

The noises produced by the aircraft have two broadcast directions: noise into the cabin and noise to the far-field. Regulation has limited both noise. The noise has multiple sources, such as aerodynamic noise.

In the Gulfstream III project, noise arising from shock-induced flow separation at the front of the fuselage led to noise propagation inside the cabin. The noise was reduced by employing passive vane vortex generators ahead of the separation point. These generators effectively delayed the flow separation, thereby mitigating the associated noise [24].

Special materials have been developed for noise reduction due to the ability to control surface flow. One notable example is porous airfoils, which have garnered attention in recent years. These airfoils consist of flow-permeable materials that can be applied to aircraft or fans to attenuate boundary layer turbulence. Previous studies have indicated that porous airfoils can reduce noise in the medium frequency range; however, they may contribute to increased noise in the high-frequency range due to surface roughness [25][26].

4.1.3 Drag reduction

The flow control method for drag reduction applied to civil aircraft is transition or laminar flow control [27–30].

Transition control aims to maintain the laminar boundary layer, which could reduce the fraction by being immersed in the turbulent flow of the wing-wetted area. Boundary layer suction, careful design of the geometry, and perturbation arising reduction could delay the transition from the laminar boundary layer to the turbulent boundary layer [31].

Natural laminar flow control (NFLC) and hybrid laminar flow control (HLFC) are two methodologies of laminar flow control [32–34]. The natural laminar flow control method is the simplest way to maintain the laminar flow. This method employs favorable pressure gradients by carefully designing and manufacturing the wing geometry and surface roughness to avoid interrupted airflow and then delay the boundary layer transition, such as the laminar airfoil. The low sweep-back angle (lower than 15°) with a moderate or small chord length, which is the classical wing's shape in the natural control methods. Because of the relatively short chord length, the laminar boundary layer covers a large part of the wing-wetted surface. The low sweep angle aims to maintain the 2-D flow. This wing shape is close to the straight wing and suitable for low speed, which is typical on light aircraft and sailplanes.

The natural laminar flow control method is unsuitable for modern civil aircraft due to the shape of the wing (nearly 45° sweep back) and speed requirements (nearly Mach 0.82 - 0.87) are different. The hybrid laminar flow control method was employed to overcome the speed limits. The HLFC is the combination of surface suction and NLFC. The hybrid control method was successfully applied to the high subsonic and supersonic regimes (up to Mach 2), such as the F16XL shown in Figure 4.4 [35].



Figure 4.4 The F16xl in boundary layer control experiment [35]

The suction system is located under the upper surface of the wing, while the porous titanium glove is positioned on the left-hand side of the wing.

The HLFC and NLFC reduce skin friction drag by maintaining the laminar boundary layer. The skin friction drag in the turbulent boundary layer is potentially reduced by applying riblets, which could potentially reduce drag by nearly 15%. The riblet method differs from NLFC and HLFC as it does not extend the laminar boundary layer of the wetted surface [36].

4.1.4 Separation Control

The vortex generator has been applied to control the flow on different areas of the aircraft, such as the wing [37–40], fuselage [41], inlet [42–45], and wind turbine [46,47]. The vortex generator could generate a vortex downstream to prevent boundary layer separation or facilitate heat transfer.

The passive vortex generator is the most traditional method proposed by Taylor [48]. The idea of the vortex generator is applied to delay the flow separation by redistributing the momentum of the boundary layer. The vertical rotation transfers the high momentum from the outer boundary layer to the near-surface area. The passive vortex generator is fixed on the surface, continuously causing additional vortex drag.

An active vortex generator follows the similarity of the momentum transfer method, which can be applied to dedicated flow control [49,50]. There are two types of

active vortex generators: one generates the vortex passively with a dynamic mechanism, and the other generates the vortex by static or periodic blowing.

Surface blowing and surface suction require more energy compared to passive methods. The surface blowing injects a large air volume into the boundary layer. The surface suction delays the separation by removing the low momentum inner regimes of the boundary layer [51,52].

4.2 Passive Vortex Generator

The passive vortex generator (Vortex Generator, VG) has shown high performance in flow separation control. However, the energy loss caused by the additional vortex drag arises from the unrecoverable turbulence in the aircraft's wake [4]. One possible solution is to scale down the VG's size to reduce the vortex drag. The smaller vortex generator is called the sub-merged vortex generator (SBVG), which is merged in the boundary layer to transfer momentum from the outer range of the boundary layer to the near-surface field. At the same time, the bigger one is the conventional vortex generator, which transfers the momentum from the free stream to the near-surface field. Based on the study of the submerged vortex generator, the size of the submerged vortex generator has referred to the location boundary layer thickness, δ . The 0.2δ (20% height of local boundary layer thickness) height of the vortex generator still produces 80% strength of the 1δ height VG, and the vane blade has the best performance compared to other common types of vortex generators [4]. The results of comparing different vortex generators are shown in Figure 4.5.

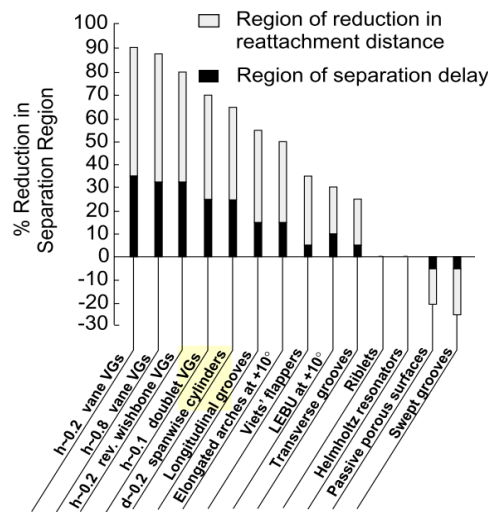


Figure 4.5 The relative effectiveness of the sub-merged vortex generator [4]

Figure 4.5 shows the effectiveness of the different types of passive vortex generators. The submerged vane vortex generator (SBVG) performs similarly to the conventional vortex generator.

Lin studied the drag of submerged devices (Forward wedge, Backward wedge, Counter-rotating vanes, and Single rotation vanes) in both zero pressure and adverse pressure gradients. The single vane blade had the lowest drag ratio compared with the spaced vane and joined vane. The drag coefficient (C_D) of the forward wedge was 40% of the joined vane. In the spaced vane counter-rotating configuration, the larger the space, the smaller the drag.

The adverse pressure gradient had an effect on the drag of devices. The adverse pressure gradient had a lower dynamic pressure than the zero pressure gradient. The drag of the generator will be lower due to this effect. The second one was the vortex generator's excrescence effect, which would be amplified by the adverse pressure gradient, which leads to an increase in drag. The data shows that the second effect is stronger than the first [53].

4.3 Vane Blade Vortex Generator

The vane blade vortex generator is the most well-studied of all types of generators. The two surfaces of the blade have different pressures. This difference in pressures experienced by the two surfaces causes the flow to roll up from the higher pressure area to the lower area, forming a vortex in the wake. The blade is applied to various configurations to create different vortex structures or interactions and meet diverse requirements.

The structures of the vortices generated by the vortex generator differ within turbulent and laminar boundary layer conditions. Some studies show that only the primary vortex can be observed with turbulent boundary layer conditions, while the multiple vortex system was studied within the laminar boundary layer condition [54].

4.3.1 Single Vane Blade Vortex Generator

The vortex generated by the vane blade was the strongest compared to the other commonly used vortex generators [4]. The vortex produced by the VG is used for separation delay and heat transfer through the monument interaction and flow exchange. The blade is typically on the flap, wings, intake duct, and turbine blade.

The flow wake behind a vane blade is complex. The vortices generated by the blade are not singular but multiple. The multiple vortices system is more sophisticated and more susceptible to being affected by angle, blade height, and boundary layer conditions. Velte studied the vortex system in a laminar boundary layer condition. The experiment was carried out in both water and wind tunnels. The result shows that three vortices were generated as the flow pass, as shown in Figure 4.6 [55].

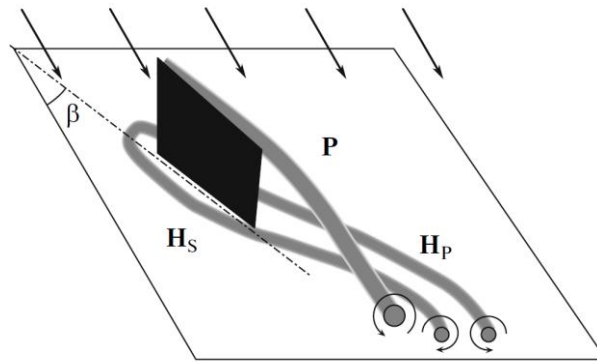


Figure 4.6 Vortex system of vane blade [55]

Primary tip vortex P , wake, horseshoes like vortices, H_s suction side and H_p , pressure side are observed.

The primary vortex and two smaller secondary vortices are on the front and back surfaces. The two secondary vortices are counter-rotating and mainly affect the primary vortex. The horseshoe-shaped vortex was not observed in all regimes. Initially, at low incline conditions, with the angle of attack increasing, the strength of the primary vortex also increased and caused stronger effects. The vorticity concentration increases and forms another induced discrete vortex. The primary vortex may also generate a secondary vortex underneath, rotating in opposite directions. The secondary vortex's strength is highly dependent on the primary vortex; if the strength of the primary vortex is large enough, another induced vortex may also be produced by the secondary vortex to balance the momentum [53].

The wind tunnel experiment and PIV (Particle Image Velocimetry) measurements were applied to study the combination of multiple vortex systems generated by a strong secondary vortex. The vortex systems are formed into three different structures, as shown in Figure 4.7.

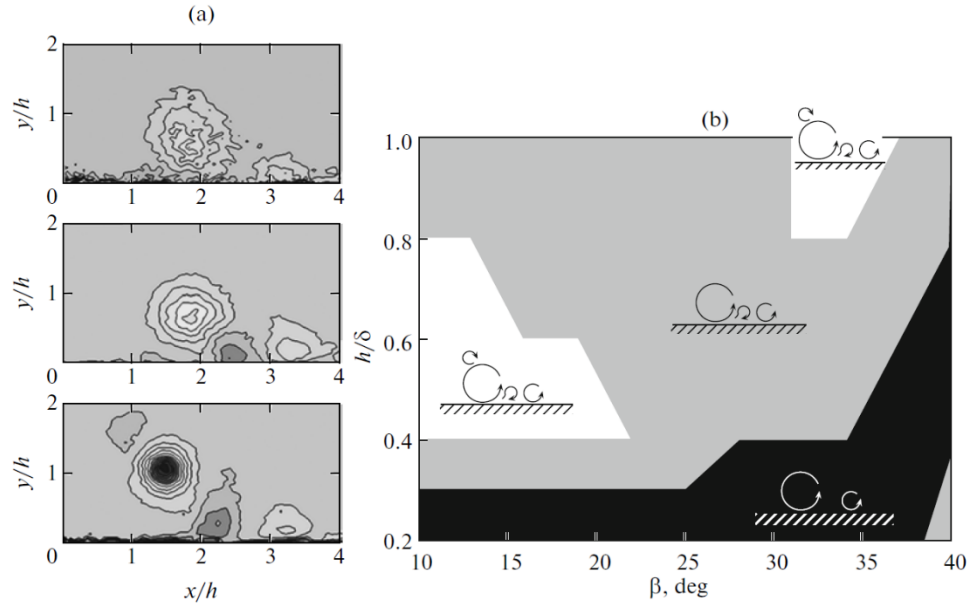


Figure 4.7 Vortex system against the angle of attack and height of the blade
[55]

(a) examples of vorticity distribution in the wake by PIV data; (b) map of vortex structure formation in the wake past the VG;

On the left of Figure 4.7 were the experiment results, and on the right of Figure 4.7 side was the summary of the multiple vortex system with the angle of attack and the relative height of the blade. The system of the vortex was sensitive to both incline and relative height, and the two vortex systems most likely appeared at a lower height range. With the height increase, the number of vortices increases, and the system of the vortex becomes sensitive to the angle of attack.

The typical vortex system downstream is the primary vortex with a single secondary vortex. Eaton has studied these two vortex systems by common-flow-up configurations (two blades trailing edge close, leading edge separated) with unequal strength vortices; one vortex is twice the strength of the other [56]. The contours of the streamwise vorticity of downstream are shown in Figure 4.8.

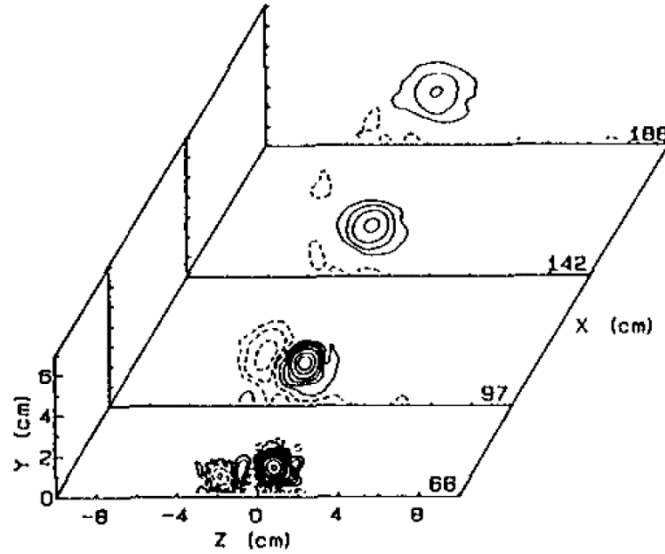


Figure 4.8 The vorticity contour of the vortex pair with unequal strength [56]

The upper contour is the streamwise vorticity. There are four downstream stages: 66, 97, 142, and 188 cm. The positive contour is the solid line, and the negative is the dashed line.

The primary vortex remains in the boundary layer through all stages, but the weak vortex only through 3 stages. The circulation of the primary vortex is similar to the common flow-up and flow-down case at the initial stage. The decrease rate of the primary and secondary vortex is the same in both counter-rotating cases. The peak vorticity decrease rate is in the middle of two counter-rotating cases.

4.3.1.1 Geometry of blade

The shape of the blade essentially affects the vortex. The height of the VG (vortex generator) is related to the strength of the vortex. The conventional vortex generator has a stronger vortex due to its size. The conventional vortex generator allows the momentum transfer from the free stream. Such a transfer has a longer control range and powerful recirculating flow caused by a stronger rolling-up motion. These results are compared to the smaller sub-merged vortex generator (SBVG), which transfers the momentum inside the boundary layer [4]. The stronger vortex may exceed the exact demand and generate a higher drag; therefore, the sub-merged blade becomes the optimal choice due to the smaller vortex drag. The 0.2 δ height of VG has a similar performance to 0.8 δ VG. The

sub-merged VG is ineffective under all conditions. For example, the swept wing has a distorted velocity profile. The height requirement of the vortex generator was similar to the local boundary layer thickness [57]. A similar experiment with different blade shapes has shown similar results [58].

As for the effect on vortex strength, the vane-type blade performed best, while the trapezoid vane blade performed better than the triangle-shaped blade. Hojoon studied the trapezoid ratio and aspect ratio. The experiment involves the delta wing, trapezoid, and rectangular blade with fixed height, as shown in Figure 4.9 [54]. The study shows the vortex decay rates were strongly affected by the shape of the generator.

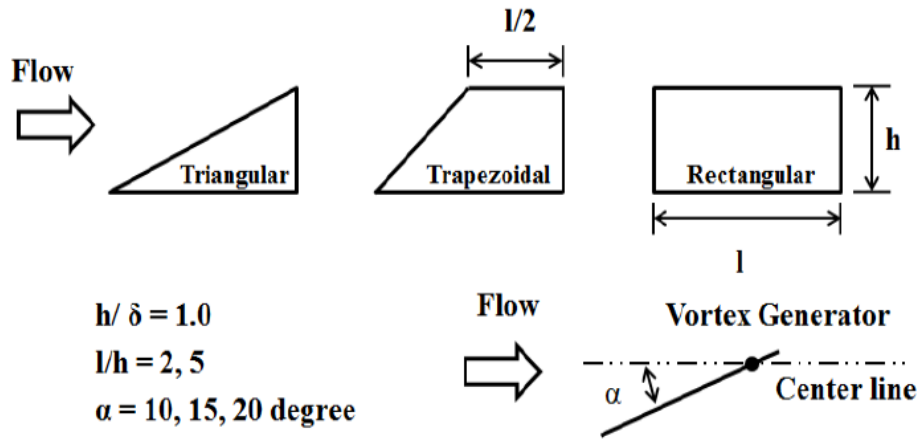


Figure 4.9 The shape of the blade and test condition [54]

The peak vorticity from the vortex generated by the delta wing shape blade shows the increasing tendency with the angle of attack increases in both laminar and turbulent boundary layer conditions. The peak vorticity obtained from the laminar boundary layer of the delta wing was higher than in the turbulent boundary layer. The peak vorticity changes with the change of incline and trapezoid ratio. The flow separation on the top of the trapezoid and rectangular blade causes these changes.

Comparing the vorticity ratios ($\frac{\omega_{local}}{\omega_{max}}$) of vortices at downstream $20h$. It shows boundary layer conditions affect the vortex decay rates. Within the laminar

boundary layer, the shorter blade ($l/h=2$) condition had similar decay rates no matter the angle or distance increases. The lower aspect ratio blade ($l/h=5$) shows that with the inclination angle increasing, the rectangular blade keeps more than half of the vorticity, then it was the trapezoid blade in the middle, the triangular blade decreases fastest. The vorticity decay under the turbulent boundary layer was similar to the laminar condition. The shape of VG impacts the vorticity decay under the influence of downstream distance and angle of attack. At the highest angle 20° , the vorticity ratio of rectangular and trapezoid blades increases at the distance of $5h$ downstream. The laminar conditions had the lowest ratio. The higher vorticity ratio indicates the vortices are more substantial under the turbulent boundary layer.

In other studies, the lower aspect ratio case (AR: 0.5) performs better than the higher condition (AR:1). The nondimensional performance and drag of the higher aspect ratio blade are not sensitive to the angle of attack changes. However, the actual performance is relative to the local flow condition and vortex core size. The higher aspect ratio might reflect a better effect and smaller vortex core than the low ratio case if the blade were much lower than the boundary layer [3].

Another experiment of the swept wing showed that the boundary layer thickness was kept the same height. The increasing chord length of the rectangular blade negatively impacted the performance. Therefore, increasing the AR ratio (increasing the AR from 1.2 to 2) had positive effects [58].

The location of the vortex core corresponds to the height of the blade. The location is 75% of the blade height from the experiment results. The spanwise location of the vortex core is affected by the vortex and surface interaction and angle of attack.

4.3.1.2 Angle of attack

With the vane inclination increasing, the vortex becomes stronger, but it also causes higher induced drag and outward trajectory. The effects of the toed in and toed out of the generator are similar on the flat plate. However, it is diverse on the swept wing due to the spanwise flow movements [24].

The circulation, helical pitch, axial velocity, and vortex core size are linearly related to the angle of attack [59]. The angle of attack affects the secondary vortex and multiple vortex systems by the strength of the primary vortex. The optimal angle of attack for the vortex generator is around 45° [4], but to achieve a stronger vortex, the angle can be increased to 45° [53,60], and even 50° under the supersonic speeds [24].

4.3.1.3 Location & distance

The distance between the vortex generator and the separation area is designed precisely to achieve the proper control effects due to the development and decay of the vortex. The minimum distance allowing the submerged vortex generator (SBVG) to generate a vortex is $2h$ downstream. It can achieve better effects with $15h$ from the trailing edge of the VG [4].

The control range of the vortex generator is the most relevant to vortex decay. The interaction with the solid surface mainly affects the single vortex embedded in the turbulent boundary layer [46]. Theoretically, the angular moment of the vortex close to the surface is reduced by the surface shear stress. However, the shear stress is considered a minor factor, resulting that a single static vortex could travel a long distance [61].

The experimental and theoretical studies show that the blade number and space between the blades strongly affect vortex decay. According to prior research, increasing the space among the blades has no impact on the effectiveness in some cases [58]. The distance between the blades is too narrow, which could cause solid interactions and lead to faster decay. The equation of the single vortex circulation variation was summarized in Equation 4.1. The only effect equation was the skin friction.

$$\Gamma_l = \Gamma_i \times \exp \left(c_f \frac{x-x_i}{h_v} \right) \quad (4.1)$$

Where the Γ is the circulation. The l, i represent the stages, which are local and initial. The x is the distance, and the c_f is the surface skin friction coefficient of

the solid surface. The h_v represents the height of the vortex from the solid surface.

The longitudinal vortex can travel a long distance downstream. There should be sufficient space between the trailing edge of the blades and downstream to produce the vortex. The optimal location of the blade has been chosen either in the highest local flow speed area or close to the separation area. These chosen locations can maintain vortex effectiveness even if the size is scaled down from conventional to the sub-merged vortex generator [58].

The boundary layer condition has also affected the location of the vortex generator. The study by ESDU (Engineering Sciences Data Unit) shows the boundary layers were different from the theoretical and experimental data, such as the full-scale model with wind tunnel experiments [3,62]. The potential locations and boundary layer are shown in Figure 4.10.

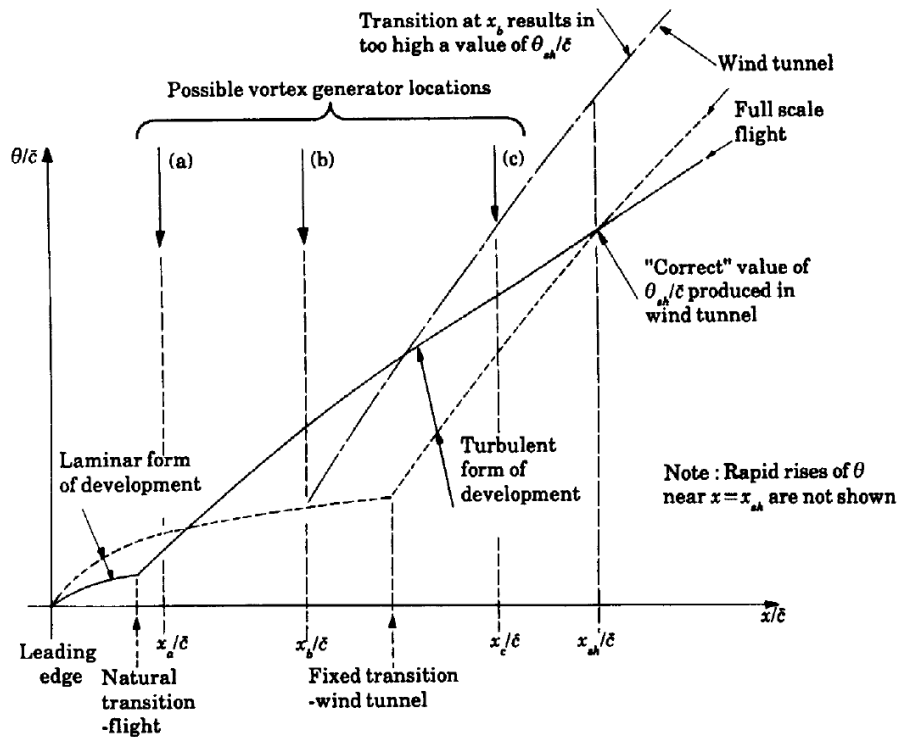


Figure 4.10 The vortex generator locations and boundary layer with correction

[3]

Solid line: full flight test. $- \cdot -$: wind tunnel test. $- -$: full scale. The *a*, *b*, and *c* mark the potential locations of the vortex generator. Labels also mark the transition locations of the three boundary layers.

Figure 4.10 shows three locations of vortex generators under the laminar and turbulent layers, respectively. The locations *a* and *b* are under the laminar boundary layer based on the full model conditions. The vortex generator may trigger the earlier transition and change the thickness of the boundary layer. In location *c*, the turbulent boundary layer will not directly cause the thickness change. The difference among the three boundary layers would cause a change in vortex generator performance. The transition on location *a* and *b* caused by the blade may lead to the full-scale model being closer to the flight or wind tunnel condition, leading to overestimation [3].

4.3.1.4 Application of Vortex generator

Previous studies have shown that flow control by a single vane blade is a multiple-parameter control method [3,54,57,63]. At the target control location, the vortex strength is affected by airspeed, blade size, shape, angle of attack, and downstream distance. Those parameters can be separated into circulation generated and circulation decay.

A single blade is not ordinarily suitable for flow control. Multiple blades are typically placed in different configurations to achieve better effects.

4.3.2 Counter-rotating with Co-rotating

The vane blade has been placed into different configurations to increase the control effectiveness through vortex interaction. The most basic configurations are the counter-rotating, co-rotating, and Biplane configurations, as shown in Figure 4.11 and Figure 4.12. The counter-rotating configurations can enhance the vortex strength by two vortices accelerating each other but also cause the vortex core to be displaced further away from the surface than a single blade [64]. The Biplane is a combination of counter-rotating and co-rotating.

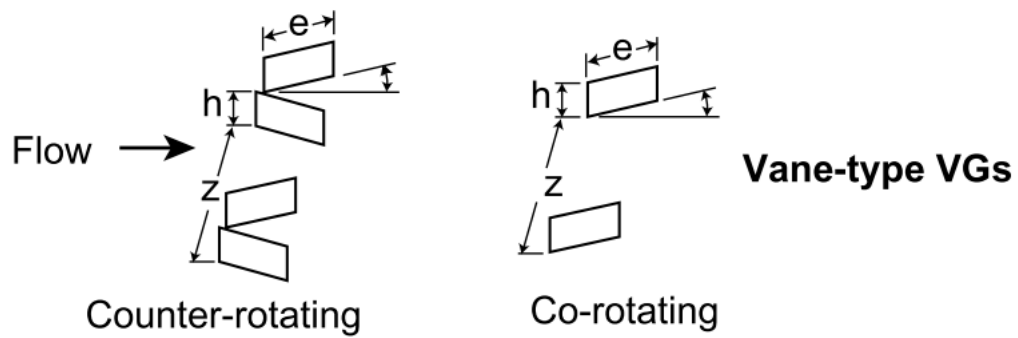


Figure 4.11 The counter-rotating and co-rotating configurations with vane-type vortex generator [4]

The left part of the plot is the counter-rotating configuration, and the right-hand side is the co-rotating configuration. h : height of the blade. e : chord length of the blade. z : space between two blades

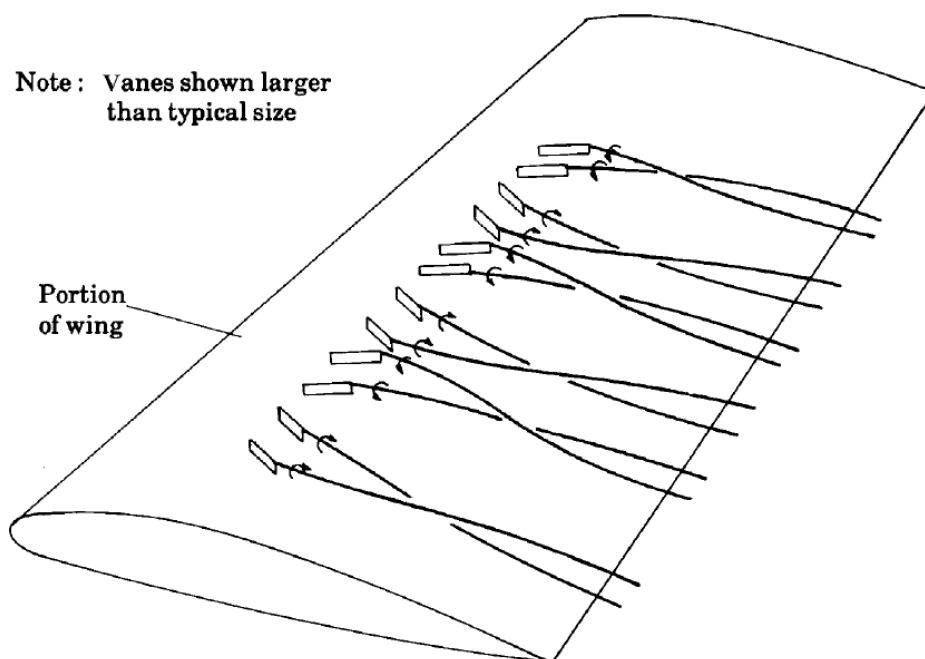


Figure 4.12 The Biplane array of vortex generators [3]

The Biplane shows the combination of both counter-rotating and co-rotating configurations.

4.3.2.1 Counter-rotating common flow up

The vortex pair developing downstream of counter-rotating configurations were studied by Eaton and Pauley [56]. The experimental devices are shown in Figure 4.13.

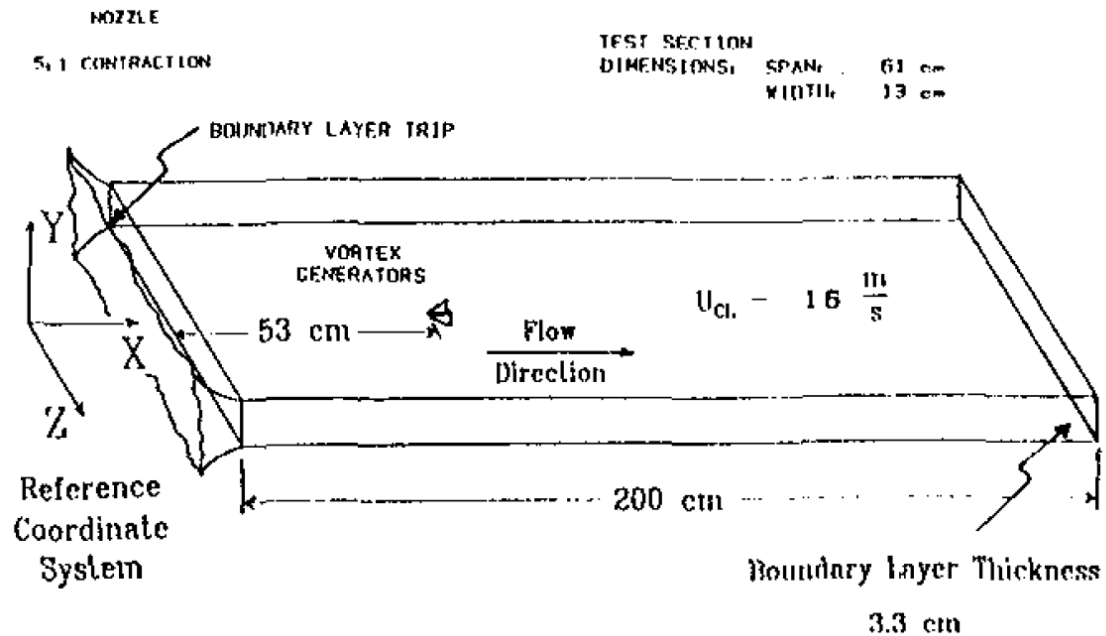


Figure 4.13 Experimental devices were involved in Easton's study [56]

The length of the flat plate is 200 cm, and the boundary layer thickness is 3.3 cm. The vortex generator is located 53 cm downstream of the leading edge.

The turbulence intensity of the flow at the inlet was 0.2% with 16 m/s flow speed, and the test section was 200 cm long. The vortex generator was half delta wing, with 2 cm height and 5 cm long. The blade was positioned 53 cm downstream of the inlet, and the boundary layer momentum thickness Reynolds number was 1700.

The common-flow-up configuration with the equal-strength vortices is unsuitable for flow control because the vortices move toward each other, causing strong interaction and eventually no longer embedded in the boundary layer. Compared to the common-flow-down condition, the common-flow-up had fewer effects on the boundary layer downstream. The vortices leave the surface due to the interactions, and the boundary layer becomes thicker [56]. The configuration of

the common-flow-up vortex generator and vortex pair is shown in Figure 4.14, and Figure 4.15.

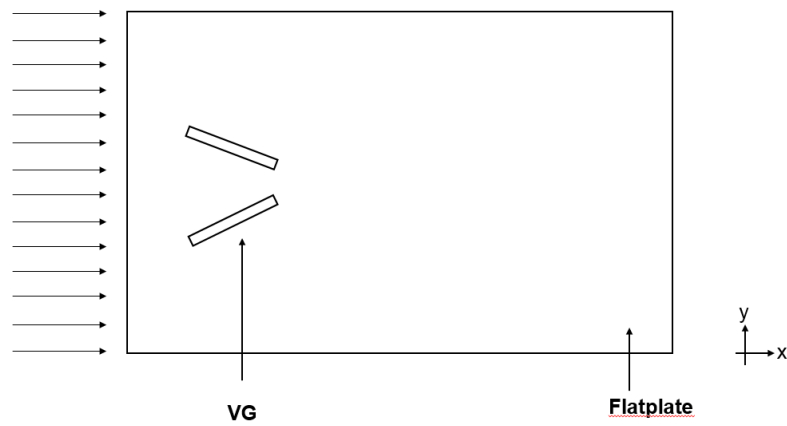


Figure 4.14 The common-flow-up configuration with delta vane blade

The common-flow-up configuration is the trailing edges of two blades close to each other.

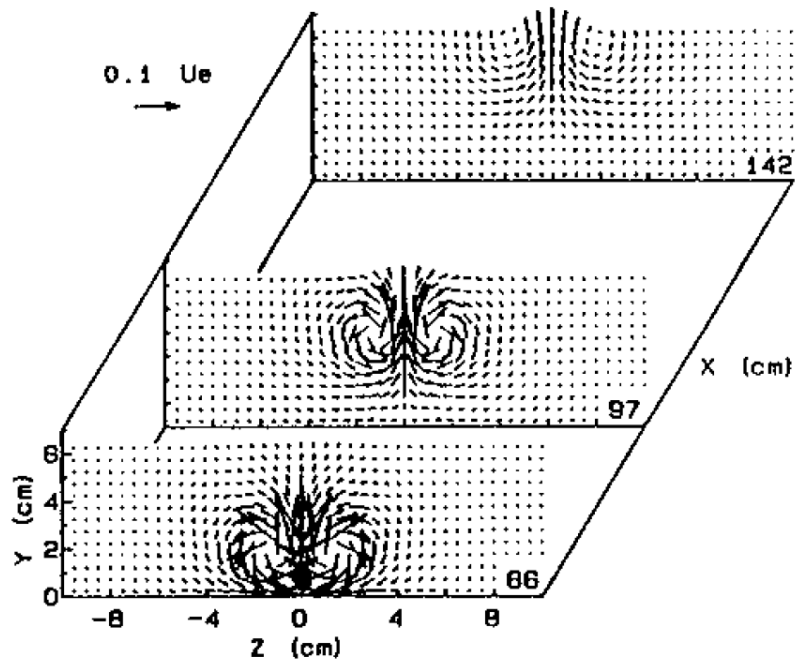


Figure 4.15 The flow vector of the common-flow-up vortex pair downstream [56]

The flow vector in the plot is the secondary flow vector. Stage one is 66 cm (33h) downstream, stage two is 97cm (49h), and the final stage is 142 cm (71h). The “h” refers to the height of VG.

Figure 4.15 shows the shapes of the vortices that have been lengthened in the vertical direction, and the two vortices are approaching closely, which leads to greater vorticity spreading compared with the common-flow-down. But the strength of the vortices decreased similarly in flow up and flow down cases. The common flow-up vortices also increased the local skin friction, but the increase was lower than the common-flow-down case. The shape of the vortices and vorticities are shown in Figure 4.16 and Figure 4.17.

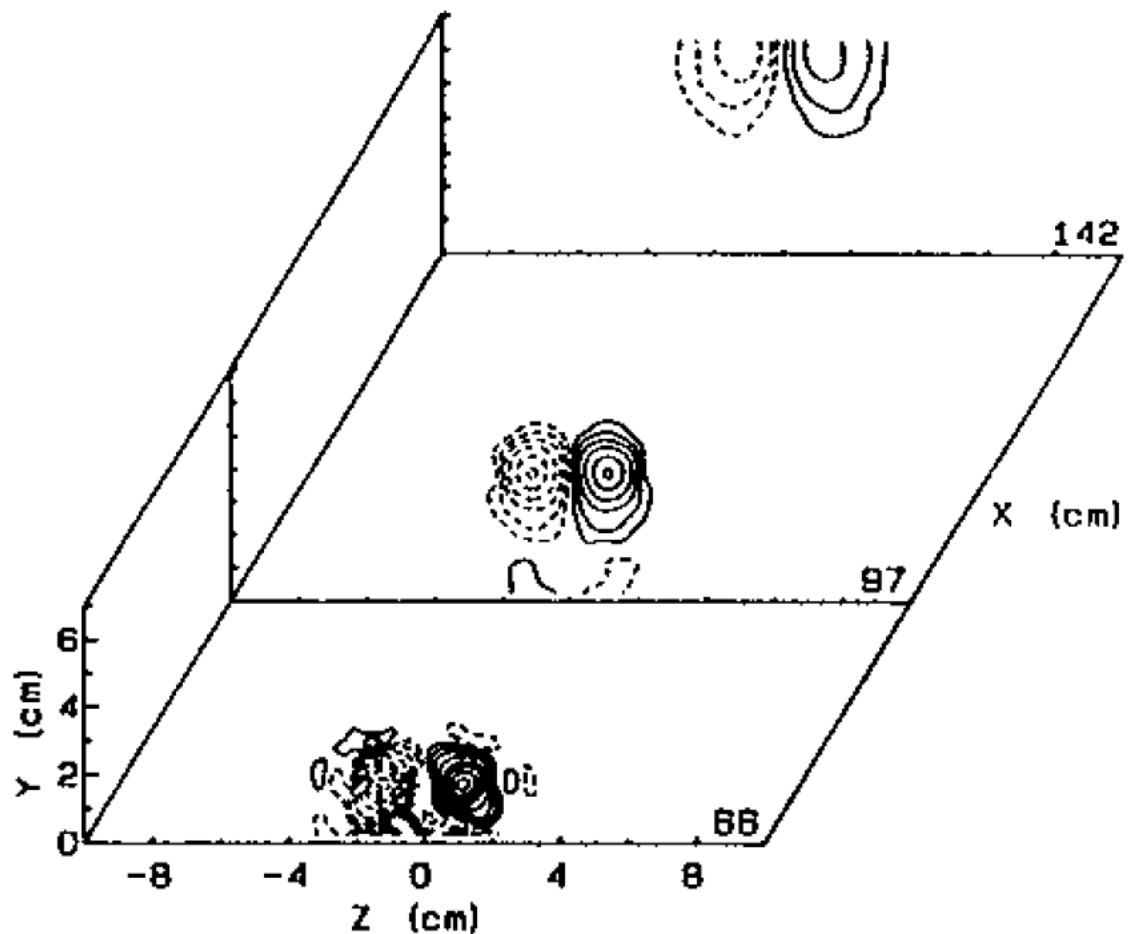


Figure 4.16 The streamwise vorticity contour of the common flow-up condition [56]

The solid line shows the contour of the positive vorticity, and the dashed line shows the negative vorticity. The stages 66, 97, and 142 cm are the 33 h, 49 h, and 71 h, The “h” refers to the height of VG.

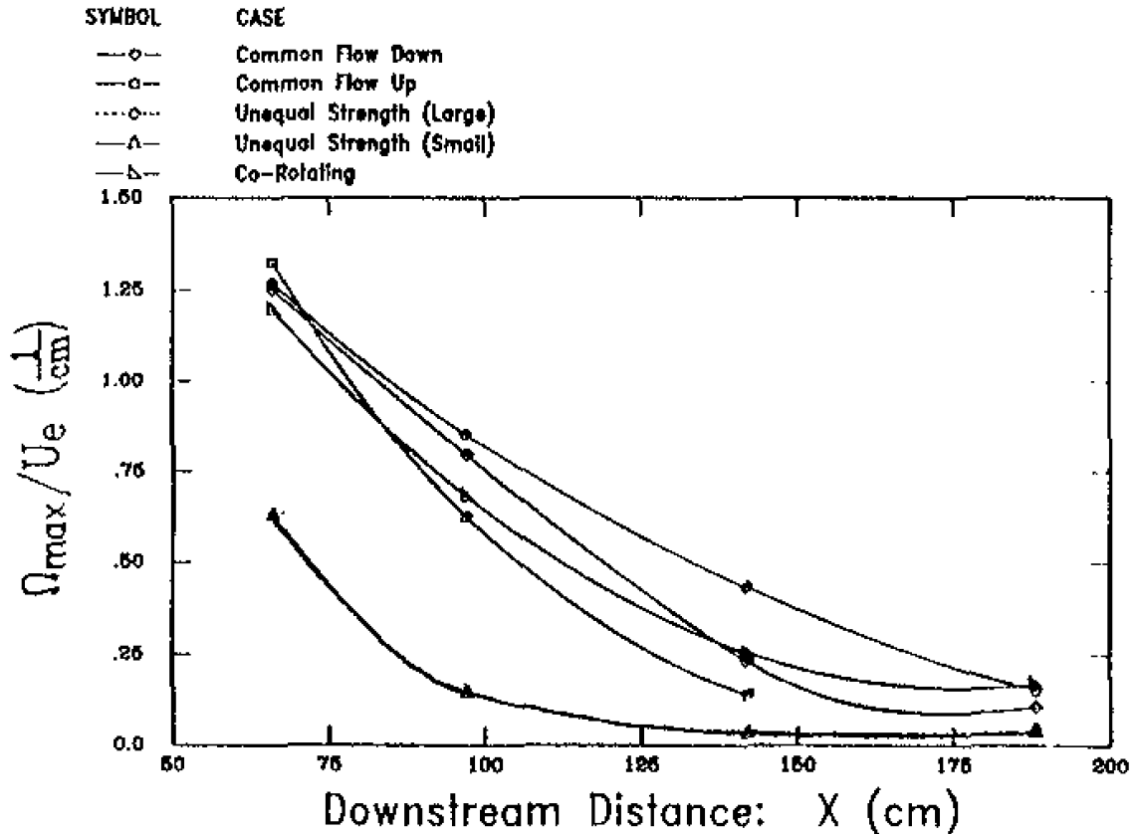


Figure 4.17 The streamwise peak vorticity development for different pairs of vortices embedded in a boundary layer [56]

The X-axis is the downstream distance, and the Y-axis is the nondimensional strength of the vortex. The vortices generated by different configurations are potted with varying points of dot.

4.3.2.2 Counter-rotating common flow down

The interaction between the two vortex cores is minor under the common-flow-down configuration, and the vortices have the strongest distortion of the boundary layer [56]. The configuration of the common-flow-down is shown in Figure 4.18. The vortices downstream is shown in Figure 4.19.

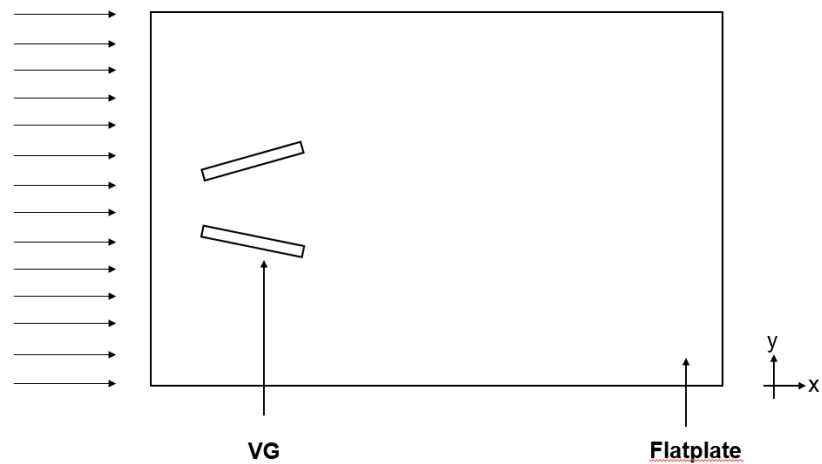


Figure 4.18 The common-flow-down configuration with delta vane blade

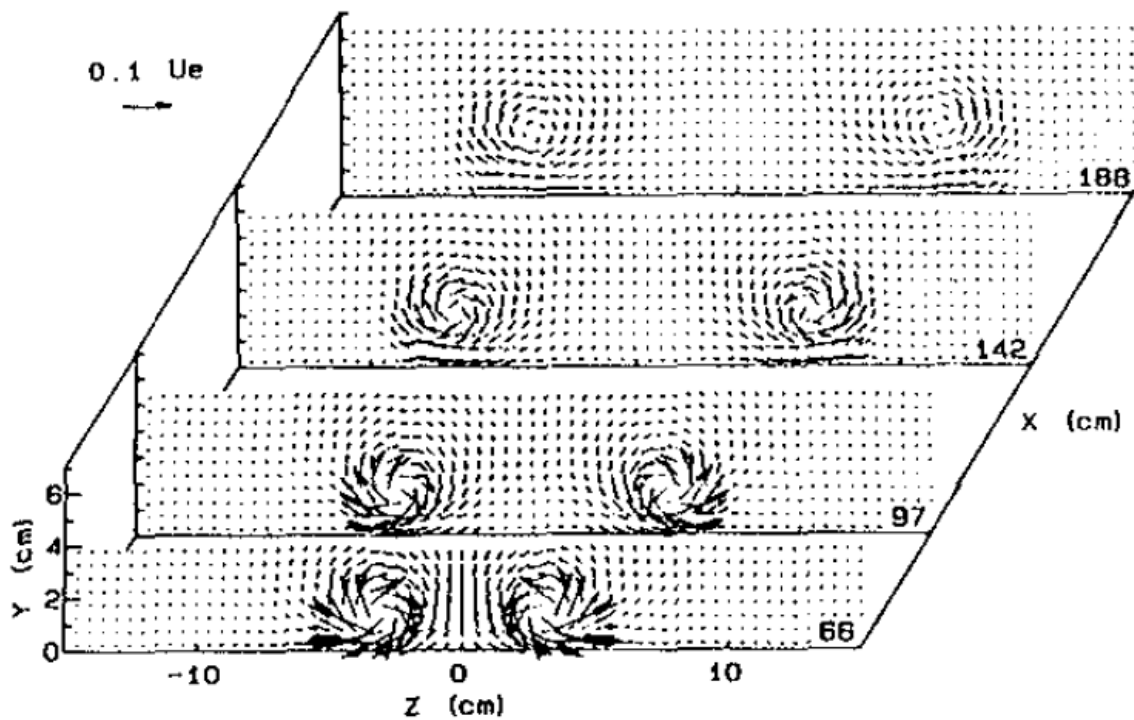


Figure 4.19 Secondary flow vectors of the common flow down [56]

The arrow represents the secondary flow vector on the vortex (4 cm spacing between two blades, AoA: 19°). Stage one is 66 cm (33h) downstream, and stage two is 97cm (49h), stage three at 142 cm (71h), the final stage is 188 cm (94h); “h” refers to the height of VG, 2 cm.

Figure 4.19 shows the clear feature of the common flow-down configurations. The vortices leave each other and close to the surface at downstream. The vortices are close to the surface due to the convention of each vortex by the flow field of the other. The interaction between the surface (image vortices) and real vortices causes them to move apart. The weak secondary vortex is also generated under the main vortex, and it lifts the main vortex up and moves the vortex toward the centerlines. The secondary vortex and main vortex as shown in Figure 4.20.

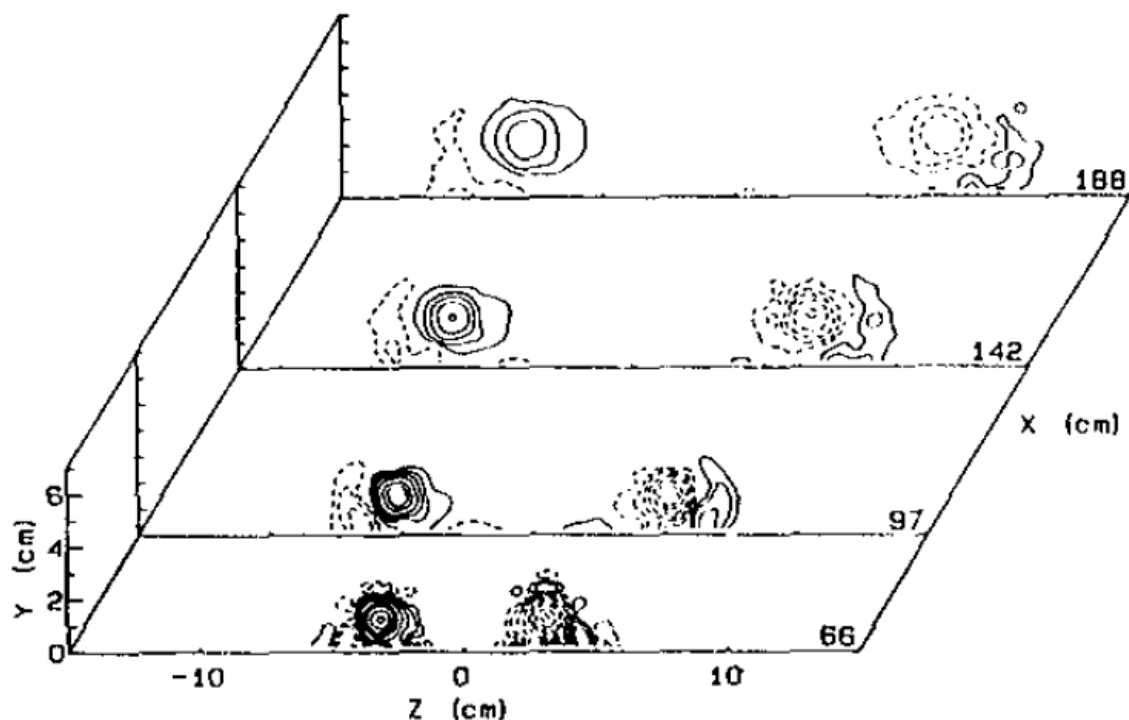


Figure 4.20 The vorticity contour of the common flow down [56]

The solid line indicates the positive vorticity, and the dotted line indicates the negative vorticity. Stage one is 66 cm (33 h) downstream, and stage two is 97cm (47 h), stage three is 142 cm (71 h), the final stage is 188 cm (94 h).

The vortices in a common-flow-down configuration can be considered as a single vortex generated by a single blade. The peak vorticity and circulation decrease as the vortex traveling distance increases, and the peak vorticity drops much faster than the circulation: almost twice as fast. The faster decay of the peak vorticity indicates the core region of the vortex spreads outward as the vortex develops. Similar to the single vortex, the shape of the vortex has been “wider”

with the increasing downstream distance caused by the uneven vorticity spreading.

The boundary layer between the two vortices has been influenced by thinning, and the local skin friction coefficient has dramatically increased. The secondary flow caused changes in skin friction; the skin friction peaked with the flow toward the surface. The friction coefficient decreased when the secondary flow was directed away from the surface. The spanwise local skin friction coefficient is shown in Figure 4.21.

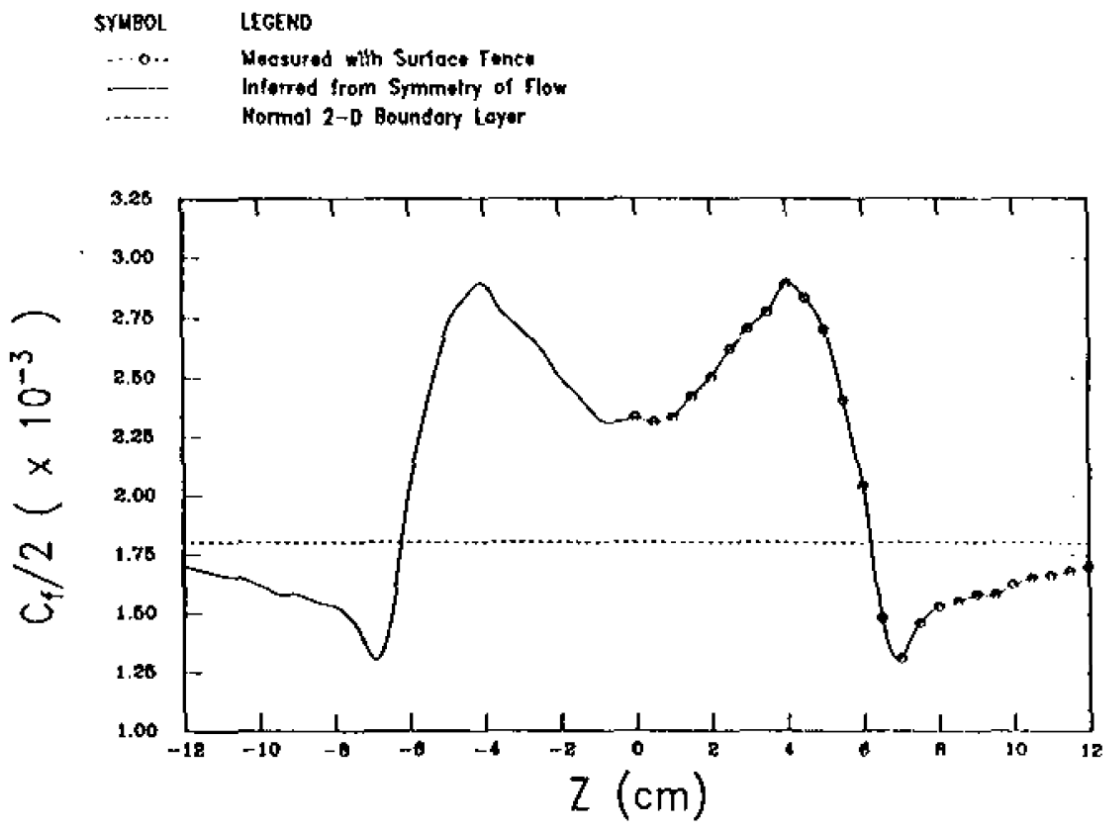


Figure 4.21 The spanwise distribution of skin friction for common flow down case at $x = 97\text{cm}$ [56]

The X-axis is spanwise of the flat plate, and the 0 is the center of the plate. The Y-axis is the skin friction. The dashed line is the skin friction of the normal 2-D boundary layer. The solid line is the skin friction caused by the vortex, and the data is obtained from the experiment.

The space between the two blades strongly affects the vortex strength and the boundary layer between the two vortices. With the space increasing from nondimensional distances (S/h_{vg}) 1 to 3, 5, and 7, the space between two vortices at downstream increased. The boundary layer between two vortices becomes thicker, and the local skin friction coefficient drops; even the vortex strength no longer changes with the large spacing.

The strength of the vortices becomes stronger as the space begins to increase. After the nondimensional space between two blades over 2 (space/height of blade), the vortex strength was unchanged with the further spacing increase. The rate of the circulation decrease is independent of the space change. The interaction between vortices is small, and the decline mainly comes from the interaction between a solid surface. The growth of peak vorticity is accompanied by the growth of space at the beginning. The vorticity is kept constant if the space exceeds the crucial distance, as shown in Figure 4.22.

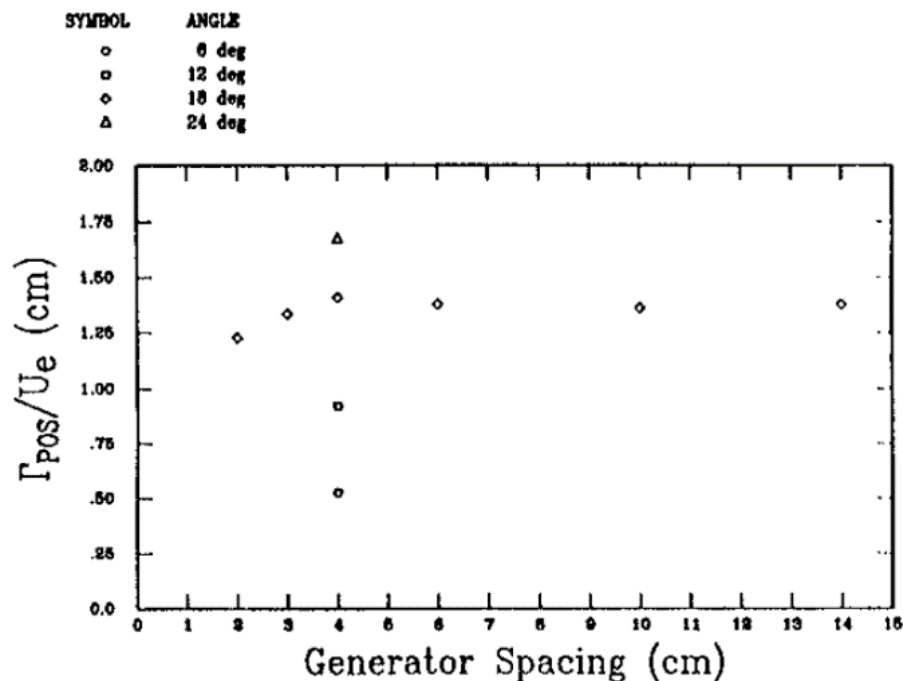


Figure 4.22 The vorticity of the common flow down with spacing increase [56]

The different shapes of data points represent the different angles of attack. The Y-axis is the nondimensional strength of the circulation, and the X-axis is the space between two blades.

Increasing the angle of attack increases vortex strength and space between two vortices. The increase in strength causes the vortices to move away from the central line, thus increasing the in-between space. The stronger vortex finally leads to a stronger secondary flow. As a result, the coefficient of boundary layer thickness and local skin friction are constant. It is called the offsetting effect.

4.3.2.3 Co-Rotating configuration

The co-rotating configuration was studied widely, and the essential feature is the two vortices become one after long-distance traveling. The vortices begin to collapse at the distance of 49 h downstream; at 71 h downstream, only one vortex remains. The vortex merging is the most substantial interaction between vortices. The interaction causes the highest reduction rate of circulation, 25% faster than two counter-rotating conditions. The reduction rate of vorticity is lower. The vortices traveling downstream are shown in Figure 4.23. The strength of the vortex in different configurations is shown in Figure 4.24.

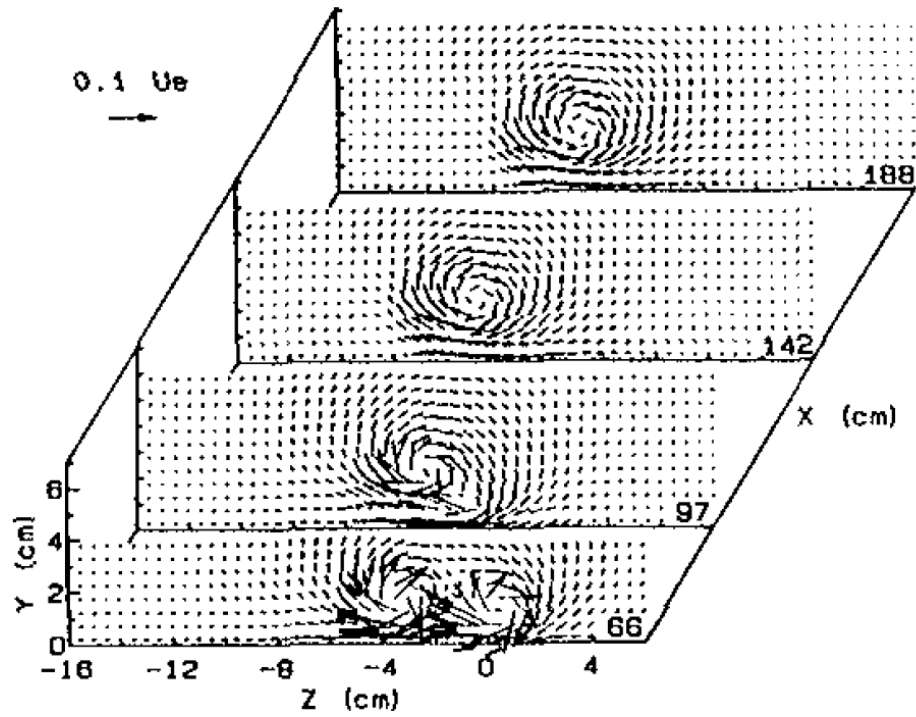


Figure 4.23 The co-rotating vortex pair downstream [56]

The vector in the plot is the secondary velocity vector. Stage one is 66 cm (33 h) downstream, stage two is 97cm (49 h), stage three is 142 cm (71 h), and the final stage is 188 cm (94 h).

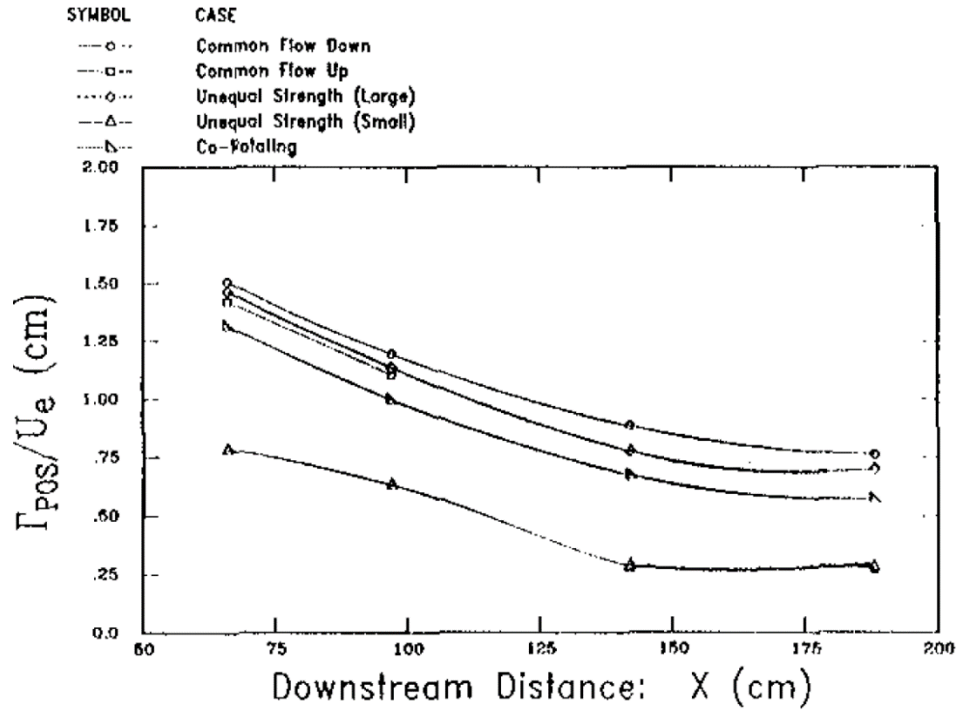


Figure 4.24 The vortices decay downstream of different vortex pairs in the boundary layer [56]

The X-axis is the downstream distance, and the Y-axis is the nondimensional strength of the vortex. The vortices generated by different configurations are potted with different dot points.

The fastest reduction rate indicates that the merging of vortexes is the strongest interaction, but the peak vortices were inconsistent with the situation changes. The result shows the rate of peak vorticity spread and vortex strength are indirectly related.

4.4 Active vortex generator

The vortex drag and uncontrollable working stat are the penalties of the passive vortex generator. Therefore, some vortex generators are located in the flap to reduce the drag in the cruise. Meanwhile, the flap's VG limits the flow control's operating frequency in cruise. An active vortex generator controls the real-time flow and minimizes the vortex drag during the cruise period.

There are two types of active vortex generators. First, it is a mechanical passive vortex generator, and the blade is retractable, as shown in Figure 4.25. Second, the air jet vortex generator blows air to form the vortex, as shown in Figure 4.26. Both types of generators impact the boundary layer by the transfer of momentum between the outer and the inner field. However, the demand for energy from active generators is higher than the static or fixed VG's [11].

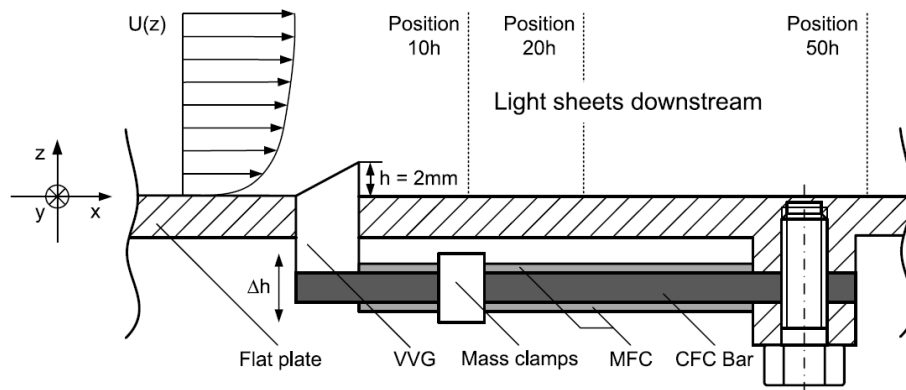


Figure 4.25 Active mechanical vortex generator [65]

The active vortex generator is the cross-section view of the AVG mechanics used in Barth's study.

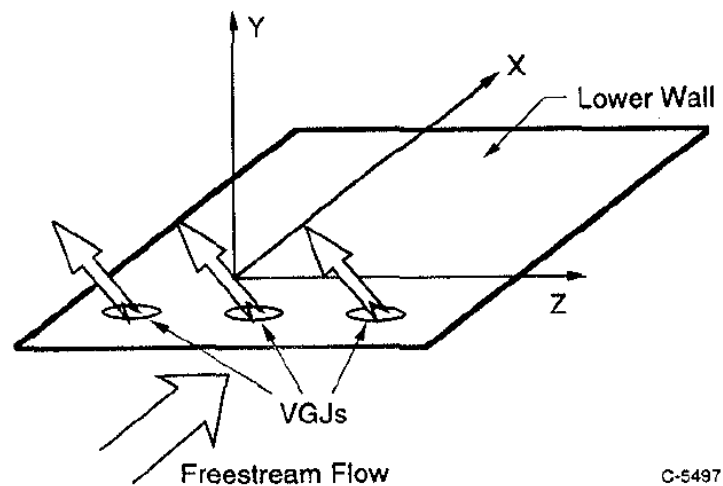


Figure 4.26 Air-jet vortex generator [50]

The sketch is the air jet vortex generator. The airflow jetted from the surface and combined with the freestream. Thus, this combination formats the vortex and moves downstream.

Mechanical active vortex generators studied in this paper are mainly designed based on the vane blade. According to the difference in deflecting frequencies, active vortex generators can be categorized into statical VG (deflected once at the beginning) or periodical VG. Both types of VG have different advantages. The frequency is transferred to the reduced frequency for the periodical VG as shown in Equation 4.2. The Equation 4.2 was defined by Wygnanski [66]. According to previous experimental studies, the reduced frequency for mechanical and air-jet have similar optimal frequencies, $F^+ = 1$ [67]. Due to the more parameters, the air jet vortex generator is more complicated in achieving the optimal frequency point than the mechanical vortex generator.

$$F^+ = \frac{f * X_{te}}{U_{\infty}} \quad (4.2)$$

The term $f *$ is the frequency in HZ of devices. The term X_{te} is the distance between the leading edge and the control devices in m , and the U_{∞} is free air speed in m/s .

4.4.1 Rotating vortex generator

A rotating vortex generator is the vane blade vortex generator. It was fixed on a rotating disc and can vary the angle of attack of the vane. The various angles of attack create different strengths of the vortex, ranging from not generating the vortex to generating a strong one.

Okamoto constructed the experiment [68]. The blade is 1mm thick, 20mm (1 δ) high, and 30mm long, with a half delta wing shape. The distance between the two blades was 45 mm. The pair of blades takes 50ms to move $\pm 18^\circ$ counter-rotating or co-rotating, stay at the position of 50ms, then take 50ms back to initial condition and remain in 0° for 50ms, the angle of attack against time is shown in Figure 4.27.

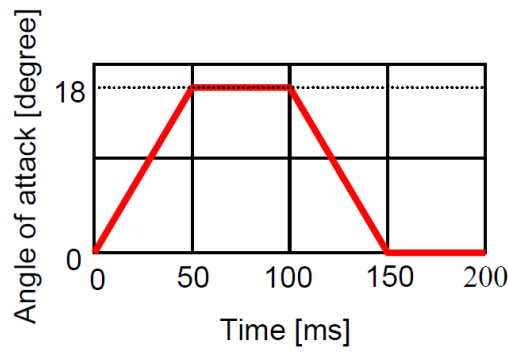


Figure 4.27 Angle of attack against time [68]

The red line in the plot is the changing angle of attack. The Y-axis is the degree of angle of attack, and the X-axis is the time pass.

The two measuring plane locations are downstream 240mm ($12h_{vg}$) and 540mm ($27h_{vg}$), away from the center of both blades. The wind speed was 16m/s, and the boundary layer momentum thickness is 1.7mm at the blade location. Reynolds's number was 1670. The equipment is shown in Figure 4.28.

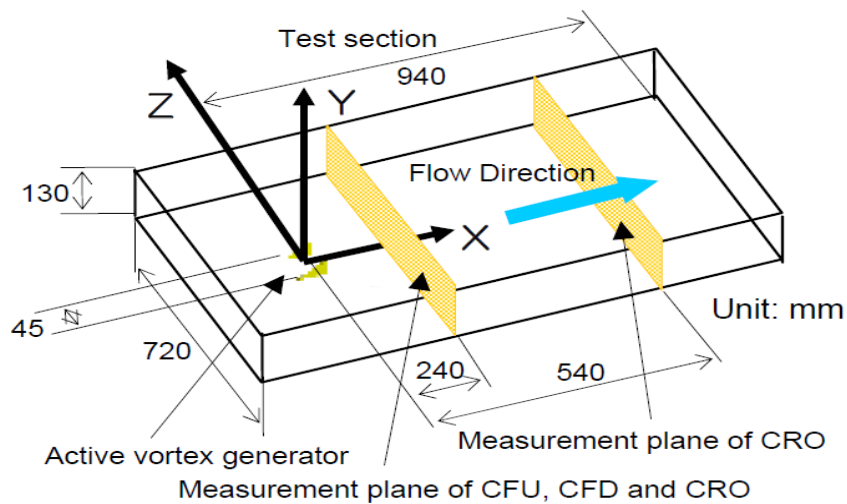


Figure 4.28 Rotation blade experiment layout [68]

The blue arrow indicates the flow direction, and the yellow sections represent two measuring stages. Two blades are located at the front part of the flat plate. The CFD, CFU, and CRO represent the common flow-down, flow-up, and co-rotating configurations.

Within the common-flow-down condition, as the angle increases, the vortex drops to the surface due to the strong downwash and moves in spanwise simultaneously due to the interaction between the vortex and surface. The high turbulence intensity is observed in the near-surface area with a lower angle of attack. As the vortex became strong, the turbulence intensity region became thicker under the upwash motion. Conversely, the region of turbulence intensity becomes thinner under the strong downwash region. This situation indicates that the vortex ‘separated’ the boundary layer by pushdown, the velocity contour, as shown in Figure 4.29.

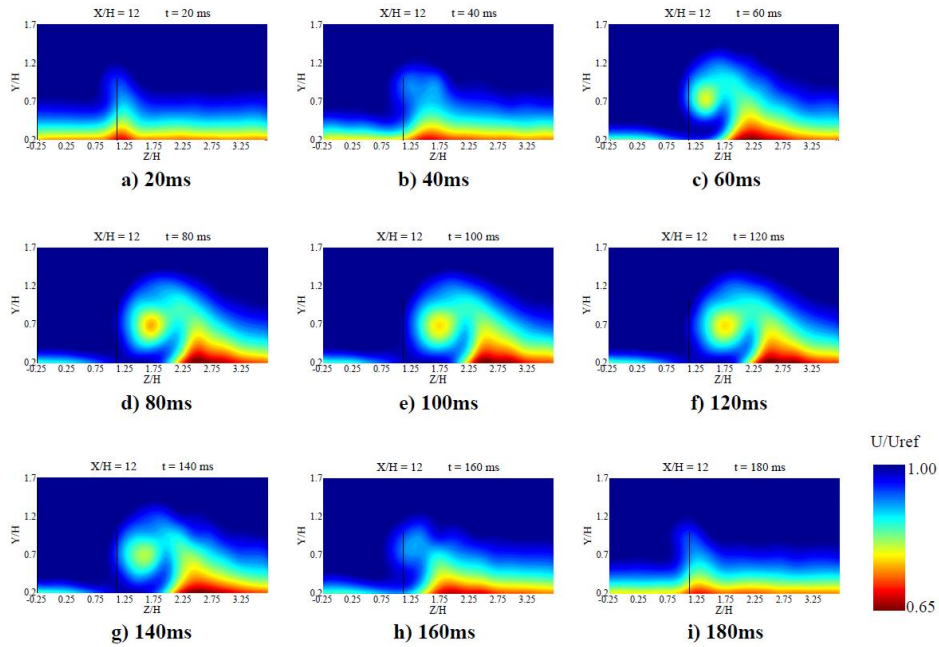


Figure 4.29 The streamwise velocity contour of the common-flow-down configuration [68]

The X hot wire measured the data at the downstream 12 h. The black bar is the location of the blade on the left-hand side.

At the common-flow-up motion, the high turbulence intensity between the two vortices increased as the angle of attack increased. Streamwise velocity decreased between two vortices, forming a mushroom shape. The secondary vortex formed at the downwash position. Compared to the common-flow-down condition, the location of the vortex was fixed during the entire period; even if the

blade did not rotate to the aim angle, the fixed location was caused by the interaction between the two vortices. The velocity contour as shown in Figure 4.30.

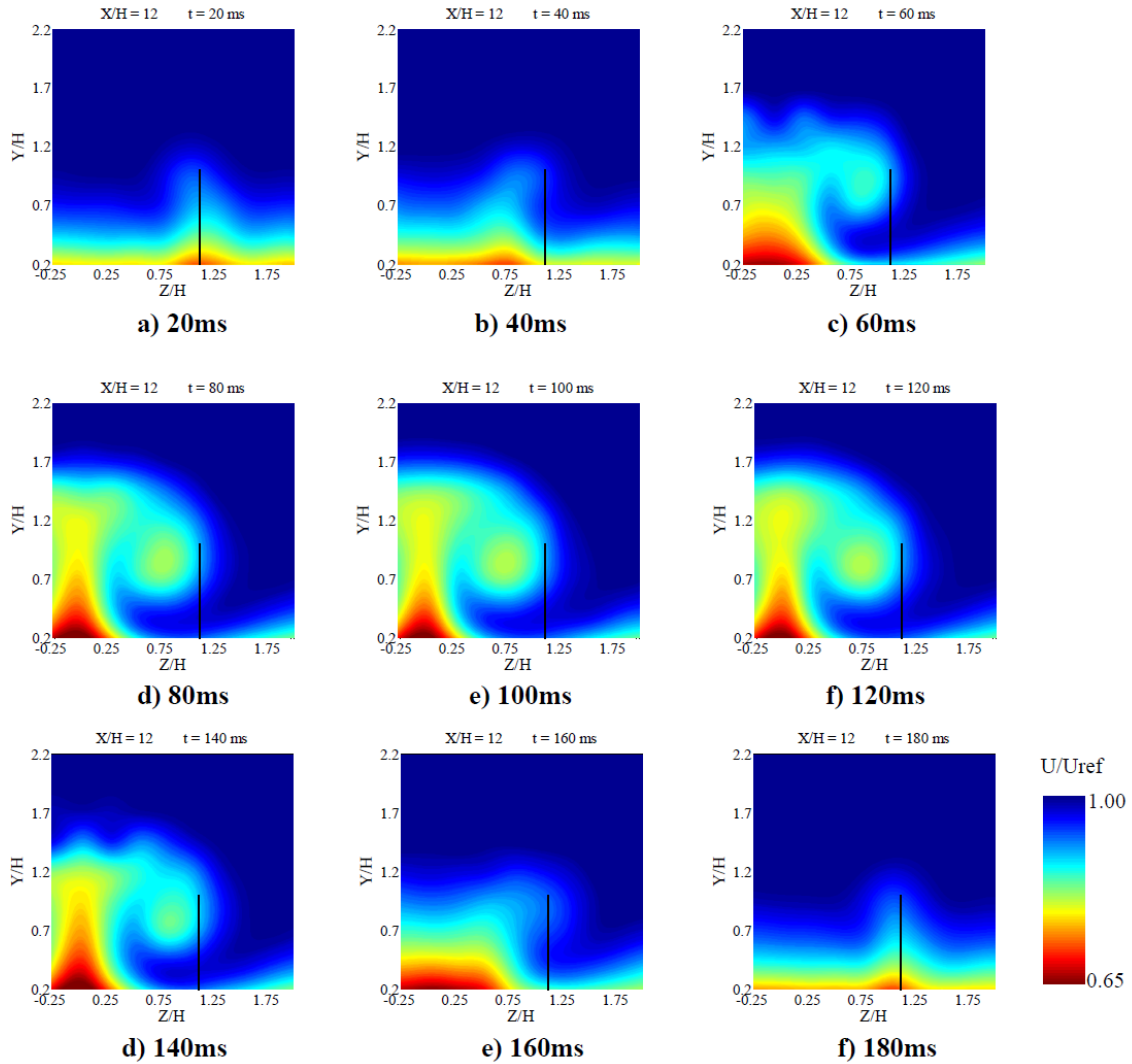


Figure 4.30 The contour of the streamwise velocity of a common flow-up configuration [68]

The X hot wire measured the data at stage 12 h. The black bar is the location of the blade on the left-hand side.

In the co-rotating case, the locations of the two vortices are different from the fully static condition. The interaction between two vortexes gradually pushes down the inner vortex when the angle increases. The interaction affects the low streamwise region between two vortexes: the higher the vortex location, the smaller the inner

vortex. Because the inner vortex had a lower height, the secondary vortex was found under the downwash effect, the velocity contour as shown in Figure 4.31.

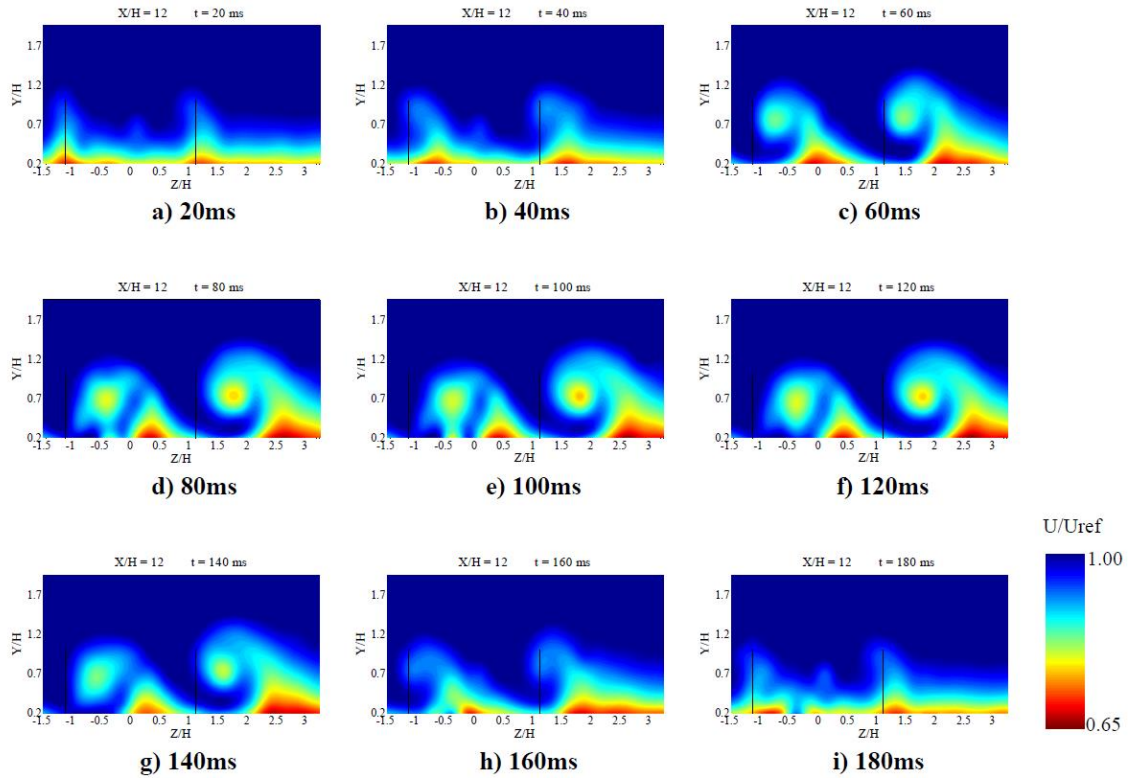


Figure 4.31 The contour of streamwise velocity in vortex form with co-rotating configuration [68]

The X hot wire measured the data at stage 12 h. The black bars are the location of the two blades.

The peak vorticities of the vortex from three configurations in the forming process of the two measuring stages have been compared. The peak vorticity of the common flow-up, flow-down, and co-rotating are similar. The peak vorticities in the co-rotating are different due to the interaction between the two vortices. The decay of the vortex between two stages causes the peak vorticity to drop the velocity contour as shown in Figure 4.32.

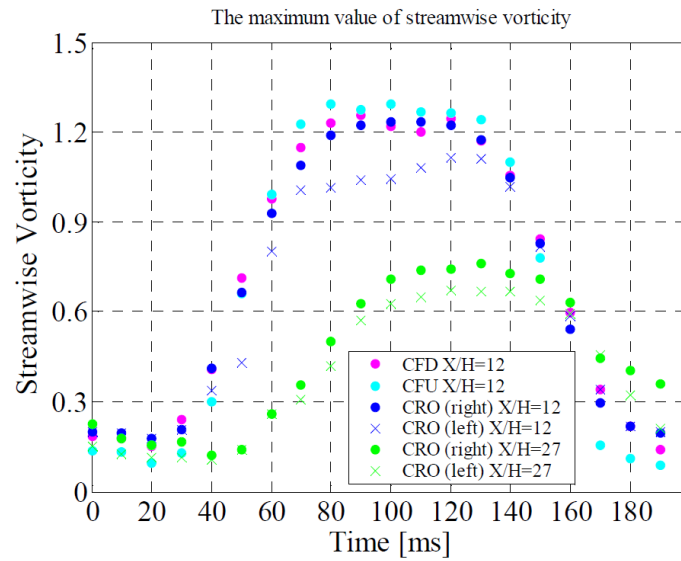


Figure 4.32 The maximum value of the streamwise vorticity [68]

The CFD, CFU, and CRO represent the common flow-down, flow-up, and co-rotating configurations. The X/H is a nondimensional downstream distance. The *left* and *right* define the location in the vortex pair.

The locations of the vortices in the forming process were recorded and compared, as shown in Figure 4.33. The trajectories of common-flow-down and co-rotating configurations reached $1.8 Z/H$ (0.44 in actual) and had the sharpest spanwise movement. The common-flow-up case has a smooth curve of location changes with the angle increasing in all three configurations. The spanwise movement of the co-rotating configuration at the far field (27 h) becomes more rapid than in the short stage (12 h).

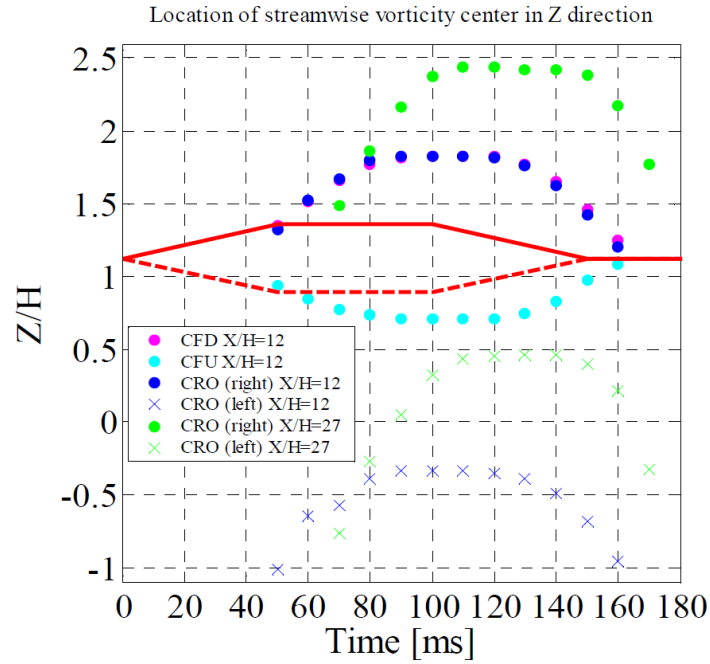


Figure 4.33 The location of the vortex centers [68]

The solid red line indicates the trailing edge of the outside blade of the configurations, and it reached 1.357 at the steady state. The dashed red line indicates the trailing edge of the inside blade reached 0.893 at the steady state.

4.4.2 Air Jet Vortex Generator

The air jet vortex generator is an active flow control method without any moving parts on the surface. This paper focuses on the mechanical vortex generator; the details of all the air jet vortex generators are in Appendix A.

4.4.3 Active Deflecting with a Steady Working State

The dynamic vortex is similar to the static vortex after the blade deflection. The advantages of active VG are that it can achieve real-time control and lower energy costs than the steady air-jet VG.

Shizawa studied a Pie-shape vane blade AVG [35–37]. The mechanical devices are shown in Figure 4.34. The airspeed was 17.2m/s with 0.15% turbulence intensity, the boundary layer thickness was 20.6mm, and the momentum thickness Reynolds number was 2600. The chord length of the blade was fixed

at 30mm, and the height was 17.23mm ($\delta/h_{VG} = 0.83$) with 1mm thickness. Blade deflected with $\omega = 21.6 \text{ rad/s}$. The configuration of the generators was the common-flow-down and counter-rotating condition, and the space between two blades was 40mm; the whole equipment is shown in Figure 4.35.

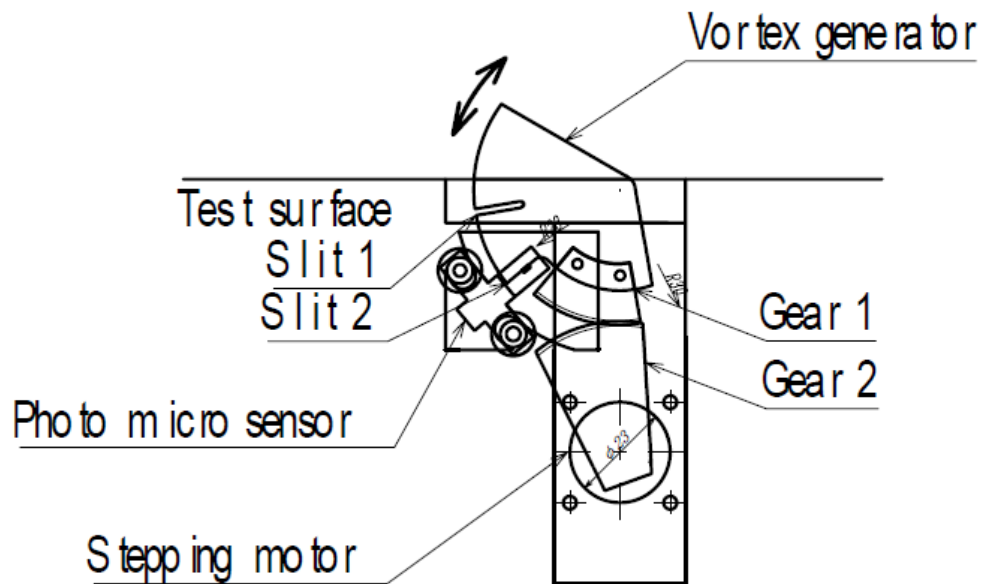


Figure 4.34 Active vortex generator within Shizawa's work [71]

The AVG's dynamic system is under the flat plate test surface. The power of the blade is a stepping motor shown in the plot.

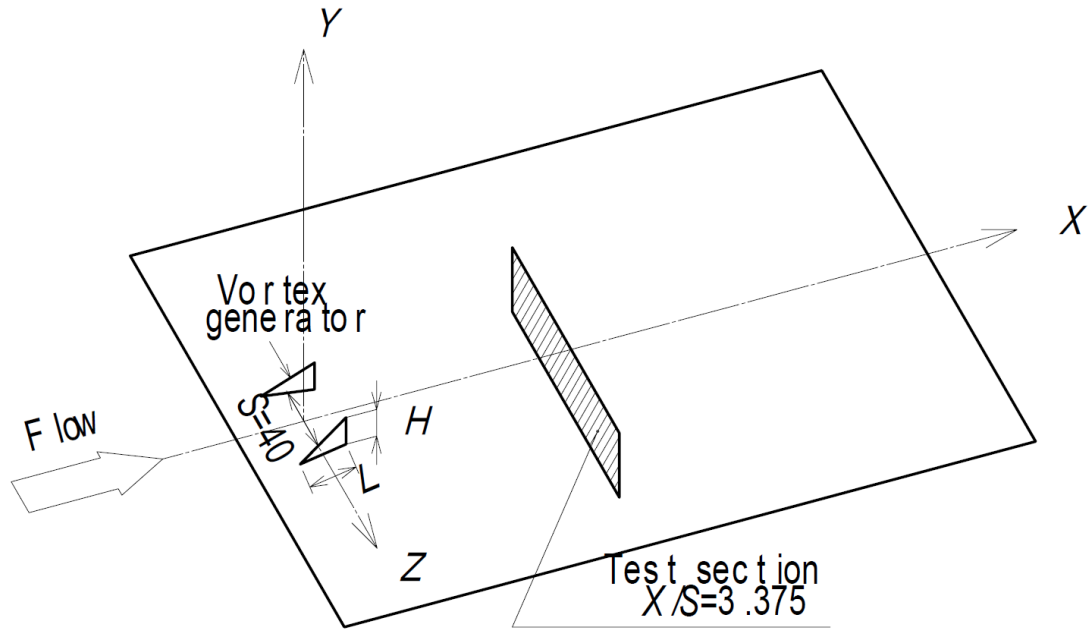


Figure 4.35 The experiment configuration [69]

The recording section is downstream $X/S = 3.375$ (135mm), the space between two blades is "S" (40 mm), "L" represents the blade's length, and the blade's height is represented by "H".

The measuring planes were at 135 mm and 250 mm downstream with a hot wire probe. The active motion was created by deflection, steady, restoration, and steady phases. All phases were tested at the same time, 50 ms, as shown in Figure 4.36. Studies show that the vortex parameters responded differently to blade deflecting and restoring within the turbulent boundary layer.

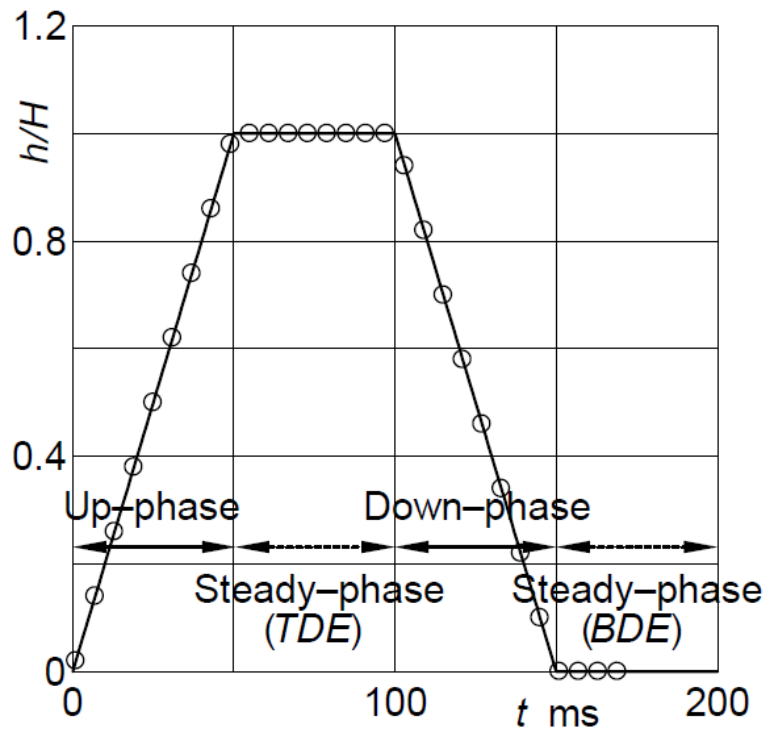


Figure 4.36 The timing chart of the active vortex generator [71]

The X-axis is the time, and the Y-axis is the ratio of the height of the blade in time and the maximum height of the blade. The solid line is the height of blade variation in the experiment ($\circ$: time of conditional average)

A “high-velocity tongue” was formed under the main vortex in deflection and deflected steady motion, as shown in Figure 4.37. The tongue appears earlier than the primary vortex. Compared with the time of blade deflecting motion, the vortex core location takes longer to move in both spanwise and vertical directions. The vortex core movement took a longer time than the strength of peak vorticity and responded to the blade deflection.

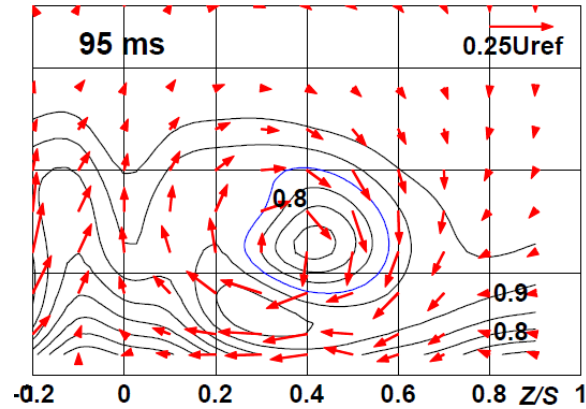


Figure 4.37 The height velocity tongue and the static vortex [71]

The contour of streamwise velocity U/U_{ref} and secondary flow vector at 95 ms in action. The red arrow is the velocity vector of secondary velocity.

The contour of the streamwise velocity and vector of secondary flow with time passed in deflection are shown in Figure 4.38. The blade fully deflected at 53ms. The vortex was first shown at 17 ms (32% of the deflection), and the transportation of high-velocity to the surface was first observed at 23 ms (43% of the deflection). The tongue of the high velocity appeared at 47 ms (88% of the deflection) of the deflection. As time passes, the contour level of the vortex core tends to be smaller, and the vortex responds to the height of the blade fast at the final stage of deflection.

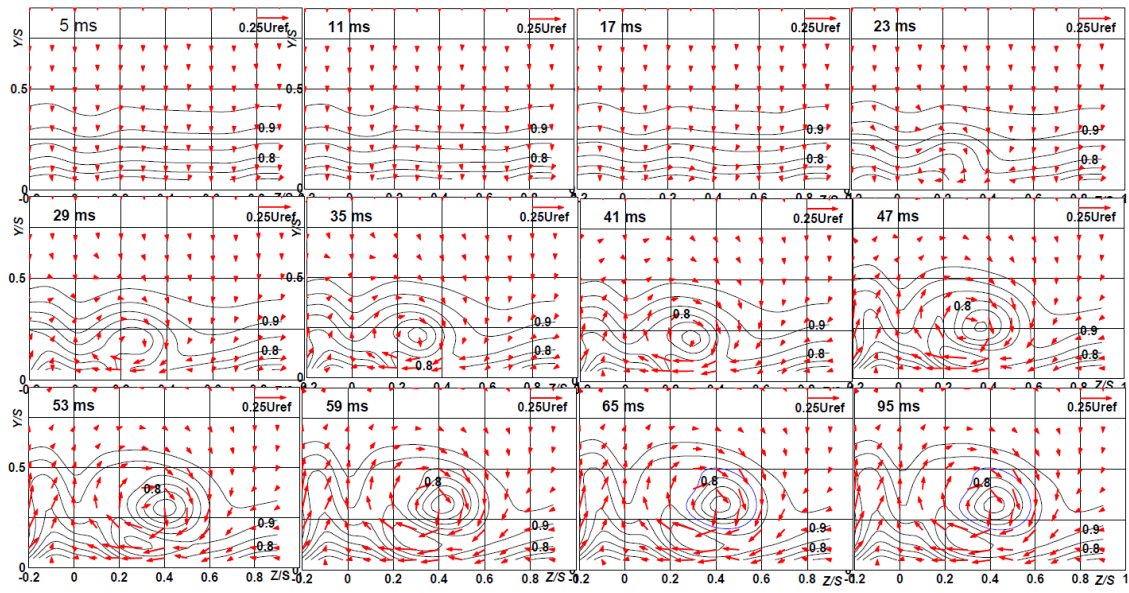


Figure 4.38 The contours of streamwise velocity and secondary flow velocity vector [71]

Deflection and steady-state, streamwise velocity ratio: U/U_{ref} The red arrows are the vector of the secondary flow. The contour is the streamwise velocity.

The contour of the streamwise velocity of the steady-state with the down phase, the plot, is shown in Figure 4.39. The slow response of the vortex was observed; the contour and velocity vector kept stable until 113 ms, but the steady state ended at 103 ms. The first change was observed at 119 ms, which was 32% of the restoration. The main vortex disappeared at 143 ms (80% of restoration). Then, the high-velocity tongue disappeared at 149 ms (98% of restoration).

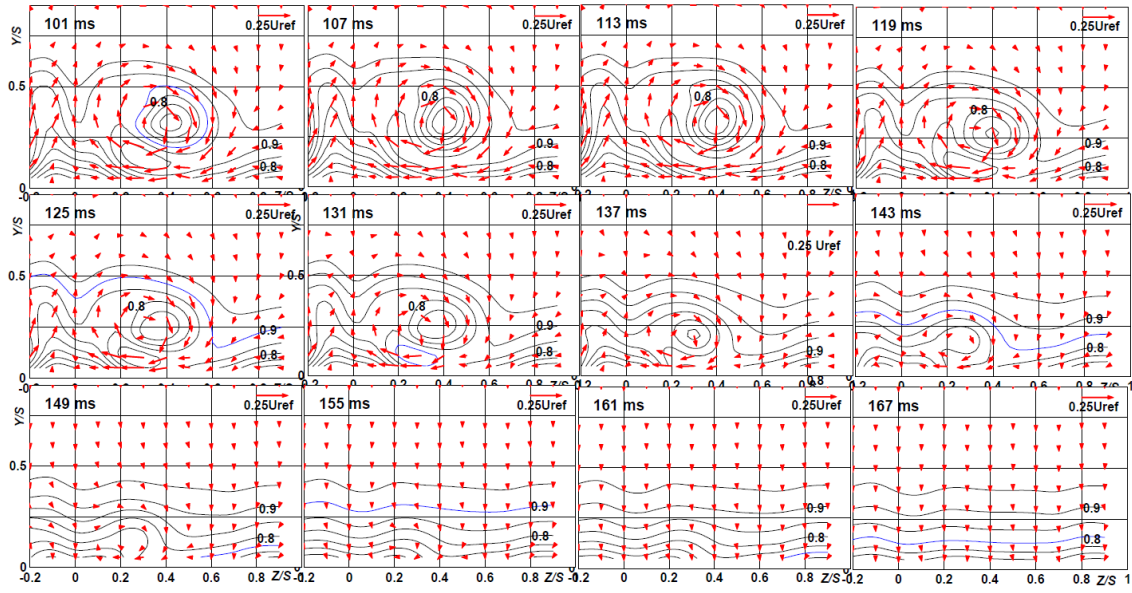


Figure 4.39 The contours of streamwise velocity and secondary flow velocity vector [70]

Deflection and steady-state, streamwise velocity ratio: U/U_{ref} The red arrows are the vector of the secondary flow. The contour is the streamwise velocity.

The phase average streamwise vorticity ω_x at downstream indicate the shape of the vortex. The vorticity in the right half of the vortex pair was recorded under a common-flow-up configuration. The vorticity contour for deflection is shown Figure 4.40.

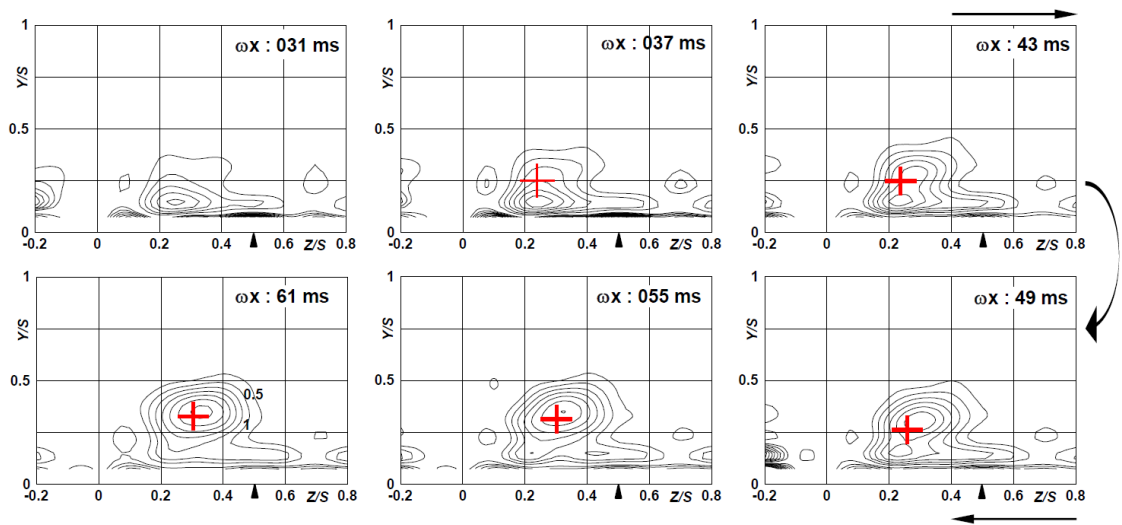


Figure 4.40 Contours plot of phase average streamwise vorticity, deflection [69]

The solid line indicates the positive vorticity, the ▲ shows the location of the vortex pair, the red cross shows the location of the vorticity peak value.

Figure 4.40 shows the right-hand side vortex's vorticity contour as time passes. The steady phase begins at 50 ms. The area of contour increase as time pass, even at the early phase of the steady state. The down phase is shown in Figure 4.41.

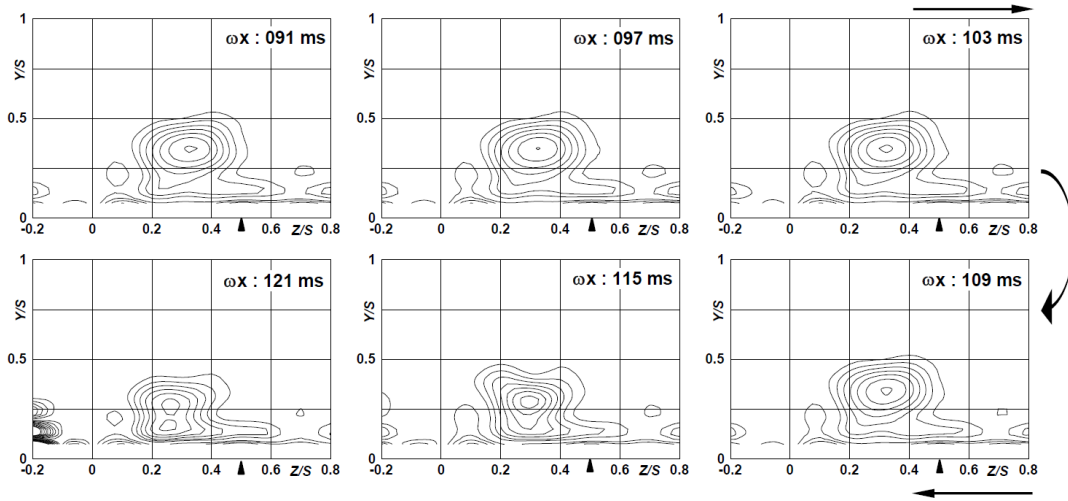


Figure 4.41 Contours plot of phase average streamwise vorticity and deflection [69]

The solid line indicates the positive vorticity the ▲ shows the location of the vortex pair.

Figure 4.41 shows the contour variation of the streamwise vorticity in the blade down phase. The steady-state ending at 100 ms. The contour is consistent until 109 ms; the streamwise vorticity contour shows a delayed response to the blade height at the initial stage of the restoration.

The peak streamwise vorticity $\omega_{x_{max}}$ changed with the increase of the height of the blade opportune and continually increased during the early stage of the steady motion. Peak streamwise vorticity was kept constant, even oscillating at the blade's early downward motion stage, as shown in Figure 4.42.

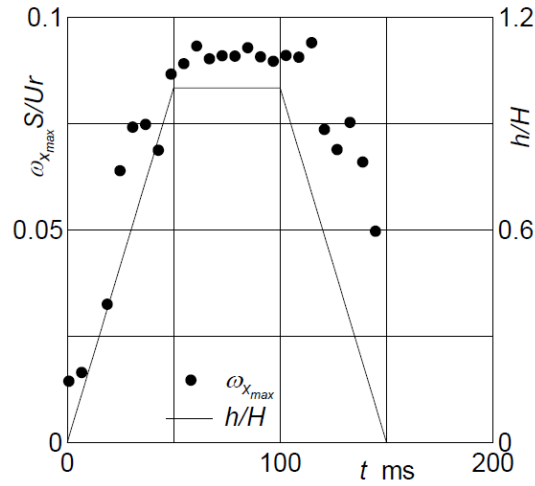


Figure 4.42 Peak value of streamwise vorticity [69]

The X-axis is the working period of the blade deflection, steady-state, and restoration. The solid black line is the height of the blade in time. The black dot is the peak vorticity from the experiment.

The peak value of the streamwise vorticity $\omega_{x_{max}}$ and the corresponding location shows different response behaviors with blade deflection. The peak values reached maximum before the blade fully deflected and then slowly responded within the early phase of the restoration.

The location of The peak value of the streamwise vorticity $\omega_{x_{max}}$ changed non-linearly with the height of the blade; the location changed with a linear deflection in the spanwise direction. The height of the vortex was kept constant at the beginning, then increased, and it reached its maximum with the development of the vortex. The location of the peak vorticity exhibits a delayed response to the blade height in both deflection and restoration, and the location stabilizes after the blade is fully deflected, maintaining the location at the initial stage of the restoration. The peak vorticity in the ZY plane is as shown in Figure 4.43.

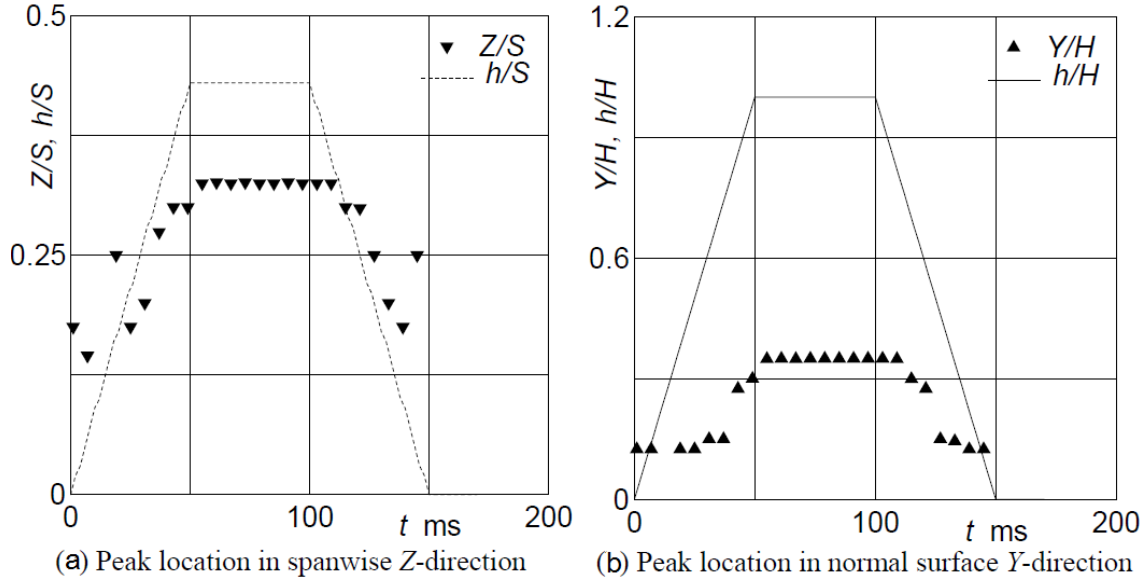


Figure 4.43 The peak location of vorticity in Z Y direction [69]

The X-axis is the active process of the blade deflection, steady-state, and restoration. The two Y-axis are the nondimensional distance, both spanwise and vertical. The solid black line in the height of the blade in time. The black triangles are locations of the peak vorticity from the experiment.

The non-linear response of peak values of turbulent kinetic energy and primary Reynolds shear stress was found at deflecting and restoration, respectively. 10% and 20% higher peak values can be observed at the end of blade up-motion and initial down-phase than in the steady condition, respectively, as shown in Figure 4.44. At the final stage of the deflection, peak locations of Z and Y directions offer a fast response to the height of the blade, at the early phase of the restoration, both the turbulent kinetic energy and the primary Reynolds shear stress showed a slow response and both peak values variation as shown below. The peak value of the three stress shows different behaviors. The peak values of $\overline{u'^2}$ and $\overline{v'^2}$ reach a higher value at the deflection end than the steady-state and increase in the down-phase motion. The peak value of the $\overline{w'^2}$ shows the linearity of the time that passed at the final stage of the deflection but a slow response at the restoration.

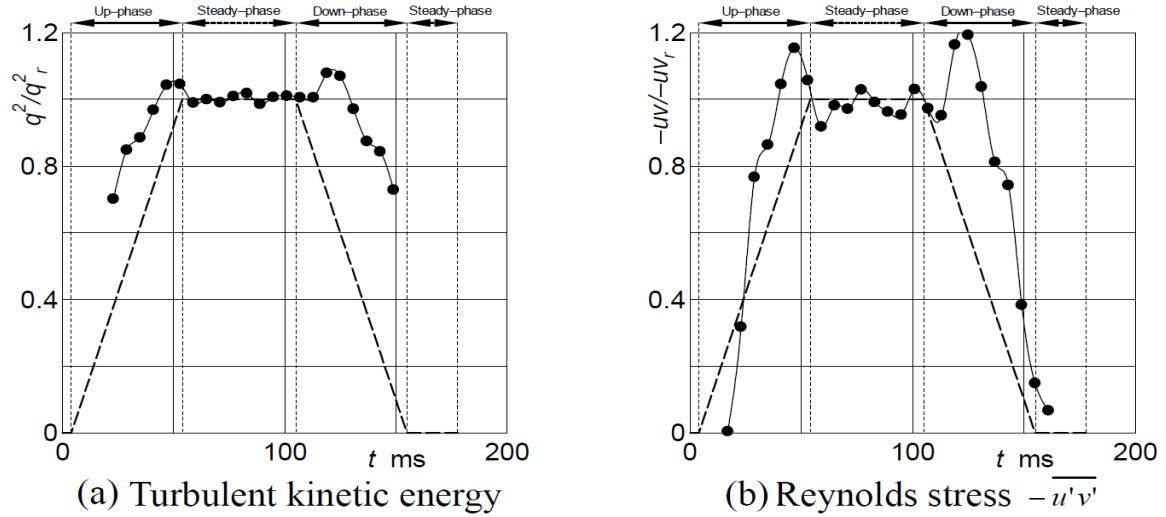


Figure 4.44 Phase average Peak value of flow properties against the height of blade variation [69]

The X-axis is the active process of the blade deflection, steady-state, and restoration. The two Y-axis are the nondimensional strength, in Turbulent kinetic energy and Reynolds stress. The solid black line in the height of the blade in time. The black dot is the data from the experiment.

The streamwise velocity “U “ was kept constant in all periods in both longitudinal vortex and ‘high-velocity tongue.’ The velocity in the vortex was slower than the free stream, and the velocity in the ‘tongue’ was similar to the free stream. The secondary velocities “V” and “W” transported high momentum from the outer range to the lower position under the main vortex and formed a high-velocity tongue. Due to the interaction effects of the vortex pair (two vortices of common-flow-up configuration), the velocity V at the up-wash side brought less momentum flow to the surface with higher velocity, which was 25% of free velocity, the velocities variations shown in Figure 4.45.

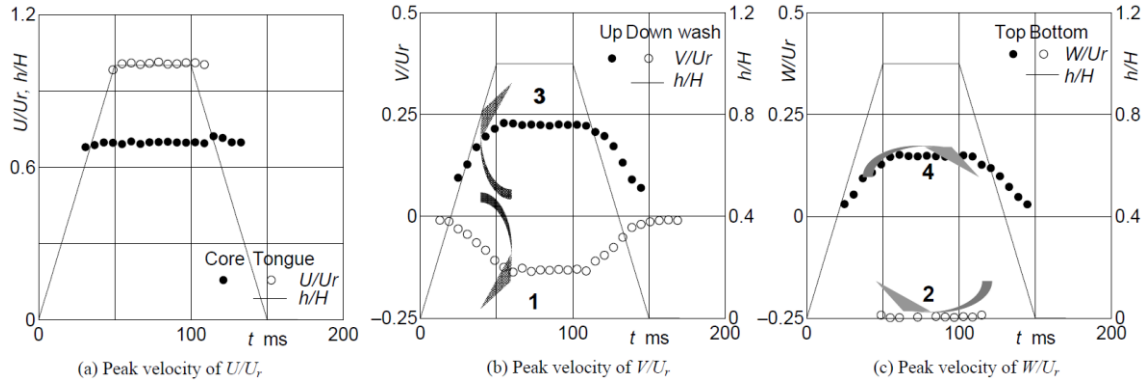


Figure 4.45 Change of phase average mean velocities [71]

The (a) is the peak velocity U , the (b) is the peak velocity V , and the (c) is the peak velocity W , all velocities in nondimensional form. The arrows in the plots show the rotation direction of the vortex. The solid black line is the height of the blade against time. The black dot is data from the experiment.

The time-dependent terms of convection in the up phase and down phase were studied. The streamwise convection term $U \partial \omega_x / \partial x$ of deflection and steady-state is shown in Figure 4.46. The positive contours first appeared at the lower area in the deflection and increased in size as time passed. The large contour was observed at the final stage of the deflection, and the area of the contour decreased faster in the early steady stage, finally vanishing in the steady phase.

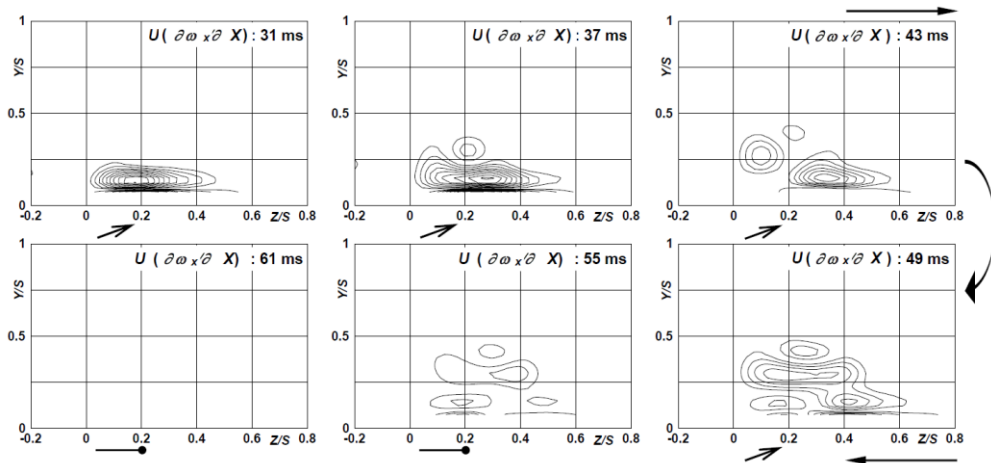


Figure 4.46 Contours of phase average convection 1st term [71]

The arrow at the bottom indicates the location of the active vortex generator at 0.2 of the spanwise. The large arrow indicates the time serial of the contours. The average term is $U(\partial\omega_x/\partial x)S^2/U_r^2$.

The streamwise convection term $U \partial\omega_x/\partial x$ with restoration is shown in Figure 4.47. The contour of the term vanished in the steady stage and appeared again at 103ms, just the beginning of blade restoration. Then the contour area increased before the final stage of restoration. In the final stage, the area and peak value decreased.

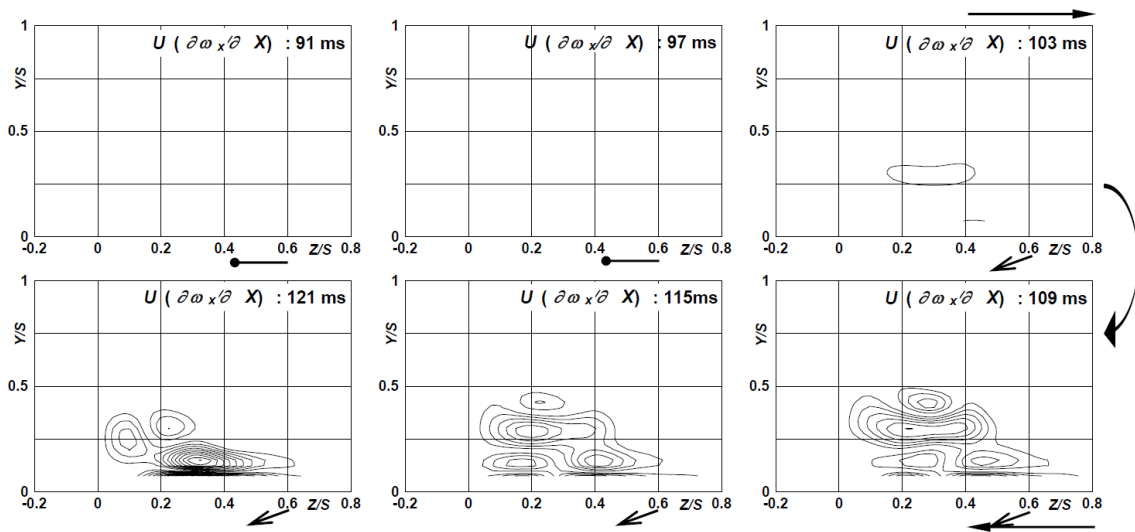


Figure 4.47 Contours of phase average convection 1st term, restoration [71]

The arrow at the bottom indicates the location of the active vortex generator at 0.4 of the spanwise. The large arrow indicates the time serial of the contours. The average term is $U(\partial\omega_x/\partial x)S^2/U_r^2$.

The contour of convection terms $V \partial\omega_x/\partial Y + W \partial\omega_x/\partial Z$ of blade deflection and restoration are shown in Figure 4.48 and Figure 4.49. The term's area and peak value increase linearly in deflection. The positive contour is at the upwash side of the main vortex, and the negative contour is at the downwash side. The contour and peak value remained similar until 109 ms, which is the early stage of restoration, then decreased linearly. The term had a delayed response to the restoration.

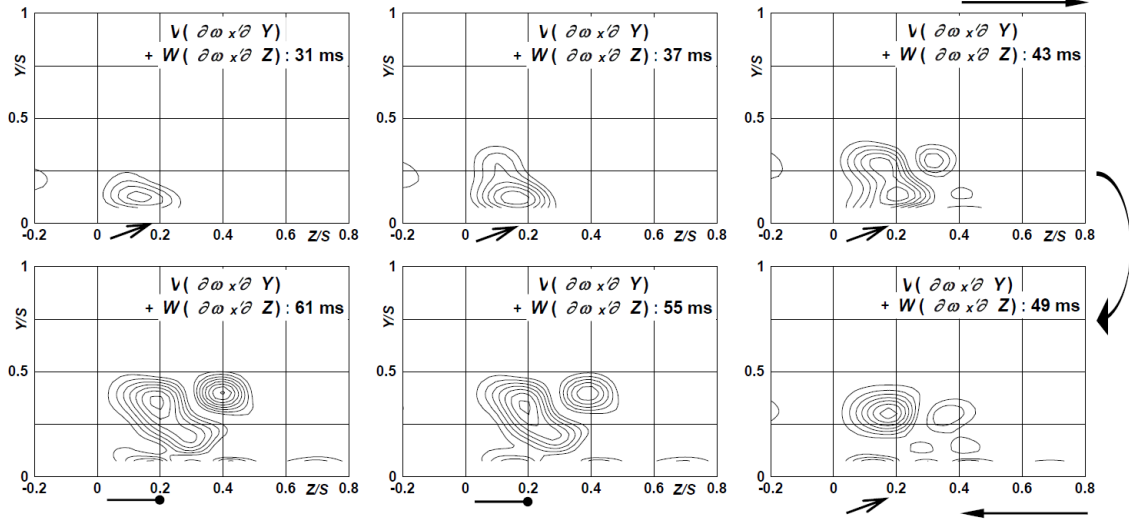


Figure 4.48 The contours of the phase averaged convection 2nd and 3rd terms in deflection [71]

Positive: solid line, negative: dash line, the arrow indicates the direction of the active vortex generator. The arrow at the bottom indicates the location of the active vortex generator at 0.2 z/s of the spanwise. The large arrow indicates the time serial of the contours. The average term is $(V \partial \omega_x / \partial Y + W \partial \omega_x / \partial Z) S^2 / U_r^2$.

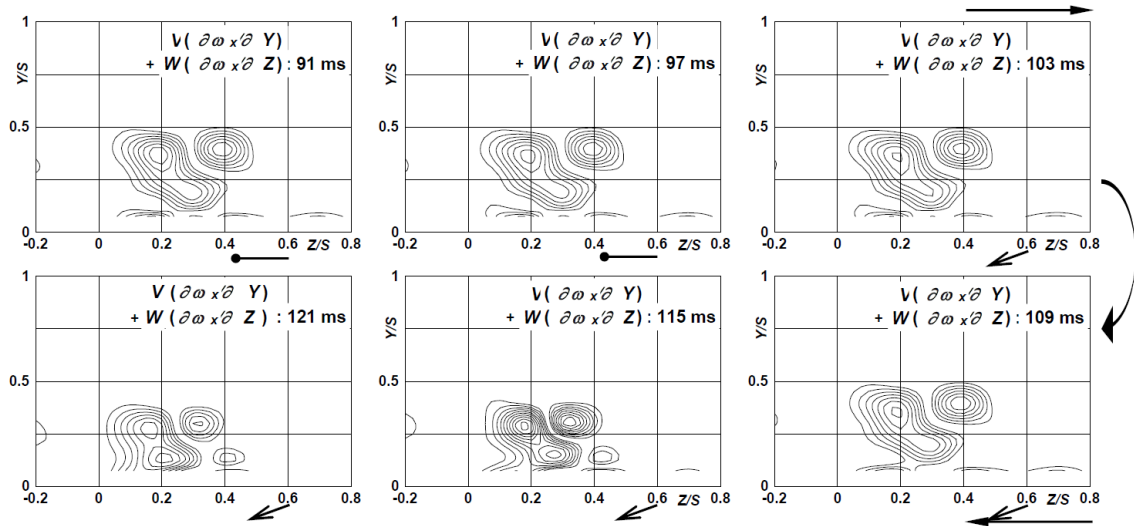


Figure 4.49 The contours of phase averaged convection 2nd and 3rd terms in restoration [71]

Positive: solid line, negative: dash line, the arrow indicates the direction of the active vortex generator. The arrow at the bottom indicates the location of the

active vortex generator at 0.2 z/s of the spanwise. The large arrow indicates the time serial of the contours. The averaged term is $(V \partial \omega_x / \partial Y + W \partial \omega_x / \partial Z) S^2 / U_r^2$.

The stretching terms of the streamwise vorticity transport equation form deflection to the steady-state and steady-state to the restoration are shown in Figure 4.50 and Figure 4.51. The stretching terms represent the streamwise changes of vortices by time. The contour represents the longitudinal vortex. The contour and peak value of stretching terms increased in deflection and rapidly decreased in steady-state. In the restoration process, the stretching terms first appeared at 103ms, which was the beginning of the restoration, and rapidly increased to 109ms.

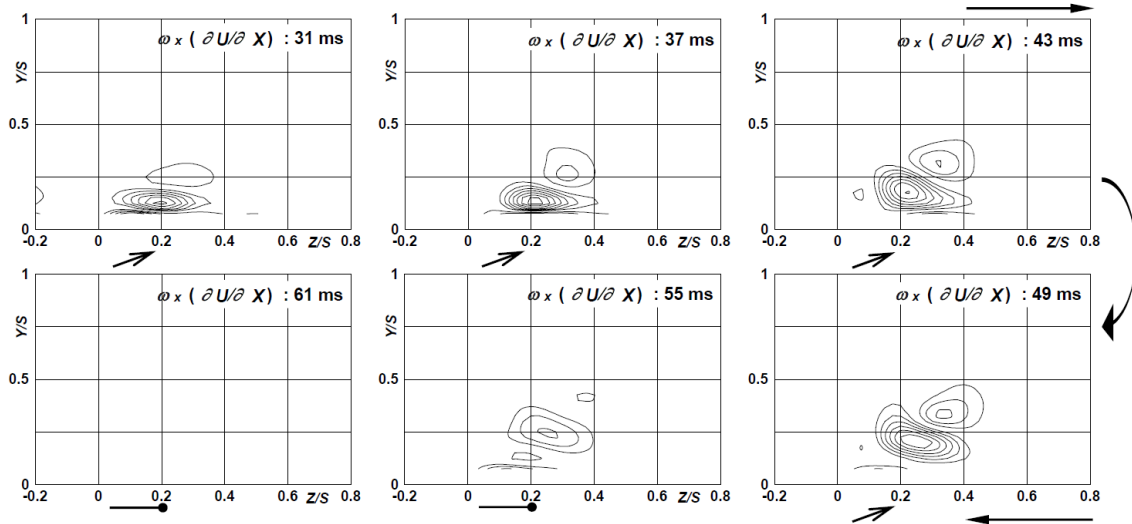


Figure 4.50 The contours of phase average stretching terms of streamwise vorticity transport equation, deflection [71]

The arrow at the bottom indicates the location of the active vortex generator at 0.2 z/s of the spanwise. The large arrow indicates the time serial of the contours. The streamwise vorticity transport equation is $\omega_x (\partial U / \partial X) S^2 / U_r^2$.

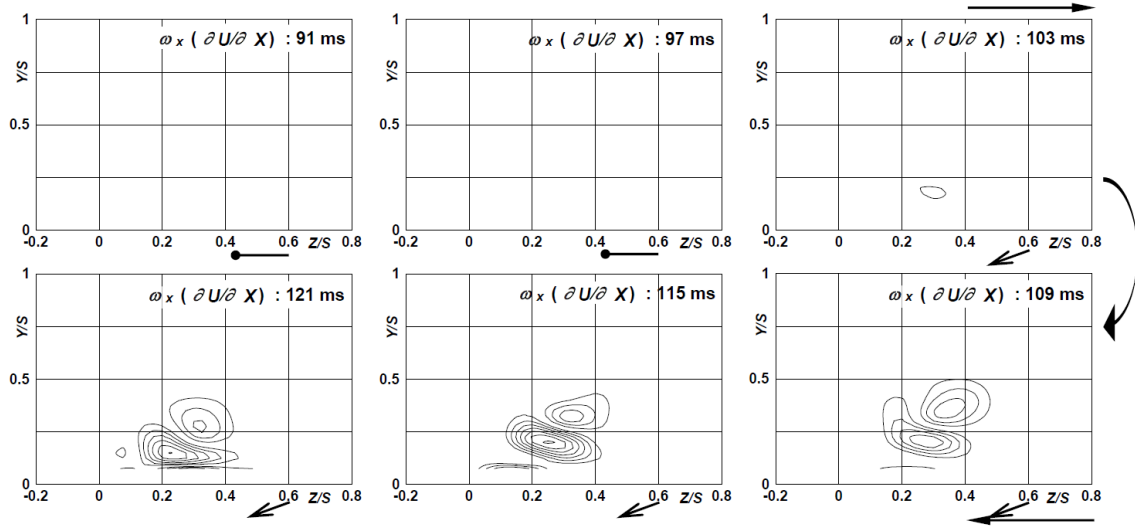


Figure 4.51 The contours of phase average stretching terms of the streamwise vorticity transport equation, restoration [71]

The arrow at the bottom indicates the location of the active vortex generator at 0.2 z/s of the spanwise. The large arrow indicates the time serial of the contours. The streamwise vorticity transport equation is $\omega_x (\partial U / \partial X) S^2 / U_r^2$.

4.4.3.1 High-frequency deflecting and restoring

The frequency of the active vortex generator has substantial effects on the downstream flow properties and flow control. The high-frequency generator differs from the lower-frequency generator and the static vortex generator. There are two types of parameters to describe the frequency, Hz and nondimensional frequency, such as the jet Strouhal number ($\frac{fd}{V_{avg}}$, for air jet only) and reduced frequency (for air jet and active mechanical vortex generator). The optimal frequency of the air jets depends on the device's geometry and parameters, such as the VR (velocity to air)ratio [72]. The frequency is extremely high, so the time between the blade deflection and restoration processes is shorter. The time is insufficient to form a coherent turbulent structure. The high frequency may cause the interaction between previous and current vortices, leading to the strength drop. The optimal location of the AVG is near the separation point. The optimally reduced frequency is $F^+ \approx 0.5$ to 1.

The Osborn studied the frequency of mechanic vane-blade VG of 50- 70Hz [67]. The equipment of the active vortex generator is shown in Figure 4.52.

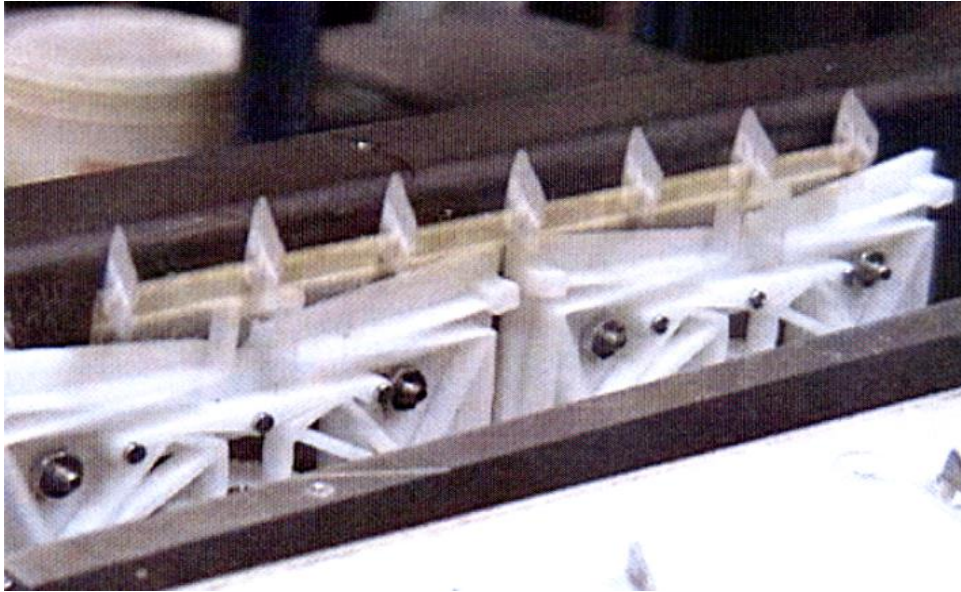


Figure 4.52 Active vortex generator structure [67]

Osborn designed the white mechanical system for the high-frequency AVG study.

The active vortex generator is on the flat plate with a 24° downward flap at the trailing edge, and the downward flap produces an adverse pressure gradient. The local turbulent boundary layer thickness is 12.7 mm (0.5 inch). The height of the blade was 5.08 mm (0.2 inches) around 0.4δ , the length of the blade was 14.224mm (0.56 inches), and the angle of attack 23° . The piezoelectric actuator powered the generator's deflection and restoration with 30 - 70 hz. The dimensions of the entire model (flat-plate) were as shown in Figure 4.53.

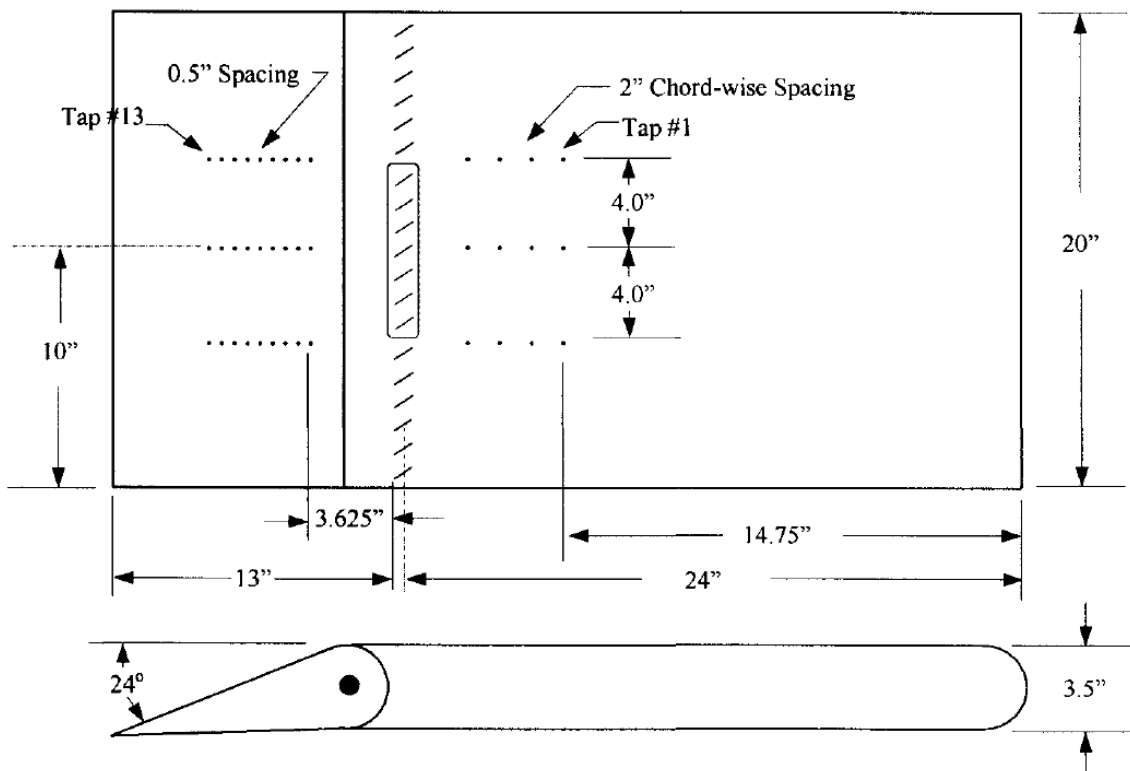


Figure 4.53 The entire model with dimensions [67]

Figure 4.53 is the top view of the flat plate, and the bottom is the side view. The unit of the plot is in inches.

There are two examples in the study; the difference is the speed, which was 16.764m/s and 21.336m/s (55ft/s, 70ft/s). The optimal reduced frequencies in this experiment are similar to the previous study in this chapter. In two speed cases, the optimal frequencies were 60hz ($F^+ = 1.18$, 16,764m/s) and 70hz ($F^+ = 1.08$, 21,336m/s), respectively. The downstream surface suction caused by the vortices became stronger in shot range and decreased rapidly as the distance increased continuously. Far downstream, the static vortex generator becomes more effective in the two cases than the active vortex generator (over 9-10 taps in the experiment).

The points of static VG performance over the active VG in the two-speed cases were different; the case 21.34 m/s was at tap 10, and the 16.76 m/s case was at tap 8. Tap 10 refers to 16.83 cm downstream, 34 h, while tap 8 refers to 13 cm,

25.63 h. The surface pressure and frequency results downstream of the two examples are shown in Figure 4.54 and Figure 4.55.

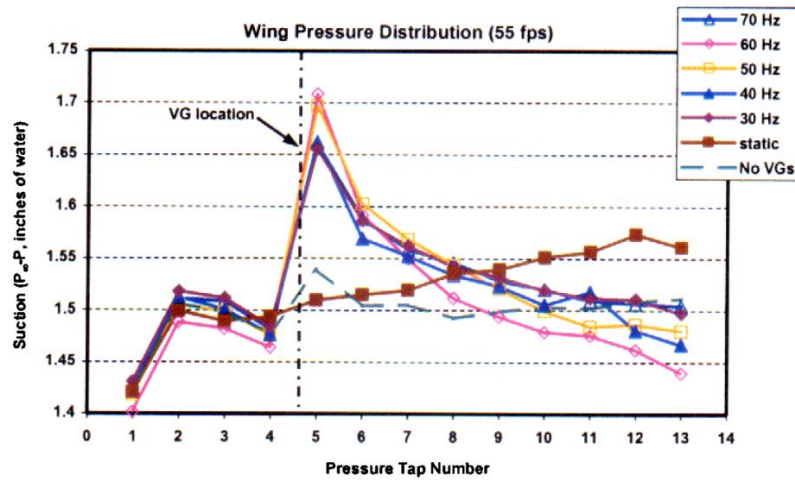


Figure 4.54 Surface suction with different operation frequencies [67]

The wind speed is 16.76m/s, 55ft/s. Different frequencies were plotted with different colors.

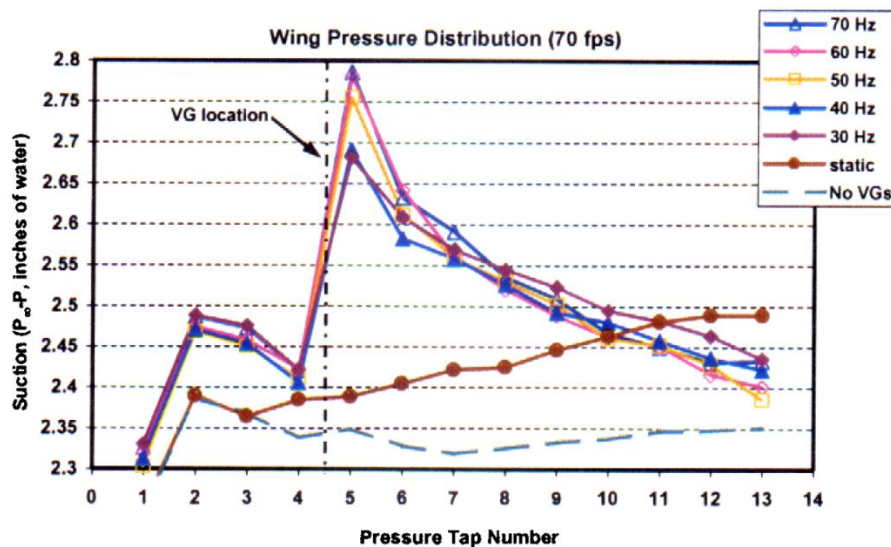


Figure 4.55 Surface suction with different operation frequencies [67]

The wind speed is 21.34m/s, 70ft/s. Different frequencies were plotted with different colors.

Osbron studied the effectiveness of the co-rotating active vortex generator, and Barth studied the counter-rotating vortex [65]. Barth's study included the

downstream flow properties with operation frequencies (112hz to 388hz). Such high frequencies were based on optimal Strouhal numbers to achieve optimal effectiveness, and the range of Strouhal numbers were 0.044 to 0.048. The configuration of AVG (active vortex generator) is counter-rotating, and the height of the blade is 2mm with a length of 5mm. The ratio between length and height is $\frac{L}{h} = 2.5$. The angle of attack of blades is $\pm 18^\circ$, and the distance between the two blades is 12mm. The ratio of the distance between the blades and the blade height is $\frac{\lambda}{h} = 6$. The cross-section view of the experiment equipment is shown in Figure 4.56.

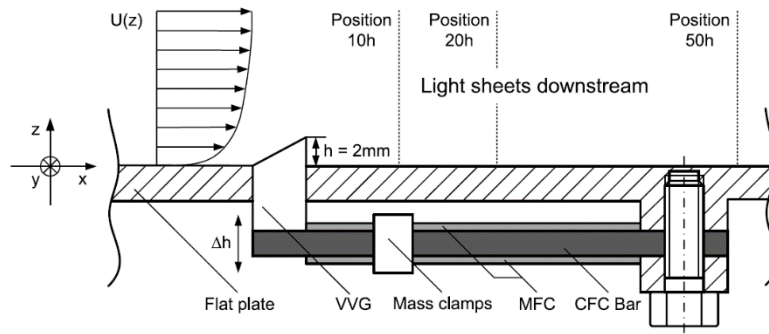


Figure 4.56 The cross-section view of the experimental equipment [65]

The experiment's equipment is shown in Figure 4.56, and three measuring sections are 10 h, 20 h, and 50 h downstream. Figure 4.56 is the same as Figure 4.25.

At the 10 h downstream, the circulations varied with the blade's up-down motions. The peak circulation in the dynamic process of each frequency case was different. With the frequency increasing, the peak of circulation and the circulation curve against time both reduced. The average circulation in the blade's up-down motion is shown in Figure 4.57.

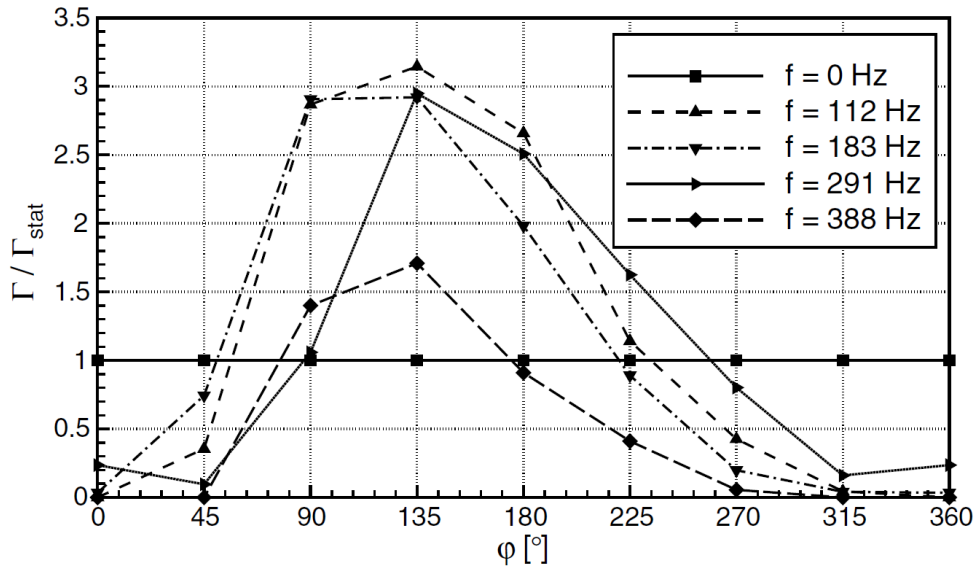


Figure 4.57 Relative circulation with Phase angle changes [65]

The circulations are measured at position $x = 10h$ for different frequencies. The Y-axis is the nondimensional strength, and the X-axis is the active process.

When the blade deflection is the phase $\varphi = 0 - 135^\circ$, at phase 135° , the circulation reaches the peak value. The results of the circulation variation in the process show different actions when the operation frequency increases (deflecting speed increases). The vortices are quasi-static with lower frequencies (slow deflecting speed). After the frequency of deflecting speed increases to the critical range, the blade is deflected in the flow immediately, and the inertial of the bulk flow cannot create a quasi-steady condition, leading to the higher initial circulation of the transient vortex. If the frequency goes too high, the short time of the blade within flow will not be enough to form a vortex, then causing the strength to drop.

The height of the dynamic vortex and steady vortex were different. The location of the dynamic vortex changes in the vertical direction of the surface. The relative height ($\frac{\text{height of dynamic vortex}}{\text{height of static vortex}}$) of the vortex in the dynamics process at $10h$ downstream is shown in Figure 4.58.

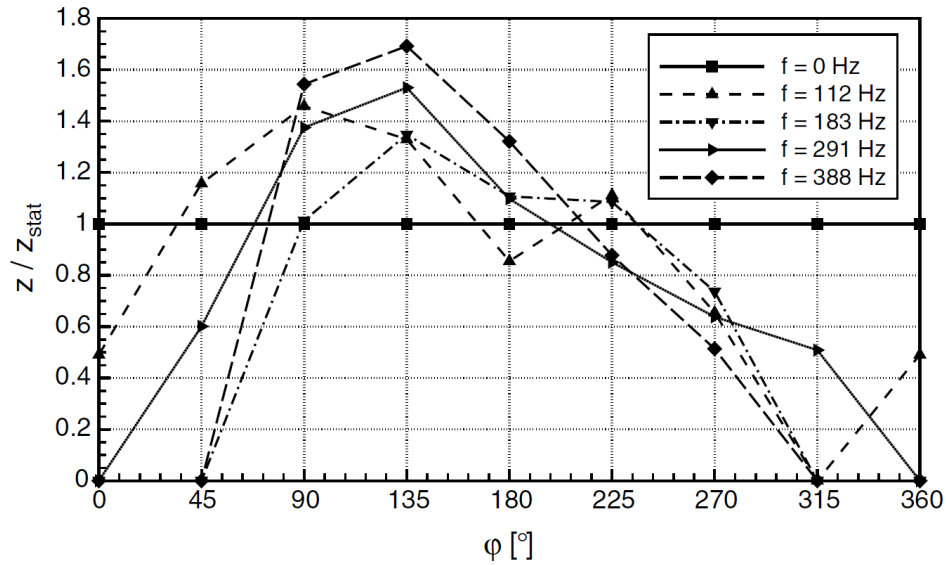


Figure 4.58 The relative position of vortex centers with phase angle [65]

The location is measured at position $x = 10h$ for different frequencies. The Y-axis is the nondimensional strength, and the X-axis is the working period.

The height changes of the dynamics vortex are not sensitive to the frequency. The plots show that the vortices with the stage of highest circulation were in the most elevated location above the surface, and the vortex far away from the surface reduces the effectiveness of momentum transfer.

As the downstream distance increased (from 10 h to 20 h and 50 h), all dynamic vortex circulations were lower than static vortex circulation. The circulation of the static vortex is higher than the dynamic vortex's circulation when the range of the downstream distance is 20 h to 50 h. The circulations are shown in Figure 4.59.

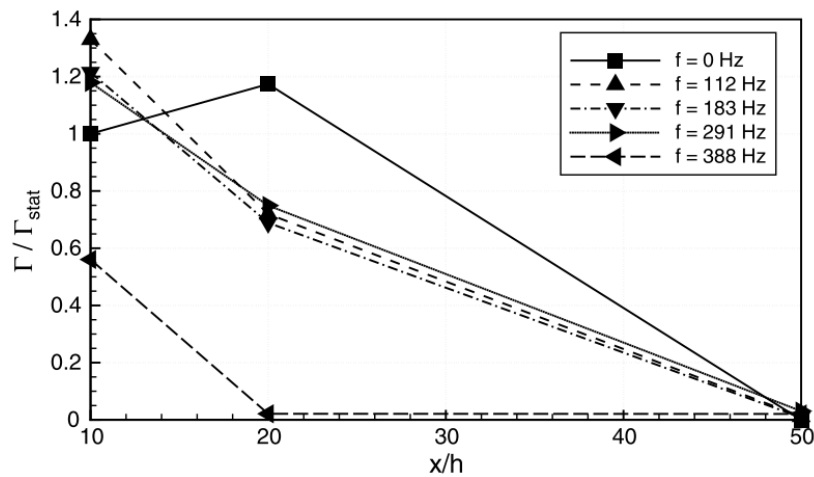


Figure 4.59 Time-averaged circulations with distance increasing [65]

The Y-axis is the circulations, which have been nondimensionalized by the static vortex strength. The X-axis is the downstream distance. The circulations with different frequencies are plotted in different dots.

The turbulence studies showed that the dynamic vortex was “large-scale momentum transport”, where the deflecting motion and frequency increase did not affect the turbulence scales. A few differences are between the lower frequency and higher frequency results. The spanwise movements of the vortex core did not happen with higher frequency, and the height of the starting vortex core ‘jumping’ did not occur within lower frequency conditions. As the frequency increased, the vortex became stronger than the lower frequency condition, but the vortex broke if the frequency went too high.

5 Summary of the active flow control

Chapter 4 covers the current study of the active vortex generator, mainly the mechanic vane blade type. There are two types of active mechanisms: retractable and rotation. Both types of devices tend to reduce the drag and achieve real-time flow control. The rotation devices cause additional drag because of the unretractable blade. Therefore, this project's active vortex generator study is the retractable blade.

The retractable vortex generator has two working conditions. The blade deflects and retracts under a special frequency called the high-frequency active vortex generator, or the blade deflects and then works as the passive vortex generator called retractable vortex generator. Barth showed that the devices generated a stronger and higher starting vortex than the static vortex with a pair of delta blades in a common-flow-up configuration [65]. Osbron showed that the high-frequency vortex generator has a solid control ability of a shorter range, but its effectiveness decreased rapidly with the co-rotating configuration and the delta blade array [67]. In both works, the delta-shaped vane blade arrays deflect and retract in the vertical direction, and both works focused on how frequency affects downstream processes.

Shizawa revealed the nonlinear vortex response to the blade rotation process with the deflection-static-retraction working process with the pie-shaped blade [35–37]. The blade is rotating to the position rather than the vertical deflect.

The previous study mainly focused on the delta shape of the vane blade vortex generator with a fixed blade height. Those studies indicate the starting vortex is one of the key features of the high-frequency active vortex generator. The starting vortex shows a complex response to the relative parameters and has a shorter control range than the static vortex generator.

The vortex forming of the rectangular vane blade with the different heights submerged in the boundary layer has not yet been well studied; therefore, the active vortex generator was chosen for the current study. This study aims to investigate the downstream flow response of the chosen active vortex generator

and try to fill the gap in the flow physics, which is about the vortex formation of the submerged vertical retractable blade.

The numerical simulation is based on the empirical model in Chapter 3. The computational fluid dynamics (CFD) models are introduced in Appendices 11.2A.2. The empirical and computational fluid dynamics methods are widely used in vortex simulation. The experiment methods are similar to Shizawa [35–37] and Barth's [65] but with a probe to measure the flowfield. The size of the vortex generator, which is a submerged vortex generator, was selected from Lin's study [4].

6 Methodology

The objective is to gather sufficient data to highlight the flow mechanism responsible for vortex formation and to guide the device's design. The experiment aims to investigate the downstream response of the retractable vane blade vortex generator, focusing primarily on understanding the vortex-forming process.

The experimental measurements have inherent limitations on vortex formation due to dynamic vortex behavior. Therefore, computational fluid dynamics (CFD) simulations and analytical approaches are employed in addition to experimental methods to provide supplementary and internal data regarding the downstream response.

The experimental design aims to capture the downstream flow response with blade deflection and retraction. Due to the relatively small size of the active vortex generator, a scaled-up experiment is essential to study the flow response comprehensively. As a result, the experimental study is divided into two phases.

The Phase I focus on exploring and evaluating the experimental methods. The experimental setup in this Phase involves the active vortex generator mounted on a flat plate, with changes in downstream surface pressure measured to analyze the flow response. A scaled-up experimental setup is employed in Phase II after examining the vortex-forming process in Phase I.

Phase II integrates both experimental measurements and CFD simulations. The vortex-forming process at the static vortex location is recorded using a single hot wire probe, capturing velocities in three dimensions. Probes are strategically positioned at various locations to cover the entire static vortex area. Due to the dynamic complexity of the flow response, the experiment is repeated 10 times to ensure robust results, although limited probe locations may result in data distortion and gaps. Parallel to the experiment, a CFD simulation models the same setup for comparative analysis, and help to inform the understanding of the physical process involved.

Data from multiple probe locations are aggregated to show the flow response to blade actions. Average results from repeated experiments are computed, and qualitative and quantitative analyses of vorticity, circulation, and vortex movements are conducted. The simulation results are compared with experimental findings to validate the reliability of static components, while the remaining simulation outcomes serve as a reference for examining the dynamic vortex formation observed experimentally.

7 Phase I experiment: Macro vortex forming

The BWB aircraft in the project is the civil aircraft, in which the operation cost is affected by penalty drag during the cruise condition and the energy requirements of flow control devices. Following previous literature studies, the active deflected vane blade vortex generator can achieve real-time, avoid penalties under cruise conditions, and lower energy consumption during the working section (single deflection). It has a long-range (more than 10 h downstream), reducing the extra flow control device and energy needed. Therefore, this paper considered and studied the active deflected vane blade vortex generator.

The study focuses on the vortex-forming of a single deflected-only vane vortex generator, including downstream vortex strength, vortex movement, flow mechanics, and vortex response related to the blade movements. Therefore, vortex forming must be examined as a premise: the vortex forming experiment. The primary objective of Phase I is to assess the experimental method for in-depth investigation in Phase II (Stage 1). The secondary goal is to identify the parameters influencing the macro formation of the vortex (Stage 2). However, due to equipment limitations in Phase II, these parameters could not be studied as originally planned; therefore, Stage 2 has been relocated to Appendix B. The section arrangement of the Phase I experiment is shown in Figure 7.1.

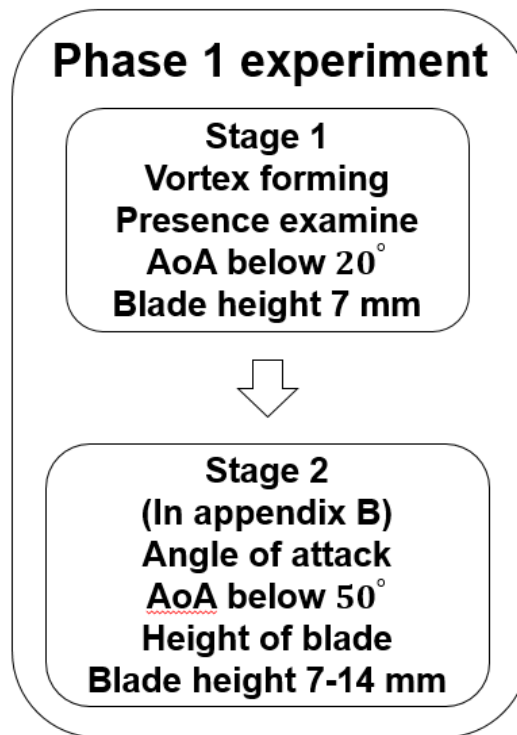


Figure 7.1 The road map of the Phase I experiment

The stage blocks show the structure of the experiments in Phase I. The Phase I experiment examines the presence of the transient process produced by the active blade and the possibility of recording the vortex forming. Once the vortex's presence and recordability were confirmed, the study was moved to Phase II for the detailed analysis of vortex forming.

(The general vortex forming will be studied in Stage II of Phase I by two variables, angle of attack and height of the blade(nondimensional distance), and those results are in Appendix B.1.)

7.1 Equipment

This study used four pieces of equipment: a wind tunnel, active vortex generator, flat plate, and pressure measuring system. The flat plate was in the open section of the wind tunnel. The active vortex generator was on the front part of the flat plate. At downstream of the blade were the static ports. Those static ports were connected to the transducer by rubber tubes. The total instruments are shown in Figure 7.2.

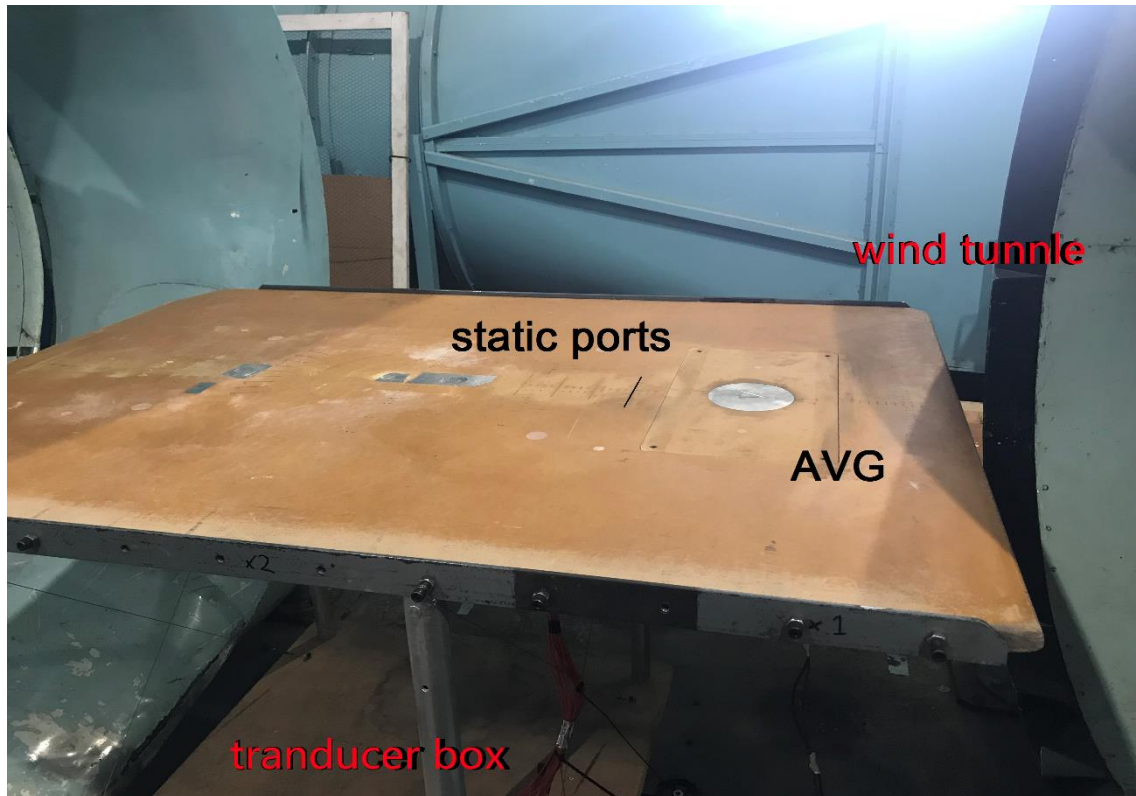


Figure 7.2 The experimental equipment within the wind tunnel in Phase 1

The wind tunnel and the rest of the devices are labeled. The silver circle is the AVG, which is the active vortex generator. The black line marks the static ports at downstream of the AVG.

7.1.1 Wind tunnel

The wind tunnel used in this experiment was the Weybridge wind tunnel at Cranfield University. The Weybridge is an open section with a closed return wind tunnel. At the open-section, the diameter of the circular jet is 1.067 m, the maximum speed is 38 m/s, and the maximum can achieve Reynolds number 22.7×10^6 [73]. In this experiment, the flow speed was 35 m/s, and the Reynolds number of downstream distance is 5.9×10^5 .

7.1.2 Active vortex generator

The active vortex generator was the key equipment in the study. The AVG is shown in Figure 7.3. The blade was a segment-shaped vane blade. The vane blade was deflected by rotation. A resistance band powered the deflecting

process, and the electromagnet held and released the blade. Due to the segment-shaped geometry, the height variation also leads to the movements of the peak point of the blade.

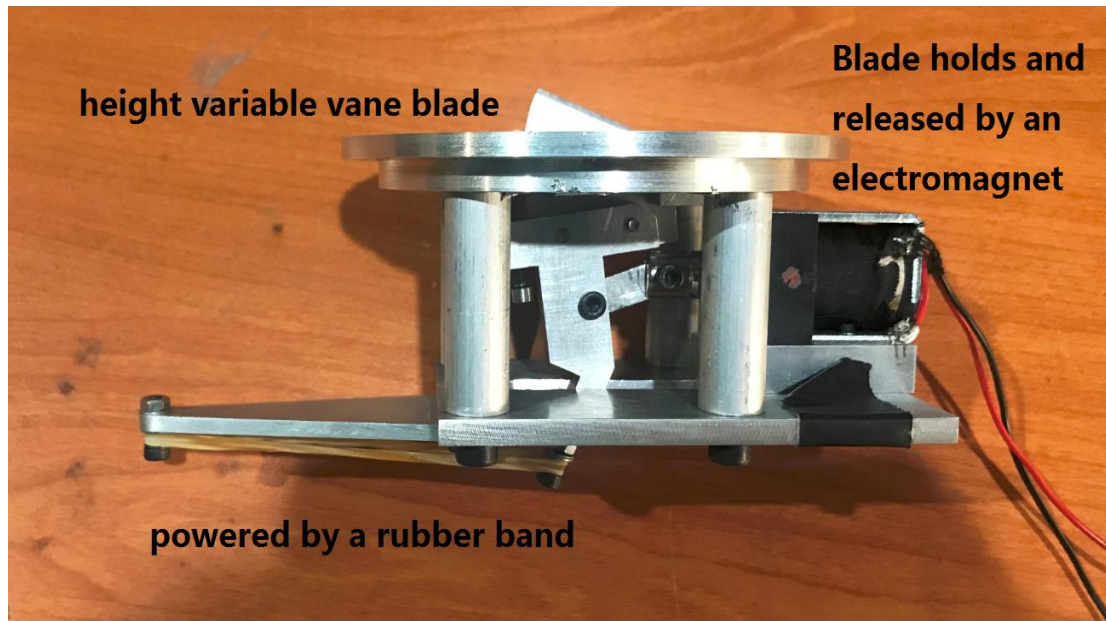


Figure 7.3 Active vortex generator in Phase 1

The VG's chord length and thickness were fixed at 30 mm and 1.5 mm, respectively. The blade is shown in Figure 7.4. The blade is part of the mechanism, and it was jammed and failed to deflect due to the wear, tear, and hit of the multiple repeats, so three blades were involved in the experiment.

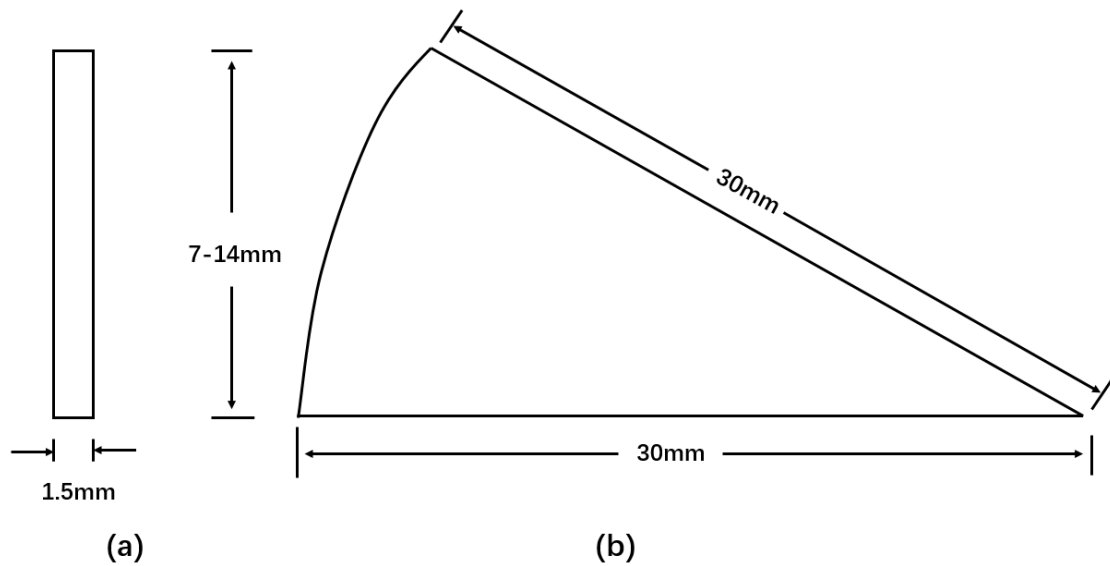


Figure 7.4 Geometry of the vane blade with the blunt leading edge in Phase I

(a): Front view of the blunt blade. (b): Side view of the blade.

During the Phase I Stage I experiment, angles of attacks were blow 20° , the blade was a blunt edge. The lad staff designed and made the devices, such as the flat plate, to fit in the experiment equipment.

(At stage II of Phase I, the angles of attack increased from 20° to 50° . The leading edge of the blade was sharpened 45° by lab staff to generate a strong vortex. The difference between the three blades was how the leading edge sharpened, and the detail is shown in Appendix B.1)

7.1.3 Flat plate & Pressure measuring system

The active vortex generator was located at the central front part of the flat plate, 25 cm away downstream from the leading edge. The length of the flat plate is 140 cm, and the width is 97 cm. It is shown in Figure 7.5 from the top and side views.

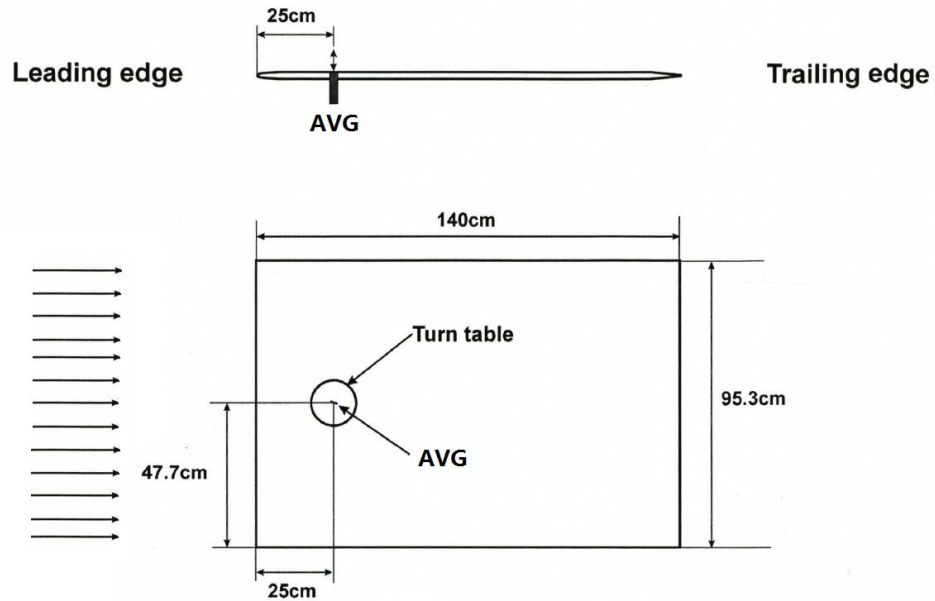


Figure 7.5 The geometry of the flat plate with active vortex generator (AVG)location [74]

The static ports were located downstream of the vane blade on the flat plate. The static ports were located in four parallel lines. The first row was 136 mm away downstream of the blade central. The distances between each row were the same, which was 50 mm, and the static ports were as shown in Figure 7.6.

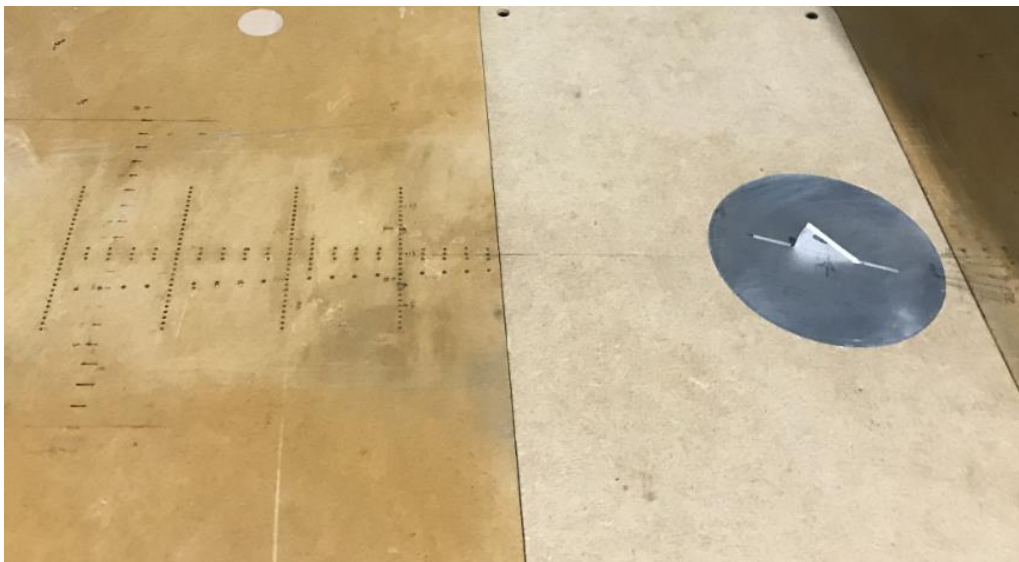


Figure 7.6 Active vortex generator with static ports in Phase I

The static ports were connected to the transducer by rubber tubes. The length of the tubes was 45 mm. Those tubes were banded together to avoid the oscillation caused by the wind blowing. In the static pressure measuring system which is used to indicate the deflecting process, one of the static ports of that system was located just behind the trailing edge of the vane blade, as shown in Figure 7.7. The pressure changes caused by blade deflection will be recorded to indicate the deflecting motion. The sampling rate of all transducers was 1 kHz.

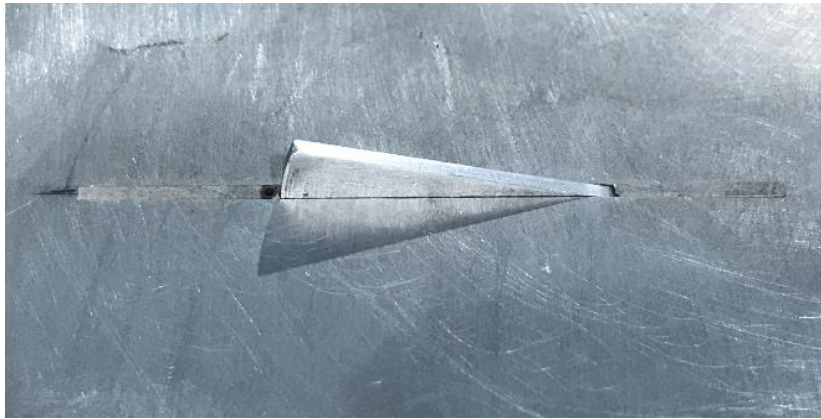


Figure 7.7 The vane blade with one static port at the trailing edge (blunt edge blade, Phase 1, stage 1)

A vertical moving probe measured the boundary layer's velocity profile at the blade location, and the local thickness of the boundary layer is around 3.2 mm, as shown in Figure 7.8.

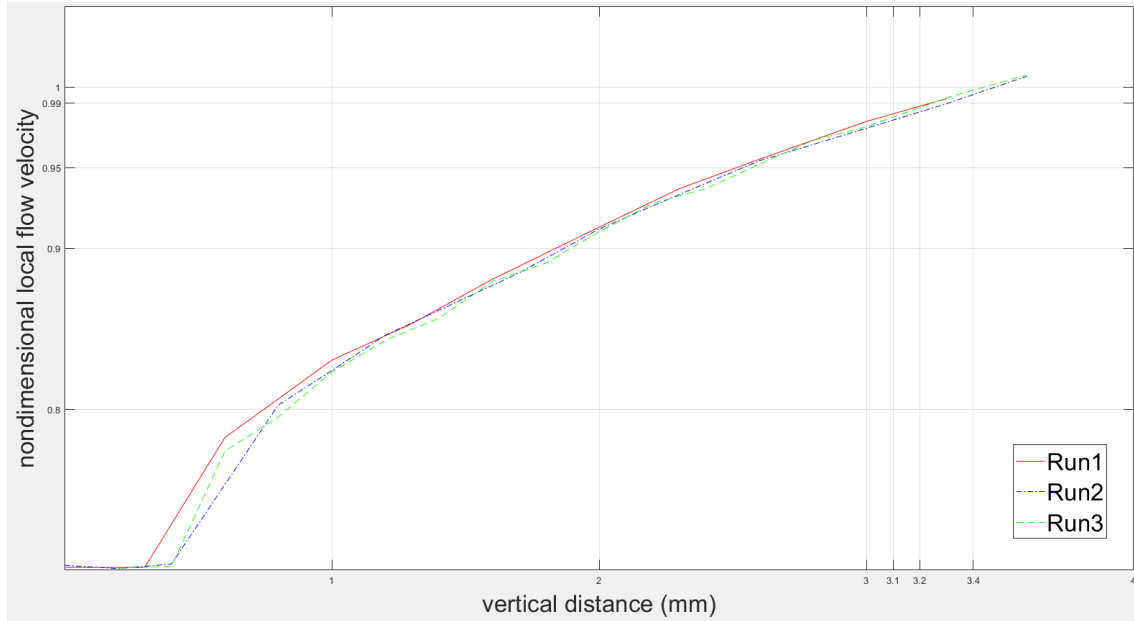


Figure 7.8 The boundary layer thickness at the VG location

The boundary layer was tested three times; each run was plotted with different lines. The thickness of the boundary layer is around 3,2 mm at the blade section.

7.2 Experiment processing

At the beginning of the experiment, set the testing angle and blade's height for the vortex generator. The vane blade was restored and held by an electromagnet. Adjust the wind speed to the target freestream velocity. After the wind became steady, the transducer was operated manually to record the pressure in the next 10s. Within the 10s, the vortex generator was manually triggered to deflect the blade. In this way, the downstream pressure changes caused by the deflecting were recorded. The surface pressure changes is because of the vortex formation and static vortex.

7.3 Data analysis

The data recorded were static pressure variation on the static ports, which are 29 in total in the row, the static pressure behind the blade, the wind speed from calibration of static rings V_x , and dynamic pressure $q = \frac{1}{2}\rho v^2$.

7.3.1 Multiple runs unify

The vortex-forming process was unified at the same blade deflecting time. After the synchronization, examining the vortex forming under different conditions is possible. The vortex leading the surface pressure changes against time is for future analysis. This procedure represents the vortex forming. After the blade deflection, the vortex core was the minimum pressure point in the static vortex pressure distribution. Due to the manually controlled blade releasing, deflecting time points differed in every operation. The pressure recorded behind the trailing edge was the indicator signal to unify the time scale.

7.3.2 Vortex forming with time

The static ports record the static pressure distribution. First, the minimum point in the static pressure distribution is the vortex core. After selecting the vortex core, the vortex forming was shown by plotting the pressure changes against time at the vortex core location, as shown in Figure 7.9. The Delta Cp represented the difference in the pressure coefficient caused by the vortex forming. The equations is shown in Equation 7.1.

$$\Delta_{Cp} = C_{p_{VG \text{ deployed}}} - C_{p_{VG \text{ stowed}}} \quad (7.1)$$

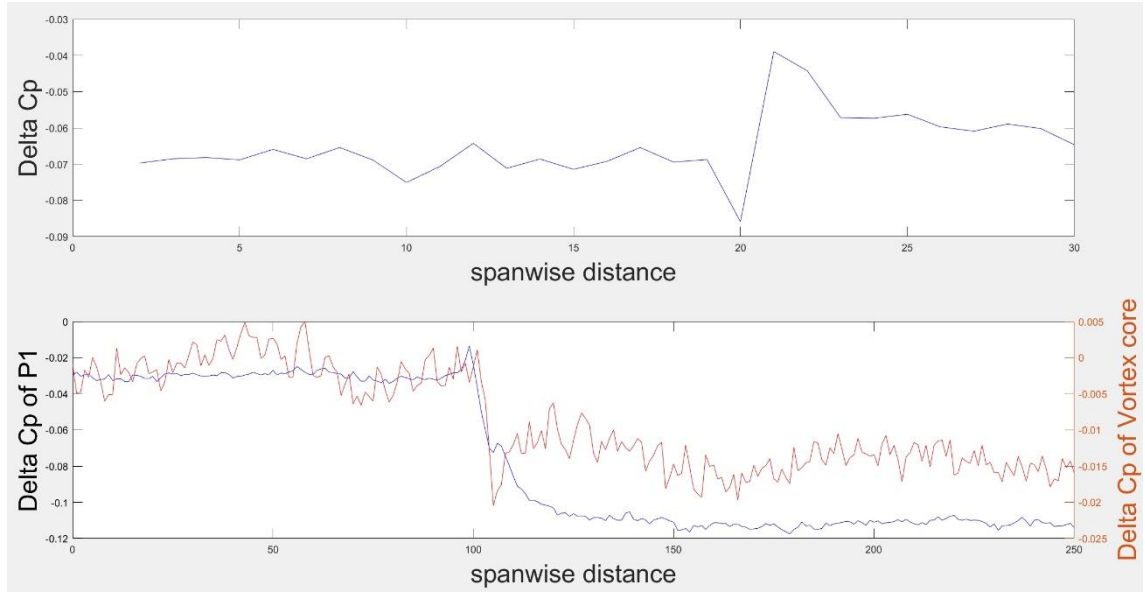


Figure 7.9 Static pressure distribution with vortex forming plot

In Figure 7.9, The upper plot is the Delta pressure coefficient distribution. The lower plot is the Delta pressure coefficient of P1 and the vortex core. The circle highlights the vortex core. The broken line shows the pressure changes of the vortex core in the lower plot. The solid line is the indicator signal. The Y-axis Delta Cp is the coefficient difference between with and without vortex. Before time 100, the wind condition was clean without VG and vortex. Time step 100 is the time point of the blade begins to deflect.

The vortex core movements are important in the vortex-forming process. The plot shows that the vortex core does not have a clear lateral movement, as shown in Figure 7.10, which is similar to Barth's finding [65].

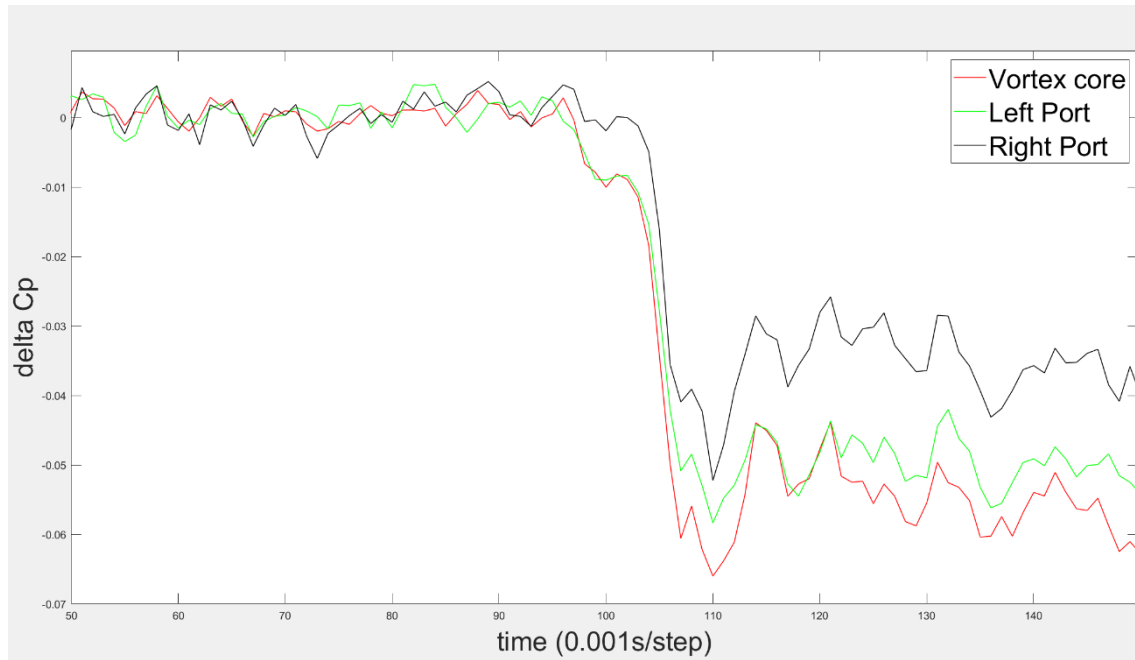


Figure 7.10 The vortex formation at the vortex core with nearby ports

The vortex-forming process at the vortex core and nearby locations is plotted in Figure 7.10. The vortex core is the red line. The left port is the green line. The right port is the black line.

7.3.3 Minimum repeat times

The vortex forming was a highly dynamic process, and the data was hard to show reality with a few tests. The test examines the minimum number of repeats. The tests were repeated 30 times, and the data were separated into several groups with different repeating numbers(5, 10, 15, 20, 25, and 30 times). Then, the average plots from every group were presented to find out the minimum repeating numbers. The results are shown in Figure 7.11.

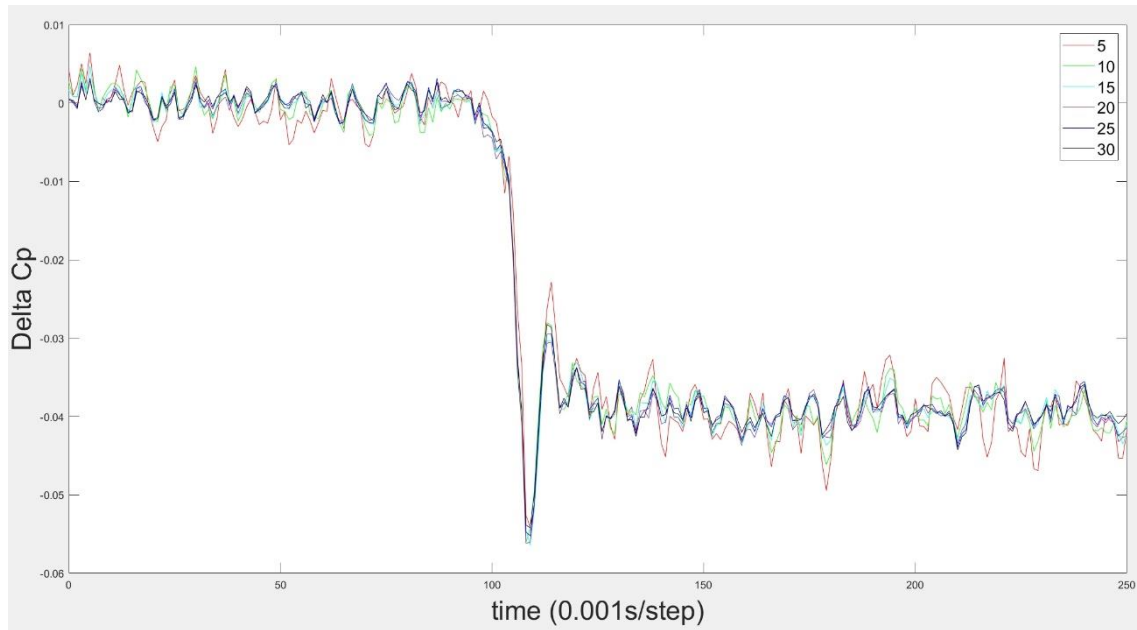


Figure 7.11 Transient repeat time test. With 10mm blade

The results indicate that the transient part became constant after 10-time repeats. Therefore, the repeating time of every variable in this experiment was 10 times. The angle of attack is 30° .

7.3.4 Error analysis

The error analysis was applied to transient motion and static vortex conditions to indicate that the vortex-forming process is stronger than the boundary layer turbulence. The results are shown in Figure 7.12 and Figure 7.13.

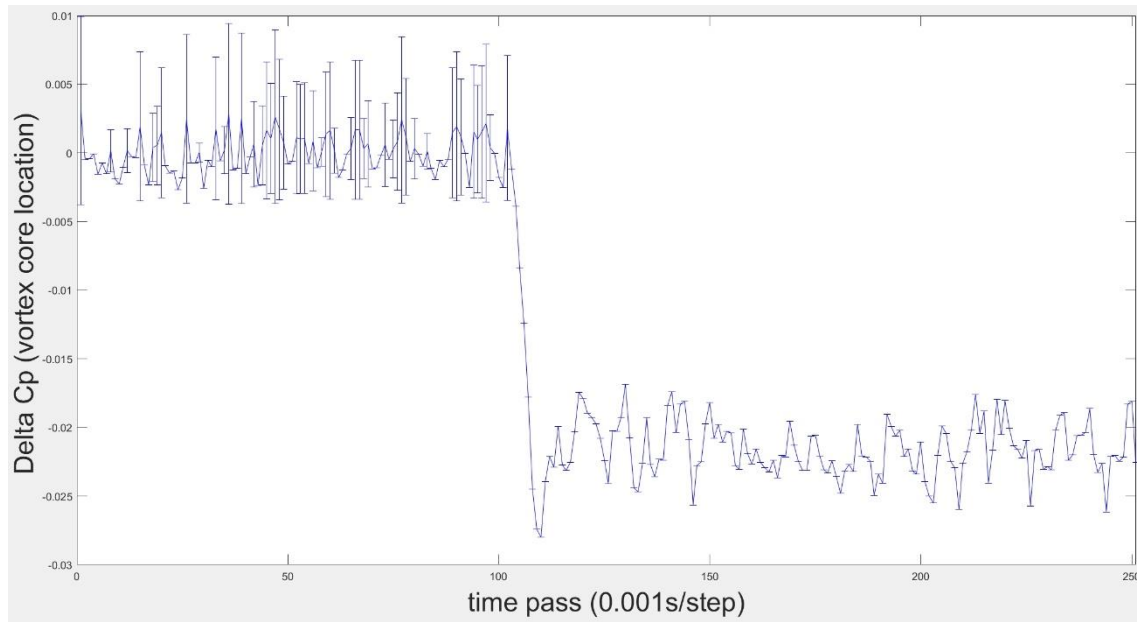


Figure 7.12 Error analysis with the vortex forming

As time passes, the solid line is the delta pressure coefficient at the vortex core. The error bar is 95% confidence. With the 7mm blade, the angle of attack is 30° .

The result shows the error range of the vortex core location is higher in the clean wind condition (around the 100 steps on the X-axis). The error became smaller after the vortex formed (pressure drops) because the vortex replaced the turbulent boundary layer at the vortex core location.

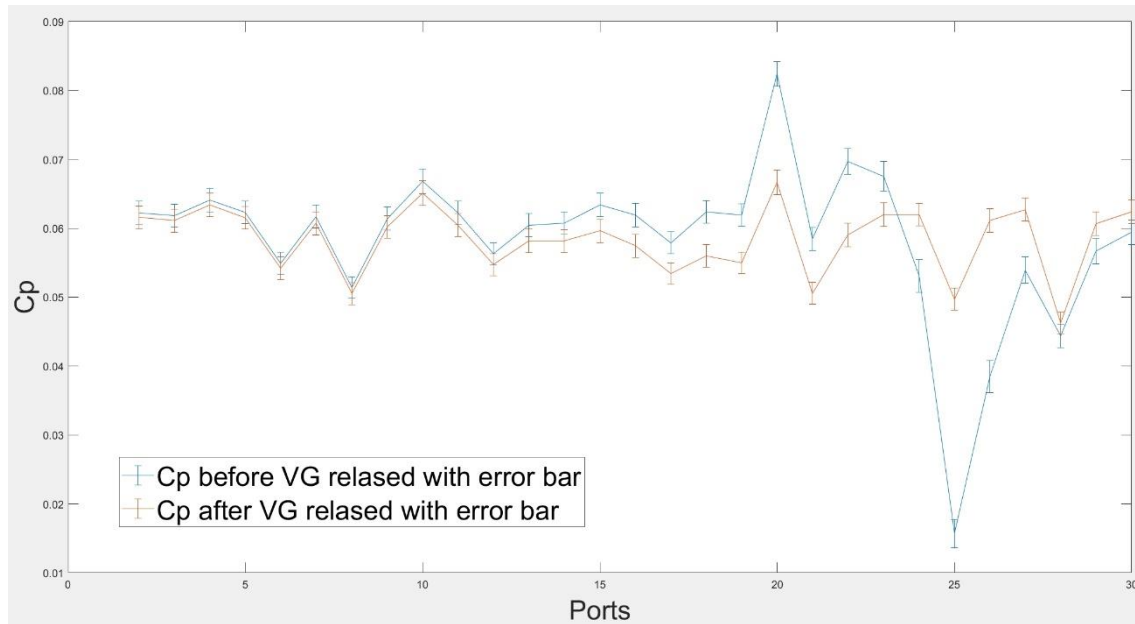


Figure 7.13 The error bar with static pressure distribution

The red line is the vortex pressure distribution, and the blue line is the pressure distribution before the vortex is formed. The X-axis is the locations of the static ports on the flat plate. The ports indicate the spanwise locations. The analysis is 95% confidence; with the 7mm blade, the angle of attack is 30° .

The error analysis shows that the errors were smaller than the changes caused by the vortex. Therefore, the vortex formation caused the pressure changes, and it was reasonable and reliable.

7.4 Stage one result

The whole project's aim (phases I and II) is to study the flow response to the blade movement at the location of the static vortex. Phase I (Stage 1) evaluates the experimental method, specifically examining its effectiveness. The current stage aims to investigate the presence of vortex formation resulting from this experimental method.

The downstream surface pressure was recorded to catch the vortex-forming process. The delta pressure coefficient at the vortex core location was plotted against time. The result is shown in Figure 7.14.

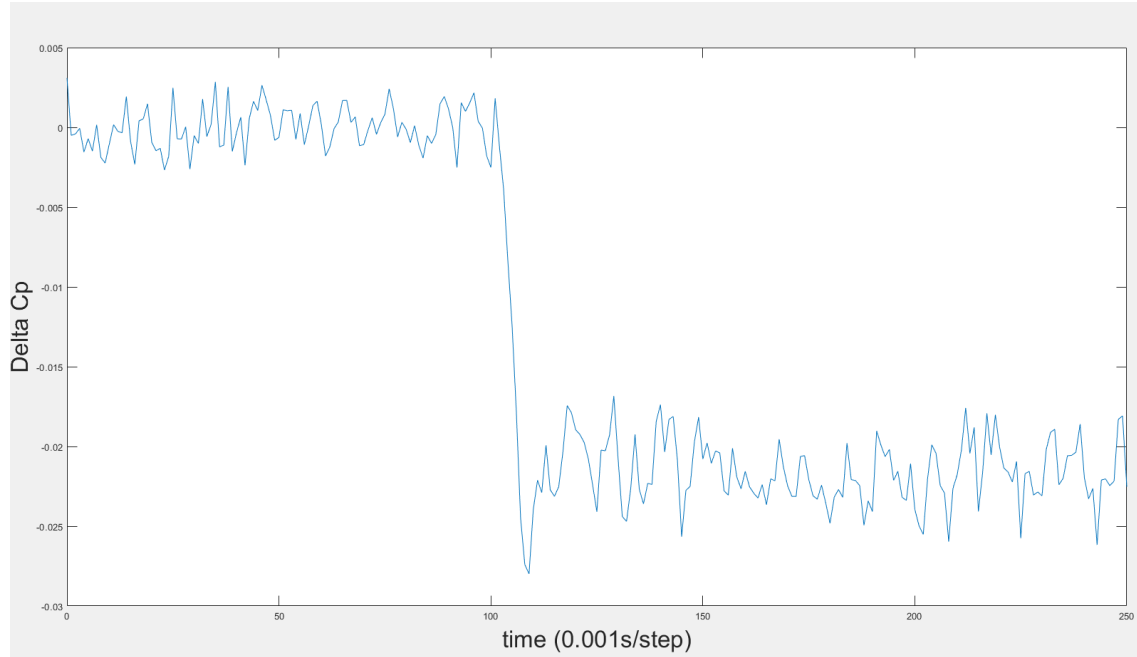


Figure 7.14 Vortex core Delta pressure coefficient

The size of the blade is 7mm, and the angle of attack is 30° , with 35m/s airspeed. Figure 7.14 shows the vortex-forming transient process was straightforward. The active vortex generator generates the vortex, and the pressure system records the vortex forming. Phase I is successful. Thus, the study moves to Phase II.

7.5 Stage two

The active vortex generator generates the transient process of forming and is recorded by static ports. The influential parameter, e.g., angle of attack, size of the blade, and downstream distances, was also analyzed to sketch a macro picture of the vortex forming. Because the experiment is unrelated to the detailed study, the results are in Appendix B.

8 Phase II: Micro vortex forming

The previous phase examined the formation of the vortex. The height variation was the primary variable in the Phase II study. The transient process of the vortex was mainly analyzed based on the surface pressure variation in Phase I. A zoom-up experiment was conducted to delve deeper into the study of vortex formation. The experiment used a large vane blade model and the thicker boundary layer wind tunnel. The probe used in the experiment recorded the vortex-forming process on the static vortex location, which records the velocity components. In the study's second phase, the main variable under investigation was the height variation.

8.1 Equipment

The experiment has three pieces of equipment: the atmospheric boundary layer wind tunnel, active vortex generator with square-shaped vane blade, and high-frequency probe transducer, as shown in Figure 8.1.

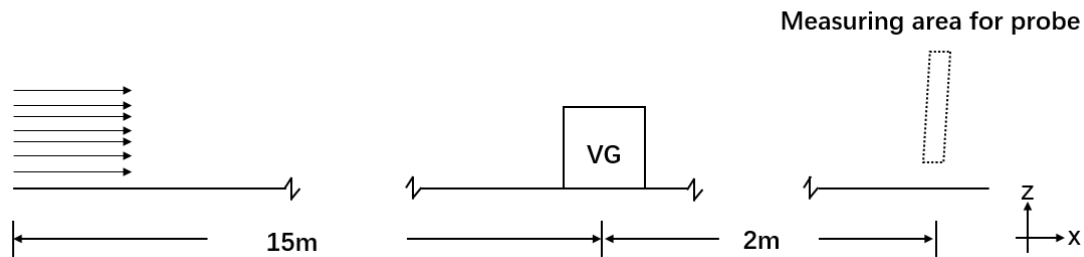


Figure 8.1 The experiment equipment layout of Phase II.

The experiment coordinates at the bottom right-hand side, Z is the vertical distance, positive above the surface; Y is the spanwise, positive on the right, negative on the left; and X is positive at the central blade downstream.

8.1.1 Wind tunnel

The wind tunnel is the atmospheric boundary layer wind tunnel (ABL wind tunnel) at Cranfield University [76]. The wind tunnel has a closed working section and an open return circuit specifically designed to make a thick boundary layer. The

upper stream distance from the air entrance to the center of the blade is 13m, while the distance to the recording section is 15 m. This design allows the wind tunnel to generate a thicker boundary layer or place more barriers to increase the “surface roughness,” causing an even thicker boundary layer.

The airspeed control was based on the fan's Revolutions per minute (RPM), ensuring precise speed control. The test section is 2.4 m wide and 1.2 m high (8' × 4'), allowing for a speed range from 0.5m/s to 16m/s. In the working section, the turntable located on the bottom surface can rotate 360°. The downstream distance Reynolds numbers varied from 162009 at 2.44m/s to 963306 at 14.75 m/s. The speed in this study was 10m/s, and the Reynolds number was Re_x :650265. The boundary layer at the blade location is shown in Figure 8.2.

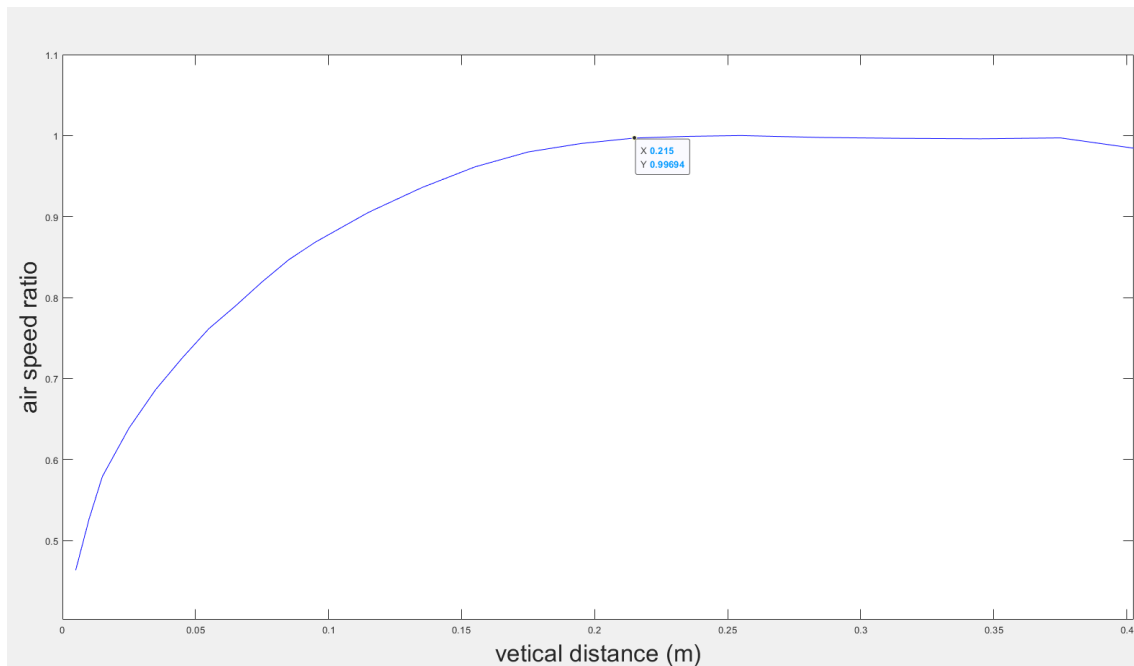


Figure 8.2 boundary layer in the Phase 2 experiment

The velocity profile of the boundary is plotted against vertical distance. The thickness of the boundary layer is 0.215 m at the blade location.

8.1.2 Vane blade active vortex generator

The new vortex generator was deflecting vertically. The height of the blades were 200mm, 150mm, and 100mm. The ratios of the height of the blade and location boundary ($\frac{BL_{local}}{h_{vg}}$) are 0.9, 0.69, and 0.46. The chord length is 200 mm, and the thickness is 1.5 mm; the squared shape of the vortex generator is well-studied and easier to manufacture.

The active vortex generator's deflection mechanism relied on rubber bands held and subsequently released by an electrical magnet. A cam-and-transfer with a motor powered the blade restoration. Both the electrical magnet and cam were controlled by a remote. The deflection and restoration of the blade are shown in Figure 8.3.

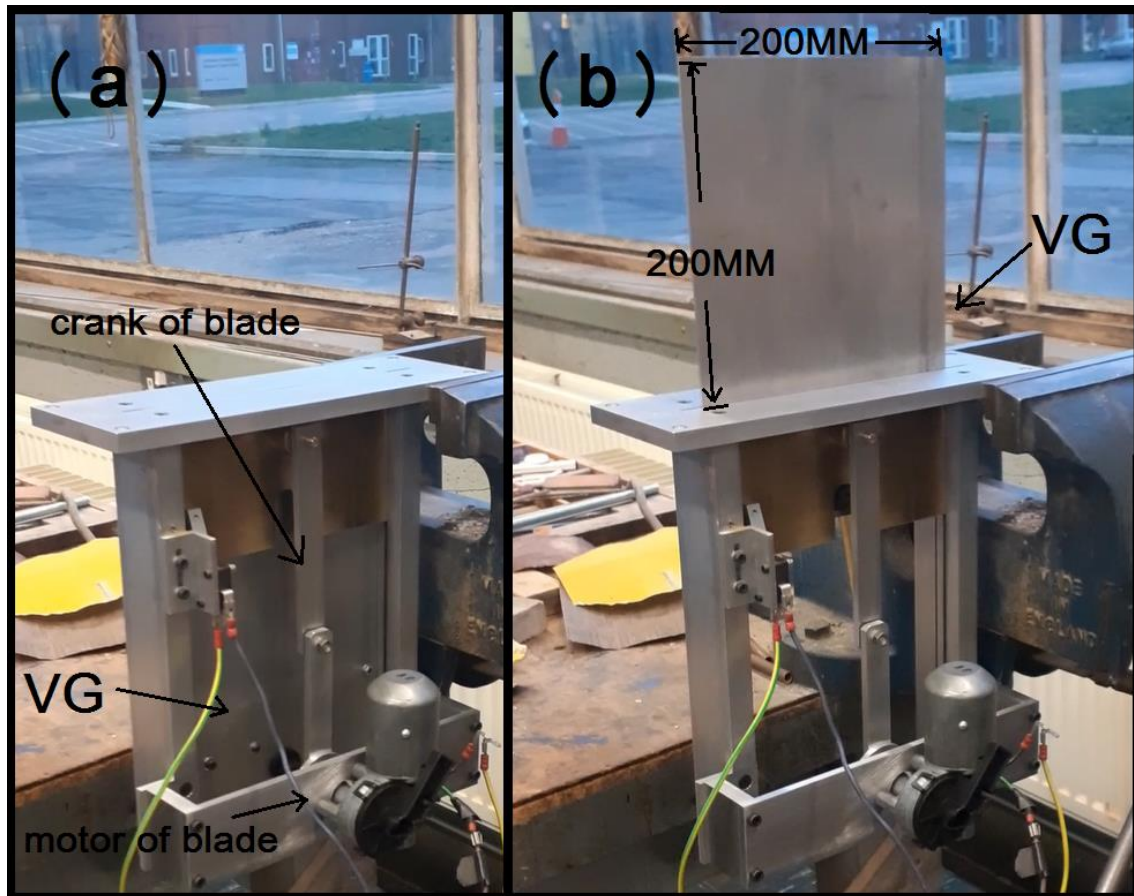


Figure 8.3 Active vortex generator in Phase II experiment

The part (a) is the resorting condition, and the right-hand part (b) is the deflected condition.

Two pairs of optical sensors were placed on the active vortex generator, both top and bottom sides of the blade, to record the deflection and restoration time data. The two statuses of the sensors are separated and connected; if the blade splits the sensors, the signal voltage will be 5 V; if not, it will be 0 V instead. The upper sensor is similar to the bottom one. The two pairs of sensors recorded the voltage signal, which is used to identify the timing of the beginning and completion of the blade deflection.

8.1.3 Cobra Probe

The transducer involved in the experiment is the Series 100 Cobra Probe, shown in Figure 8.4. It can measure the velocities in three-axis and static pressure. The sampling frequency is up to 2kHz, and the measuring speed range is from 0.0001 up to 100m/s. The velocities and axis system are shown in Figure 8.5.

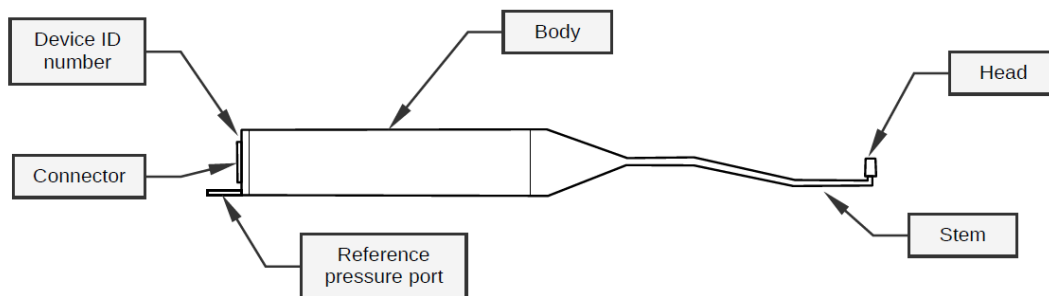


Figure 8.4 Croba Probe involved in Phase II [77]

The Croba Probe is the Series 100, which is involved in this project. The head of the Probe needs to be placed in the flow to measure the velocity components.

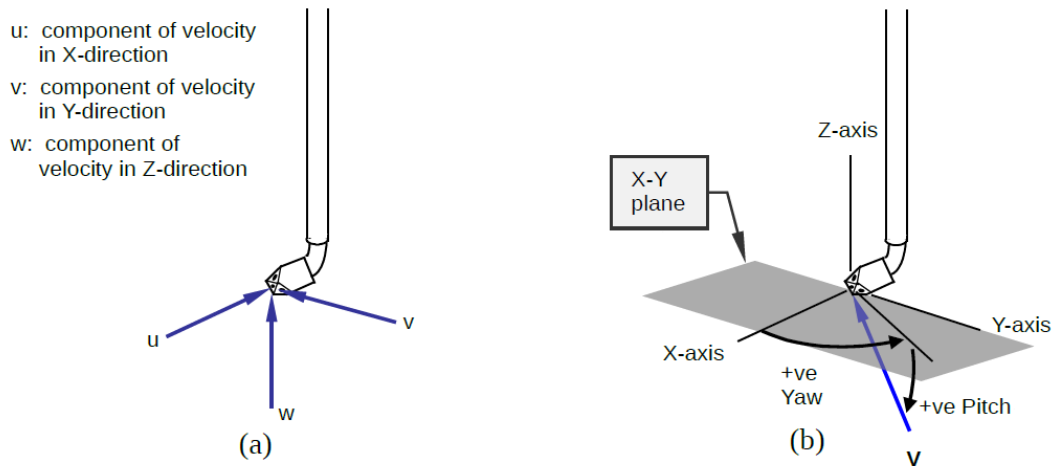


Figure 8.5 Cobra Probe with axis system [77]

(a): flow axis system with Cobra probe. (b): axis system of pitch (azimuth: rotation angle of the "z" axis) and yaw (elevation: angle between the velocity vector and surface plane(XY)) with respect to probe head

Within the experiment, the sampling frequency was 1250hz. the pitch and yaw angles between the probe head and free stream were less than 1° , and calibrated in the data process.

8.2 Location of the vortex core

Locating the vortex core is necessary before putting the cobra probe into the vortex. The tuft grid, placed at the measuring section to locate the vortex, was 2 m downstream of the vortex generator. The size of the measuring surface of the tuft grid is $1.2m \times 1.2m$. Each small grid is $30mm \times 30mm$, and the data was recorded by the camera behind the tuft grid. It is shown in Figure 8.6.

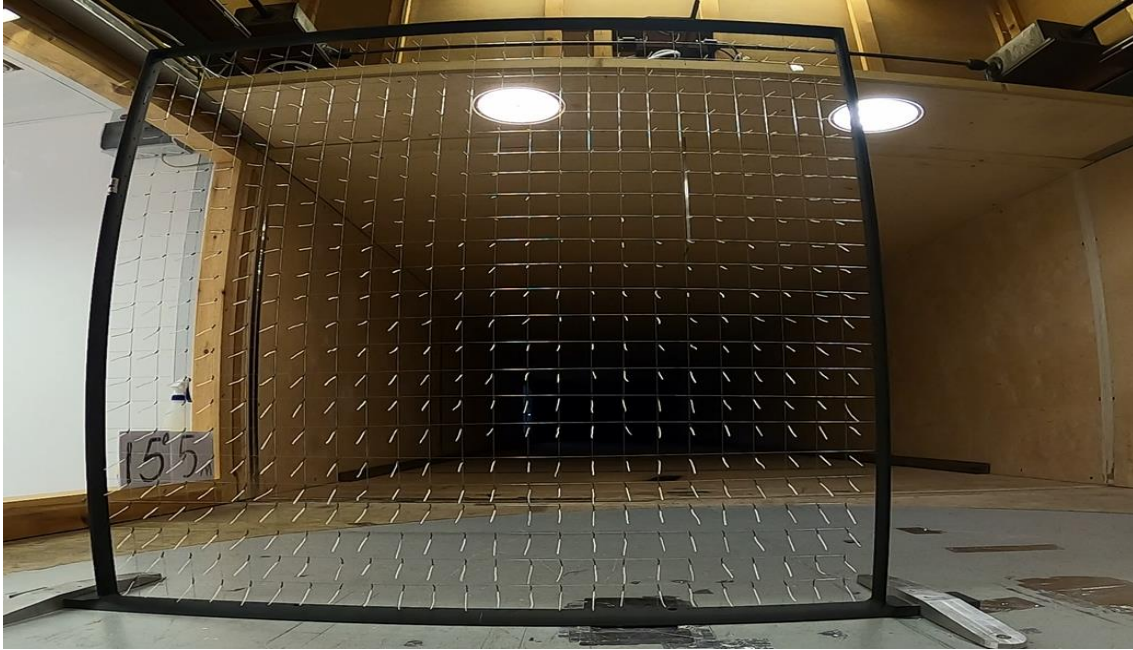


Figure 8.6 Tuft grid test

Tuft grid: width:1.2m, height 1.2m, each small grid is 30 mm width and height. In a plane, 2m downstream of the vortex generator, looking upwind.

In the experiment of the tuft test, the angle of attack of the blade is 10° , 15° , 20° , 25° and 30° , the airspeed was 10m/s . The cream recorded the data behind the tuft grid at the 60 or 100 Hz sampling rate.

8.2.1 Result of Tuft grid test

The vortex-forming processing was shown by the tuft grid and then recorded by the camera. As the angle of attack increases, the static vortex core goes bigger and moves towards the left.

In the transient motion, the vortex core also moves. As the angle gets more significant, these movements become clearer. The vortex core goes in the static position directly from the central wind tunnel, the blade position. The movements are shown in Figure 8.7.

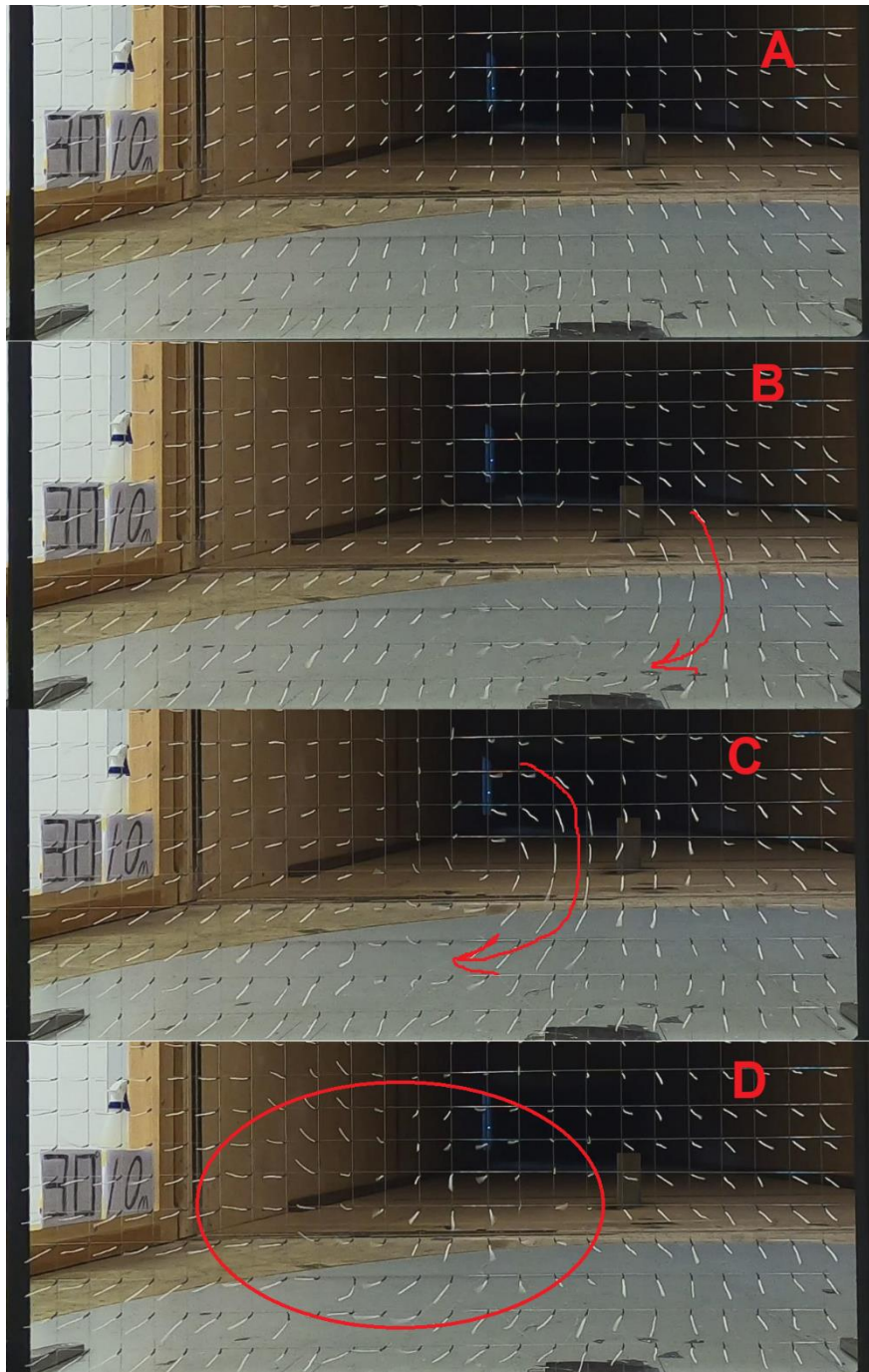


Figure 8.7 Vortex core movements

In the transient process, the vortex core moved from right to left and then back to the static vortex position. A), The blade is beginning to deflect, time 0 ms. B) Vortex, see at the bottom, time: 17ms. C), Vortex moves to the left-hand side, time: 32 ms. D), Static wake, time: 46 ms. The experiment is at 30° , 10m/s .

Based on the grid, the location of the vortex can be transferred to the axis systems by the height and spanwise from the tuft locations. It is shown in Figure 8.8.

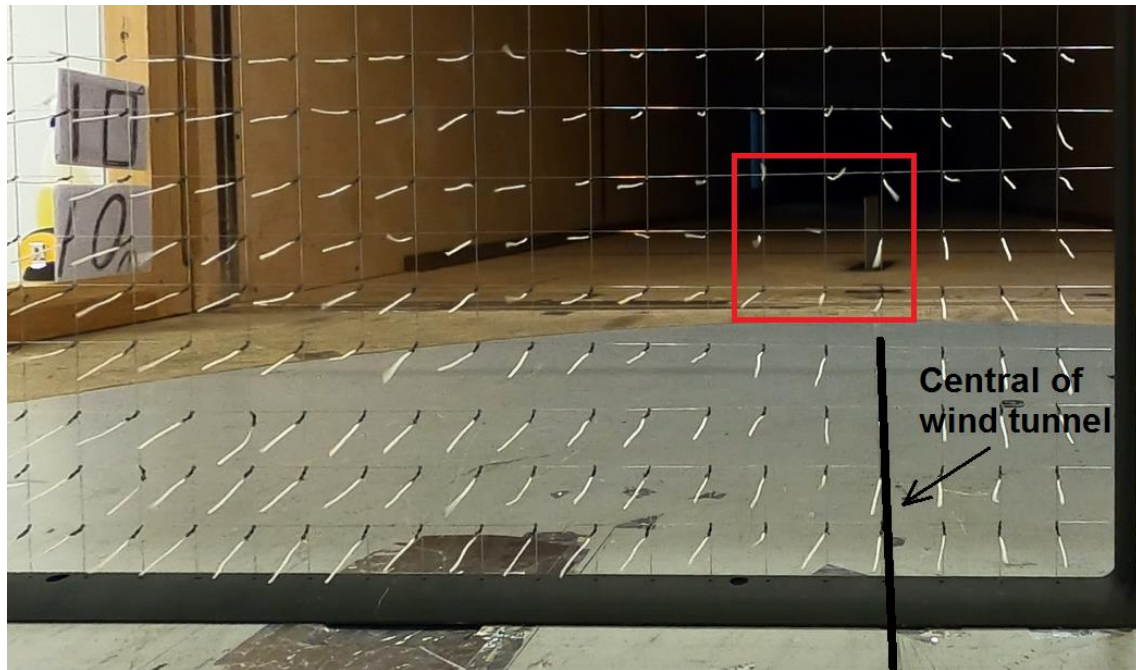


Figure 8.8 Vortex core implied by tuft grid

A red square shows the vortex. The center of the wind tunnel is marked by a solid line. At 2m downstream of the vortex generator, looking upwind. At 10° , and 10 m/s condition. The area of the vortex core (10° , 10 m/s) covered 9 points, with three different heights (150 mm, 180mm, and 210mm) and three spanwise locations (0 mm, 30mm, and 60mm).

8.3 Experiment plan

The angle of attack for the phase two experiment ranged from 10° to 30° initially, after which a test angle of 10° was chosen for detailed study because the tuft shows the vortex is strong and small. The minimum repeating times of each point were studied in this chapter.

8.3.1 Probe locations

The grid tuft test identified the location and area of the vortex. The location and area were indicated by the tufts, marked in red circles, and the distance between the two tufts was 30 mm in both vertical and horizontal directions. The red and

green inside the vortex location (red box) were probe recording points. The red points were cross points of grid tufts, which indicates the vortex area. The green points were the intermediate points between the tufts points. They were added into the vortex area to increase the measuring resolution. The example of 10° , 10m/s, 200m blade height is shown in Figure 8.9. The picture comes from the Tuft test under steady vortex conditions.

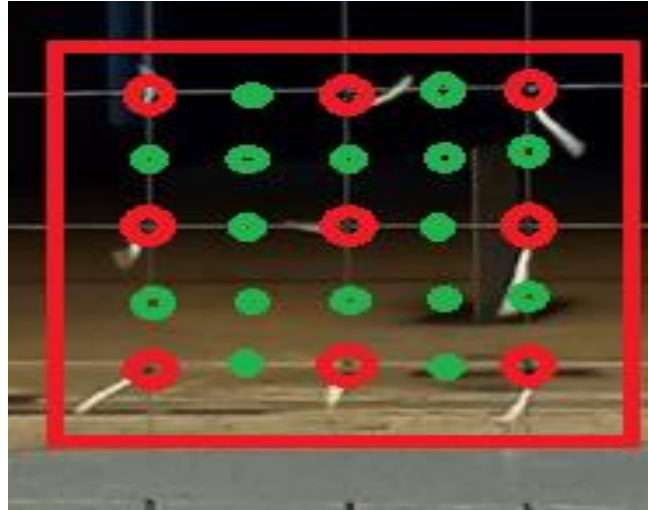


Figure 8.9 The testing locations within the vortex of the 200 mm blade

The location of the probe is fixed on the X-axis, positioned 2 meters downstream of the central blade. As the blade height varied, The relative distance changed due to the fixed downstream measuring distance. The relative distances were 10h, 13.3h, and 20h, corresponding with the 200 mm, 150 mm, and 100 mm blades.

8.3.2 Experiment processing

The blade was stored under the bottom surface, and the probe was located at testing points before commencing calibration. The airspeed was set at 10 m/s, and the probe began recording the flow data once the wind speed stabilized.

However, during the recording period, the blade deflection and restoration were manually triggered, leading to variations in the timing of blade deflection for each run. This introduced challenges during analysis. To address this issue, the sensors on the blade also recorded the deflection data simultaneously. So, those

sensors' outputs served as an indicator to align all the data to a common time base.

8.3.3 Average active motion processing

The blade sensors were located at both the top and bottom of the blade. The two statuses of the sensors were separated and connected, associated with 5 V and 0 V on the real-time signal. The typical signals of two sensors within the experiment are shown in Figure 8.10.

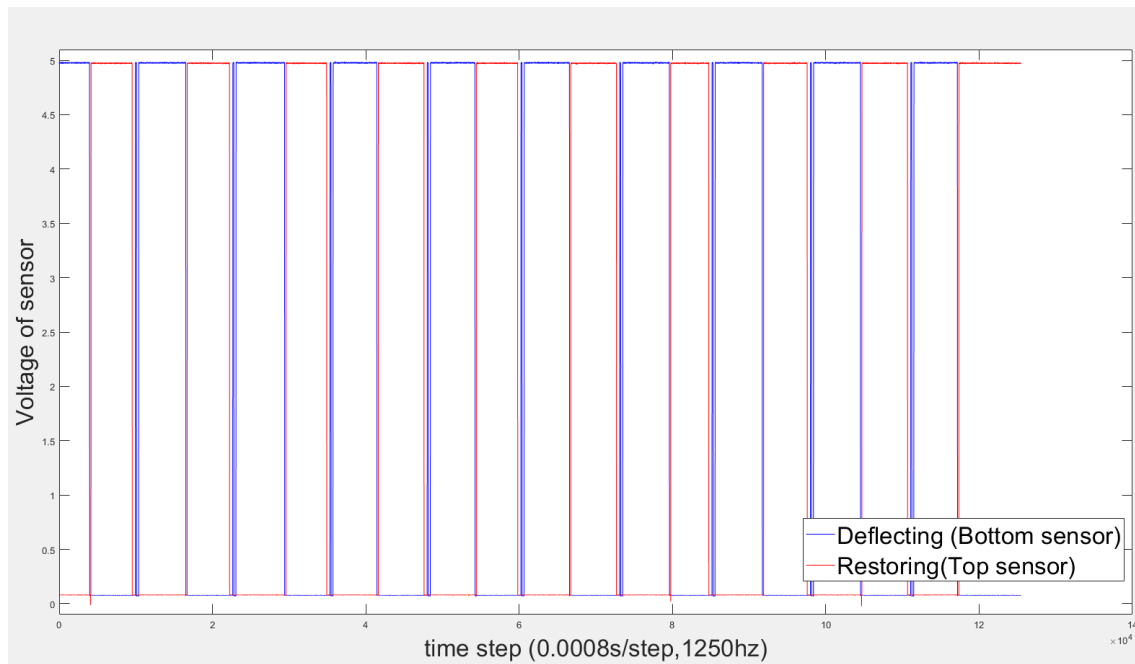


Figure 8.10 The signal of deflecting and restoring

The blue line is the indicator given by the sensor at the bottom of the blade. The red line is the indicator provided by the sensor at the top of the blade. The X-axis is the time. Y-axis is the voltage recorded by the sensor.

The deflection is represented by the drop of the blue line and the increase of the red line, while the restoration was the opposite, i.e., jumping of the blue line and dropping the red line in the Figure 8.10. Figure 8.11 shows the beginning and ending points of blade deflection and restoration.

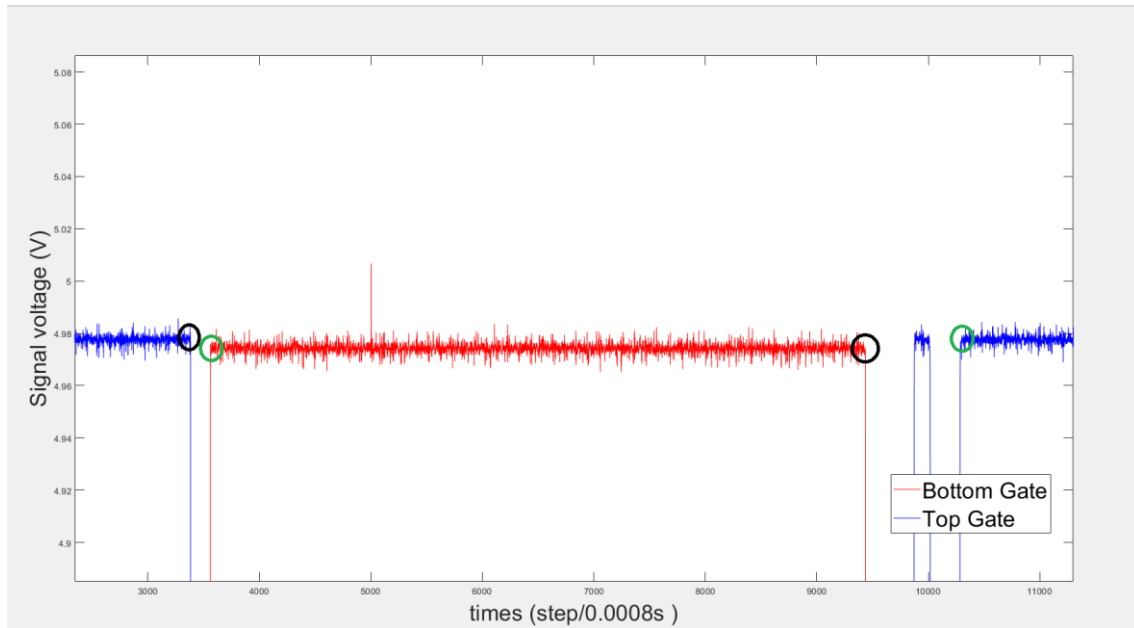


Figure 8.11 Deflecting & Restoring signals with key marks

The black circles mark the beginning points of deflecting and restoring. Green circles mark the finishing points. (10 degrees, 200mm, Spanwise 20mm, Height 165mm).

Figure 8.11 shows the key points of the whole active motion. The beginning points of the blade deflection and restoration are the first points that cross the error bar of steady motion and continue dropping, marked by black. The finish point is the first point that reaches the steady level and is characterized by green circles.

After identifying the beginning and final points, the active motions can be selected from the time series by the beginning point, as shown in Figure 8.12.

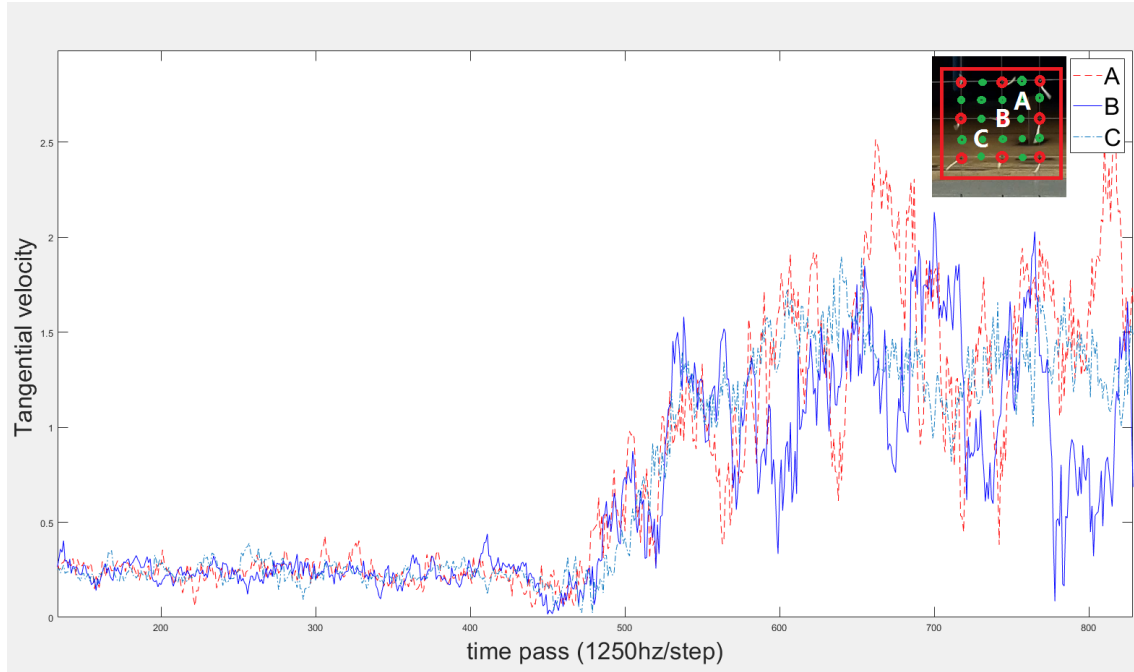


Figure 8.12 The blade deflects time unification

The different locations were shown by different lines. The solid line is the tangential velocity at the vortex core, oscillating due to turbulence and shaking.

The blade deflecting time unification does unified time scales in different runs, with tangential velocities increasing simultaneously. After the velocity increased, the condition went into a steady-state with more noise than the clean wind one (no VG, no vortex).

8.3.4 Tangential velocity

The data were recorded within the experiment by the probe, the three hot wires on the probe recording the three velocity components, ' u ', ' v ', and ' w '. Tangential velocity is one of the key parameters of the vortex, and the equation of the tangential velocity computed from velocity components is shown in Equation 8.1.

$$V_{tangential} = \sqrt{v^2 + w^2} \quad (8.1)$$

The tangential velocity within the Phase 2 experiment were all computed by equation 50. The example is as shown in Figure 8.13.

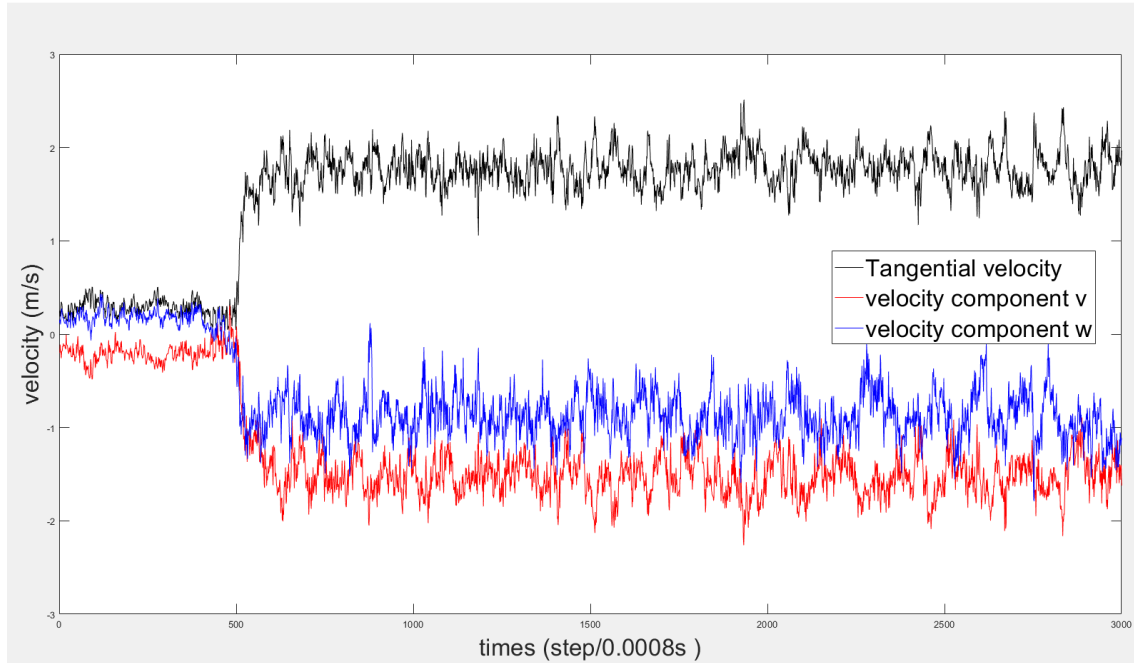


Figure 8.13 Tangential velocity with velocity components (200mm)

The location is spanwise -15 mm, and the height is 150 mm. The tangential velocity (black line) shows an increase with the blade deflecting (0 at X-axis), which means the vortex core was correctly recorded.

8.3.5 Repeat test

The minimum repeat times were checked in the 200 mm blade case experiment. Three locations were tested: the vortex core, middle point, and outer part of the vortex, as shown in Figure 8.14.

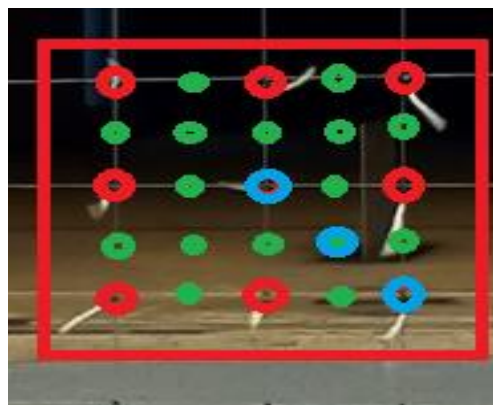


Figure 8.14 Analysis points of the repeating test, 200mm case

The three blue points are the repeating test analysis points: the vortex core, the middle point, and the outside of the vortex.

Outer part: The velocities, u, v, w , have been plotted separately with time past to determine the repeated times effects. The blue point at $X:0\text{mm}$ (spanwise), $H:150\text{mm}$ (height) in the wind tunnel (outer region of the vortex, bottom, right side of Figure 8.14 is shown in Figure 8.15, Figure 8.16, and Figure 8.17.

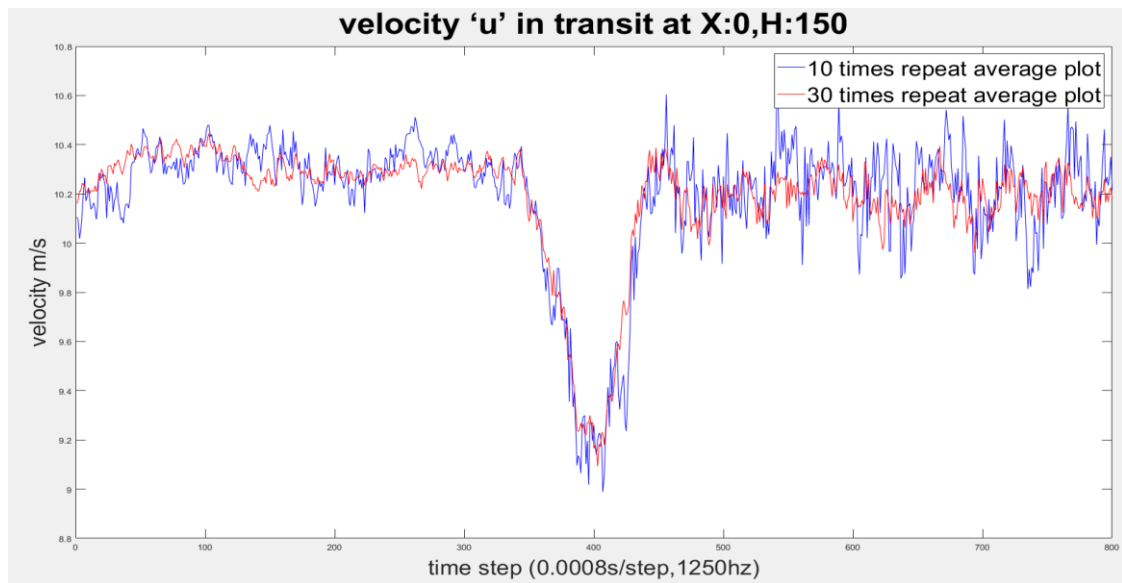


Figure 8.15 The velocity “u” in transit of vortex at the outer range

The velocity “u” in transit of vortex at $X:0\text{mm}$, $H:150\text{mm}$ location in wind tunnel. The blue line is the experiment repeated 10 times , and The red line is repeated for 30-time.

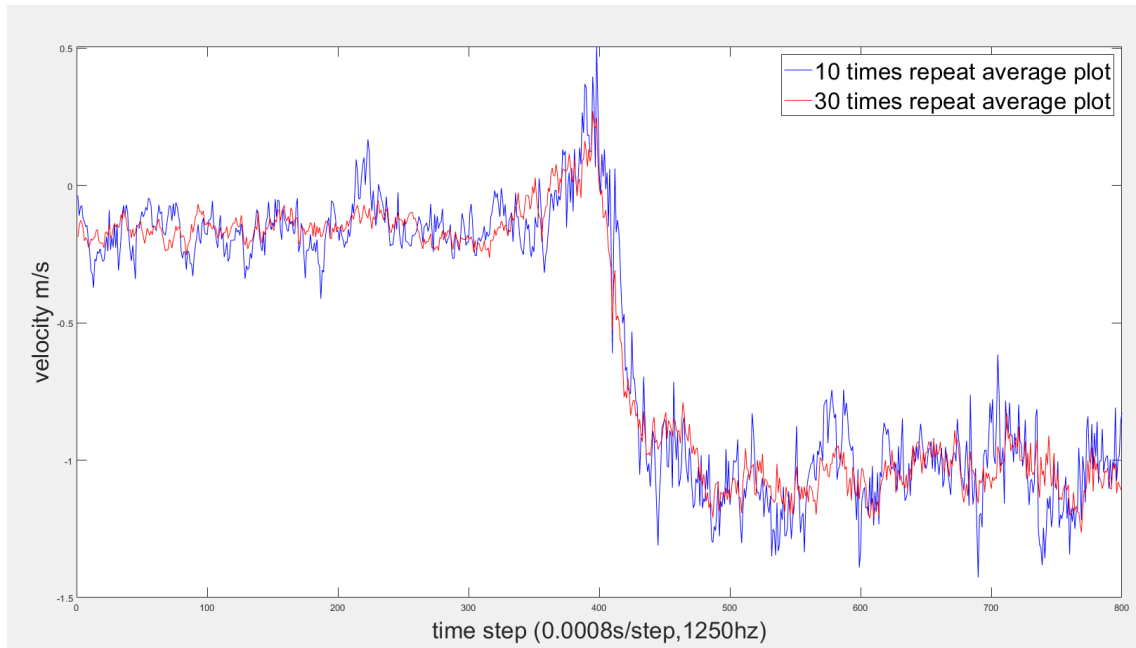


Figure 8.16 The velocity “v” in transit of vortex at the outer range

The velocity “v” in transit of vortex at X:mcm,H:150mm location. The blue line is repeated 10 times, and The red line is repeated 30 times.

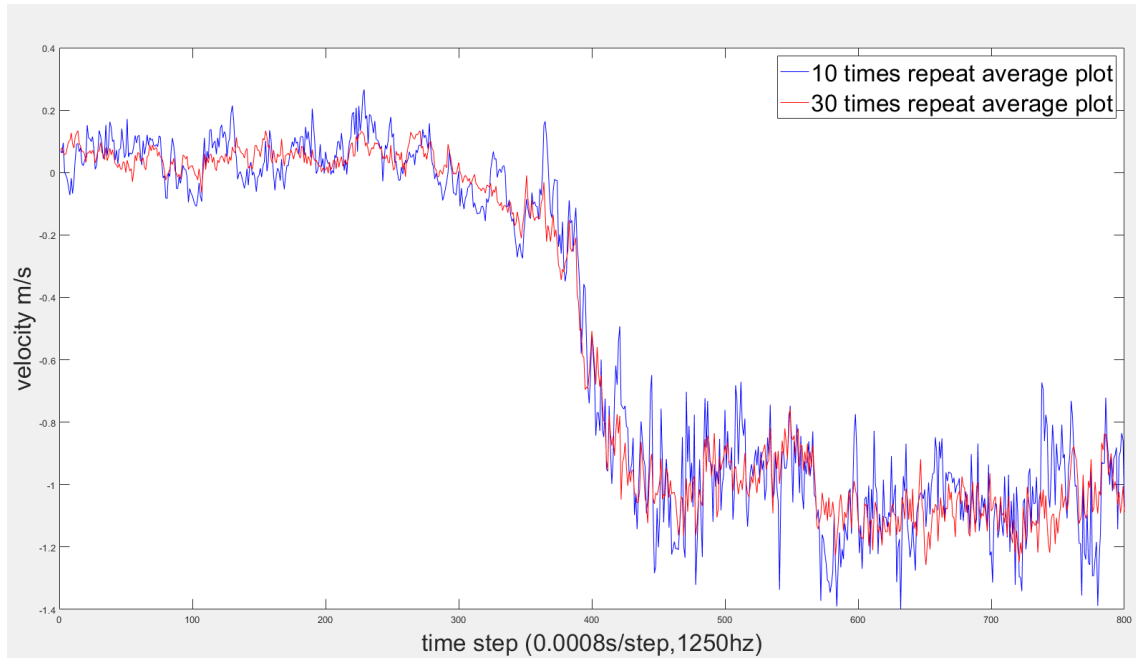


Figure 8.17 The velocity “w” in transit of vortex at the outer range

The velocity “w” in transit of vortex at X:0mm, H:150mm location in the wind tunnel. The blue line is repeated 10 times, and The red line is repeated 30 times.

The middle point was between the vortex core and outer point, at spanwise:15mm, height:165mm. The repeated results were as shown in Figure 8.18, Figure 8.19, and Figure 8.20.

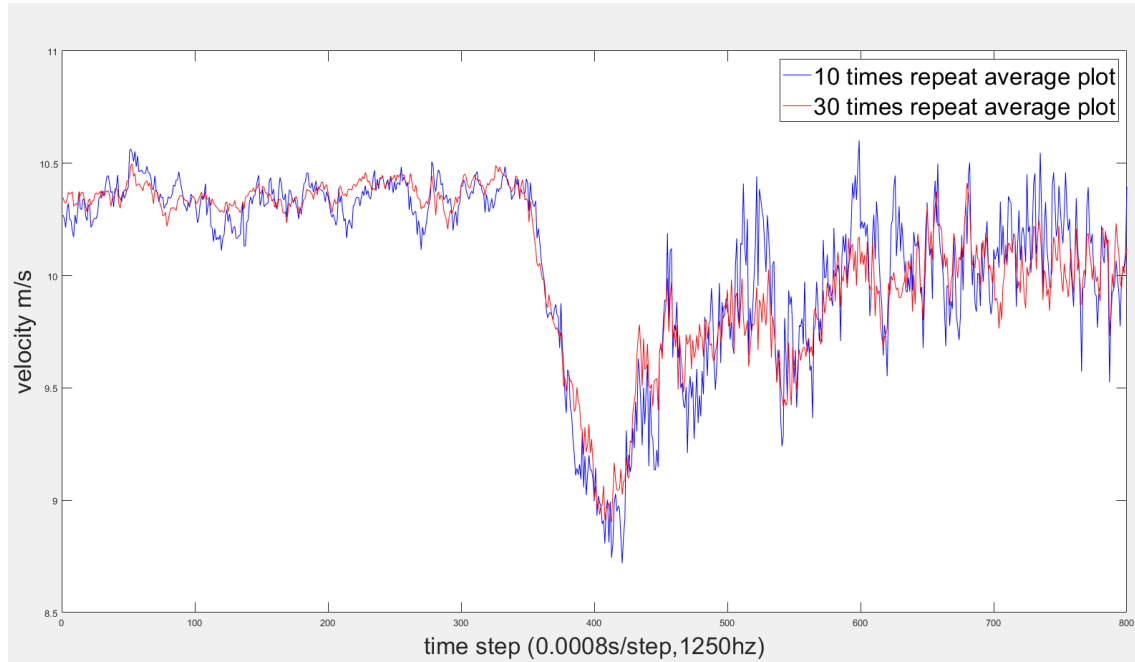


Figure 8.18 The velocity “u” at the middle location of the vortex

The velocity “u” X:15mm, H:165mm. The blue line is the experiment repeated for 10 times, and the red line is the experiment repeated for 30 times .

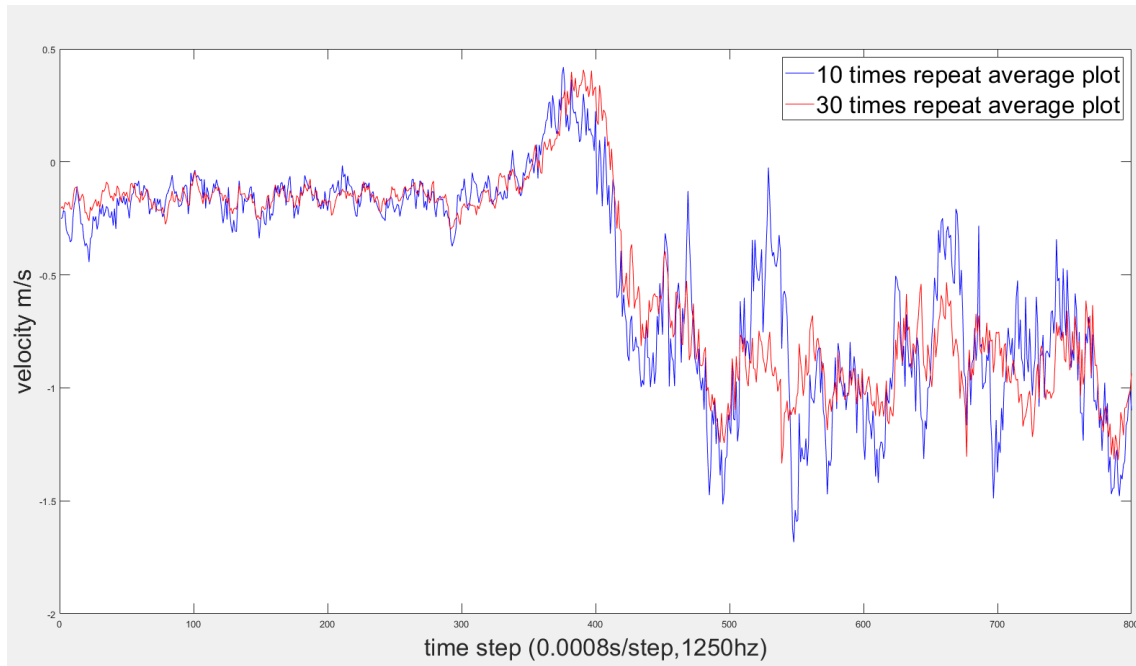


Figure 8.19 The velocity “u” at the middle location in the vortex

The velocity “u” at X:15mm,H:165mm. The blue line is 10 times repeat, and the red line is 30 times repeat.

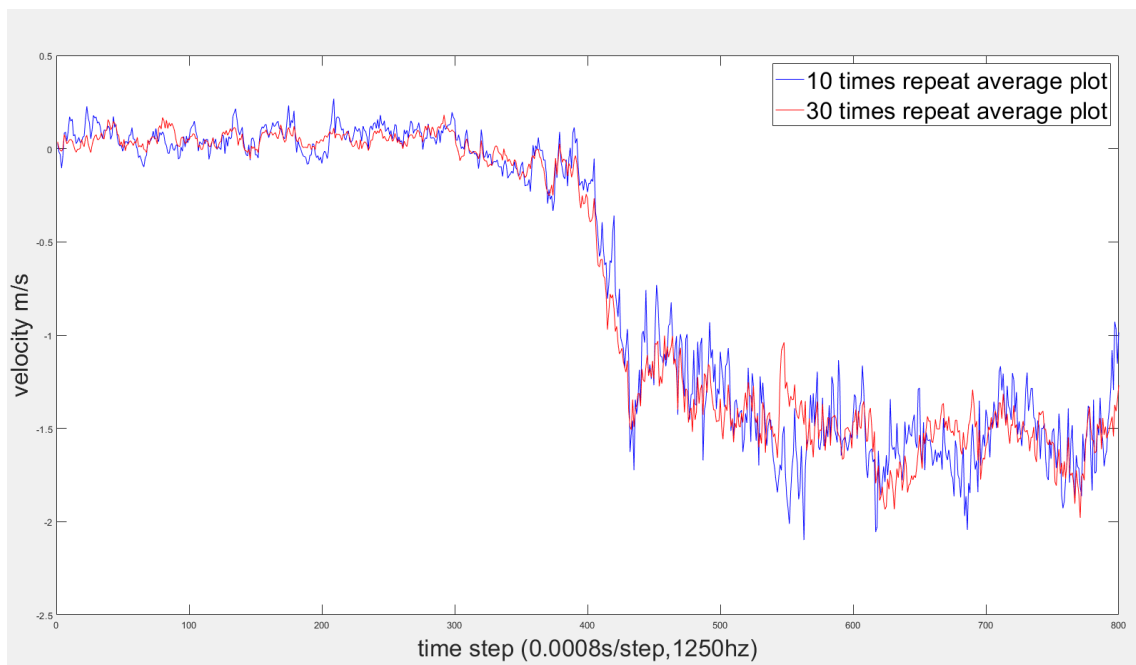


Figure 8.20 The velocity “w” at the middle location of the vortex

The velocity “w” at X:15mm, H:165mm. T The blue line is repeated 10 times, and The red line is repeated 30 times.

The velocities plots of the vortex core are used as the core indicator by variants of the velocities. The results are shown in Figure 8.21, Figure 8.22, and Figure 8.23.

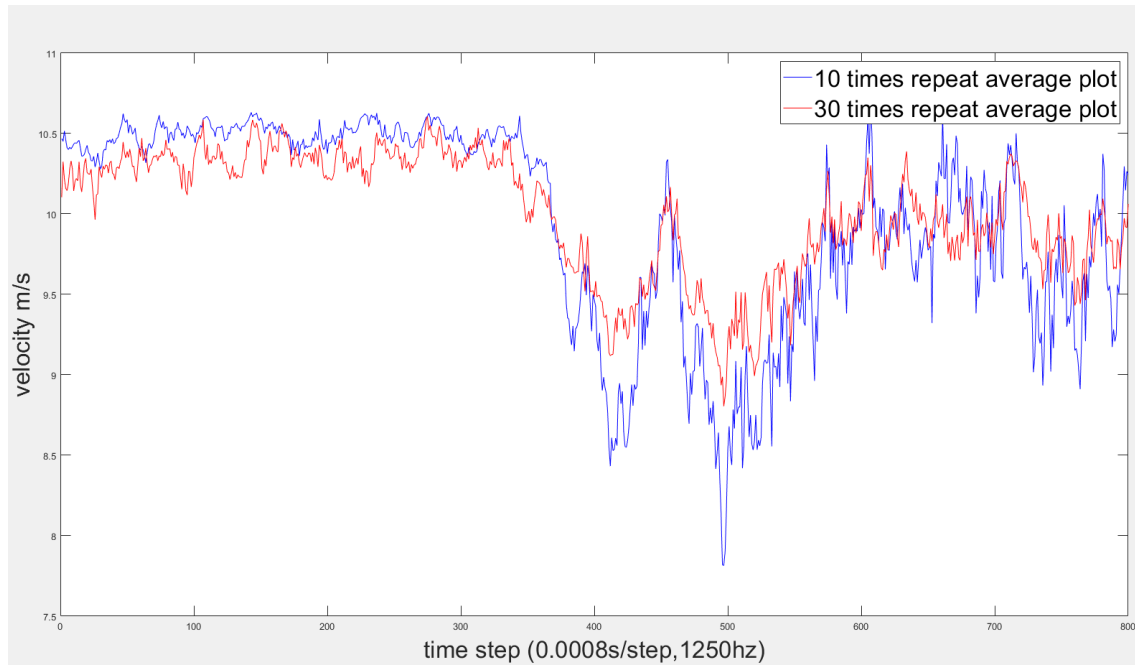


Figure 8.21 The velocity “u” at the vortex core location

The velocity “u” at X:30mm, H:180mm. The blue line is repeated 10 times, and The red line is repeated 30 times.

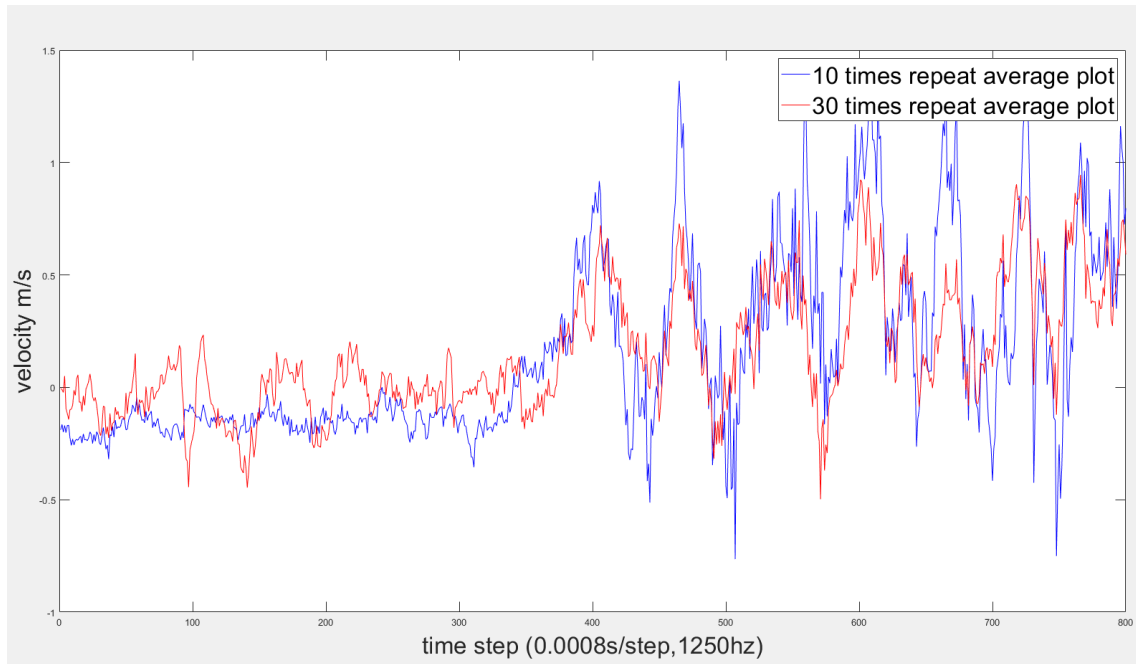


Figure 8.22 The velocity “v” at the vortex core location

The velocity “v” at X:30mm, H:180mm. The blue line is repeated 10 times, and The red line is repeated 30 times.

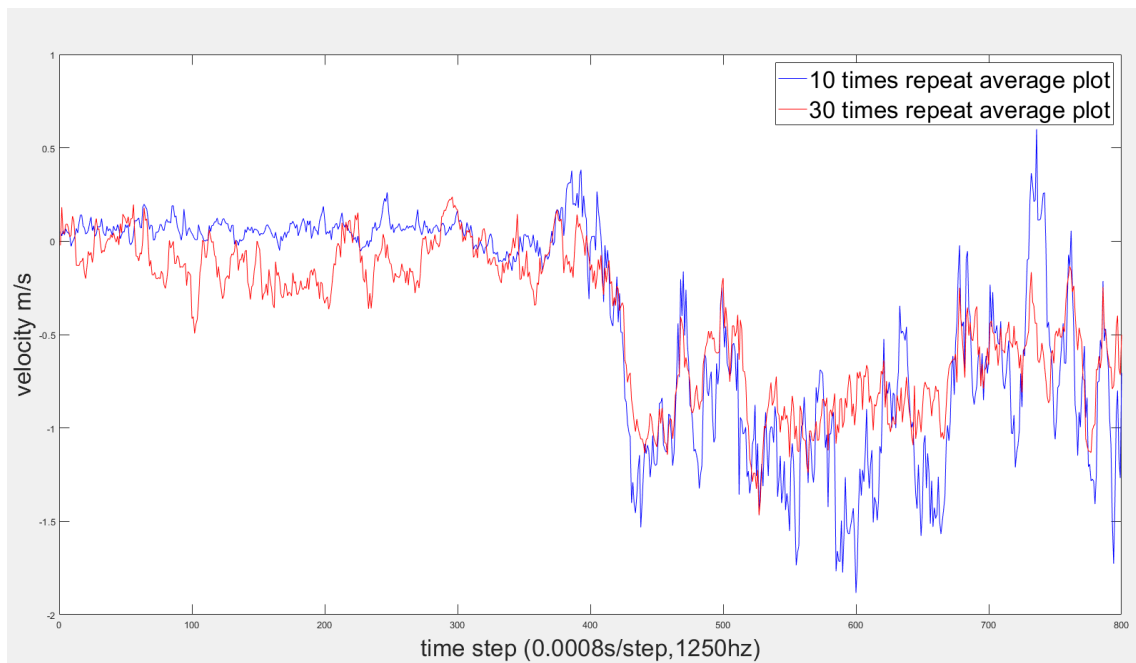


Figure 8.23 The velocity “w” at vortex core location

The velocity “w” at X:30mm, H:180mm. The blue line is repeated 10 times, and The red line is repeated 30 times.

From the repeated test, the experiment's results repeated 10 times shows more noise than one of the results repeated 30 times, but the tendency keeps constant. Therefore, in the study, the experiment repeated 10 times was applied.

8.4 Analytical methods

The analytical circulation was computed to compare with the experimental circulation. The equation given by Wendt is used to compute the circulation with the boundary layer thickness and the height of the blade [2]. The equation is shown in Equation 8.2. The k_1 to k_4 were obtained from the experimental data by least-squares regression.

$$\Gamma = \frac{k_1 v_\alpha \alpha c}{1 + \frac{k_2}{AR}} \tanh \left[k_3 \left(\frac{h}{\delta} \right)^{k_4} \right] \quad (8.2)$$

$$k_1 = 1.61, k_2 = 0.48, k_3 = 1.41, k_4 = 1$$

The result of Equation 7.7 based on the 200mm blade case was $0.3344 \text{ m}^2/\text{s}$, close to the experimental data $0.3259 \text{ m}^2/\text{s}$. The peak vorticity was computed by Equation 8.3. The viscosity involved in the equation was 35 times higher than the laminar boundary layer.

$$\omega_{max} = \frac{v_{zc} \Gamma}{4\pi \nu z} \quad (8.3)$$

The peak vorticity of the 200 mm blade obtained from equation 56 was 206 s^{-1} , close to the peak vorticity from the experiment, 218 s^{-1} .

8.5 CFD simulation

Only one probe measured the vortex in the Phase II experiment. The single probe and finite measurement locations highly limited the understanding of vortex forming. Therefore, the CFD simulation could provide a broader internal view of the vortex; the simulation results help to enhance the understanding of the vortex forming in the Phase II experiments.

The CFD simulation was represented in this section. This includes the turbulence model and mesh sensitivity check, the mesh details, and simulation settings that are finally applied to the simulation.

8.5.1 Model sensitivity

The model sensitivity check is important to the simulation in that the different models have different appliance ranges. All models were run on the same mesh to facilitate a direct comparison to find the most suitable model for the simulation. The models involved in the current sensitivity check were previously introduced in Chapter 6, and they include the $k - \varepsilon - realizable$, $k - \omega - sst$, and *Spalart-Allmaras* (SA model) models. The result of the test is shown in Figure 8.24.

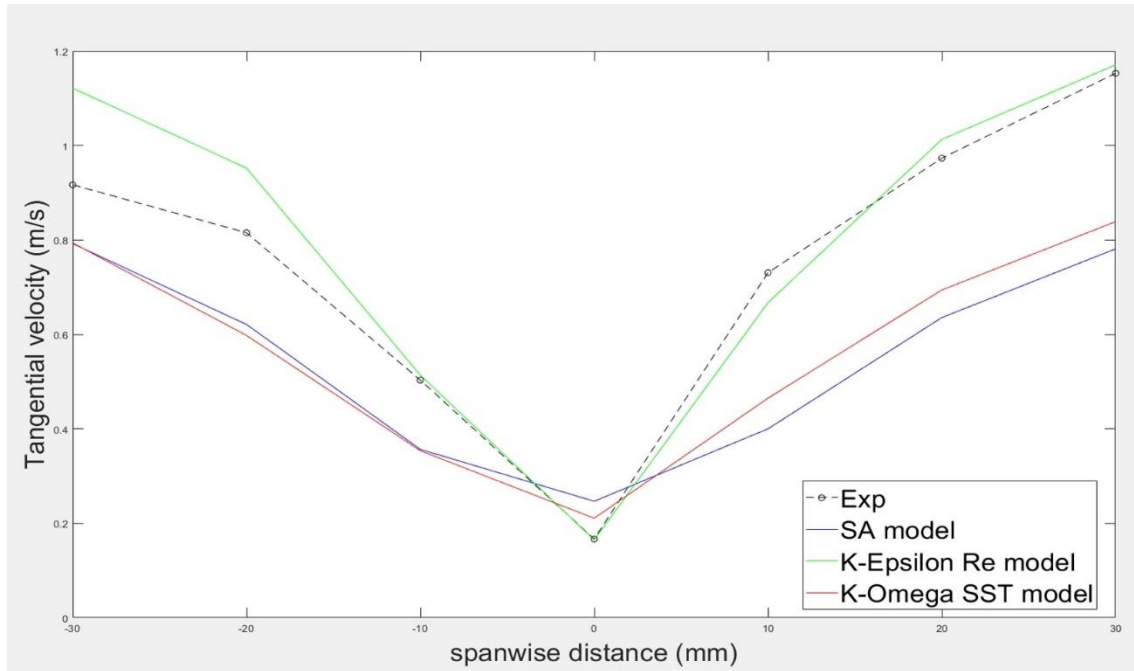


Figure 8.24 The model sensitivity check

The results given by model $k - \varepsilon - realizable$ in the model sensitivity test show better similarity compared to the rest of the two models. The simulation in this study will use the $k - \varepsilon - realizable$ model.

8.5.2 Mesh sensitivity with mesh detail

The mesh quality significantly impacts the simulation results. The detail of the mesh and model are introduced in this section. A mesh sensitivity check is

conducted to ensure accuracy. The mesh sensitivity check increases the mesh quality until the simulation results show minimal differences, thus determining the optimal mesh for simulations. The model of the simulation is illustrated in Figure 8.25.

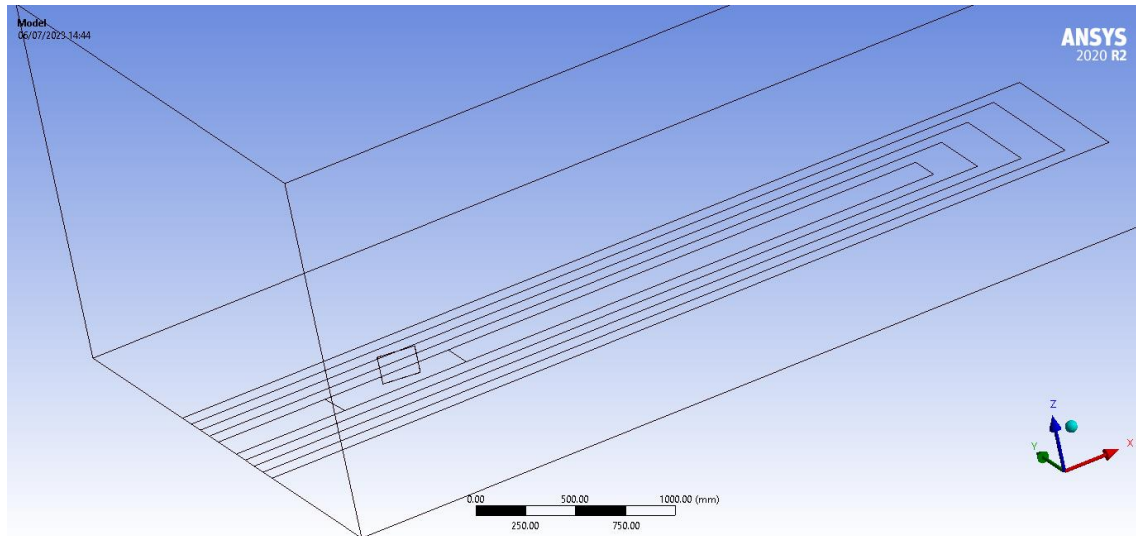


Figure 8.25 The model of simulation

The bottom surface of the model has been divided into several areas. The mesh size is increased to a coarser level to reduce the computational load as the distance between the blade and the area grows larger. The bottom surface is set as the wall. The front surface face of the blade is the velocity inlet. The surface behind the blade is set as a pressure outlet. The other surface is pressure far-field. The spanwise of the model is 3m, the model's height is 2m, and the length of the model is 15m.

A mesh sensitivity check was carried out to determine the proper mesh for the simulation. The results of the mesh sensitivity check are shown in Figure 8.26.

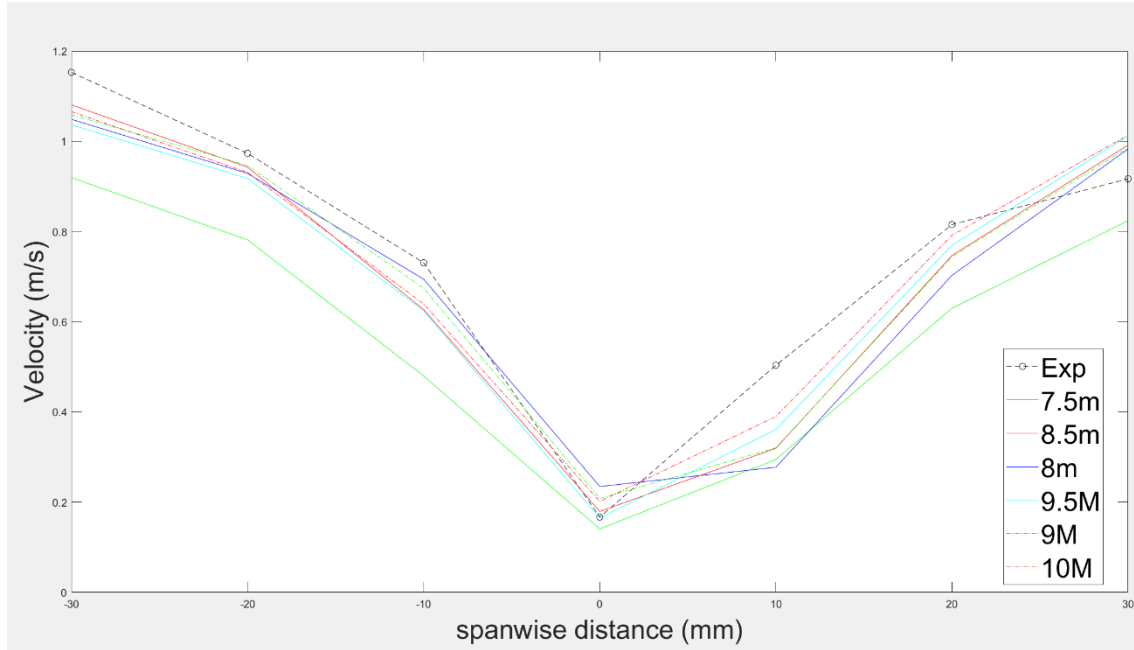


Figure 8.26. The mesh quality check.

The unite “m” means the mesh size of a million. The mesh check in Figure 8.26 shows that the mesh with 10 million elements has a good result compared to the rest of the test. As the element number increases, the results stabilize. The details of the mesh are shown in Figure 8.28 and Figure 8.29. The area of vortex forming was also intensive in capturing the detail of the vortex, which is shown in Figure 8.27.

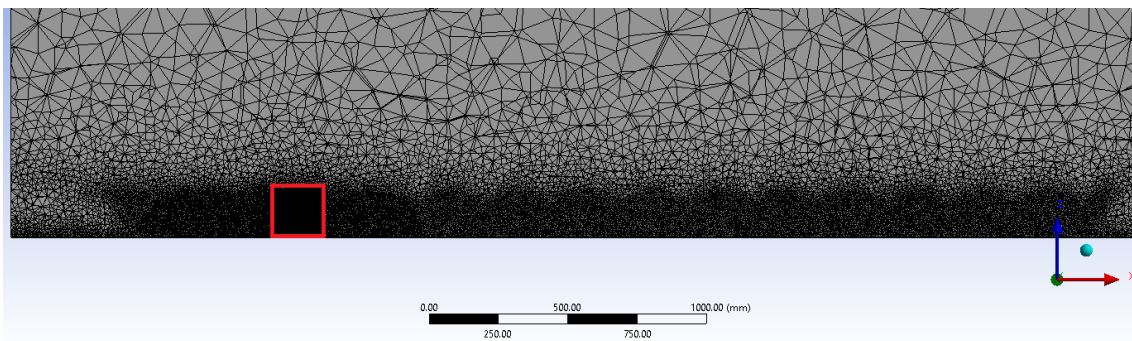


Figure 8.27 The section view of the vortex traveling space

The red square in Figure 8.27 represents the vortex generator, and the space on the right-hand side of the blade is the vortex traveling space, which is intensive for capturing the vortex accurately.

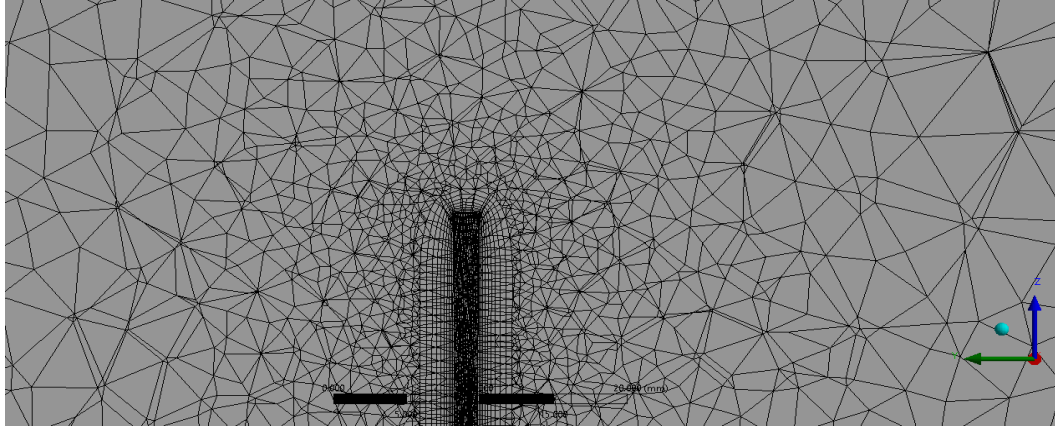


Figure 8.28 The mesh detail of the blade tip

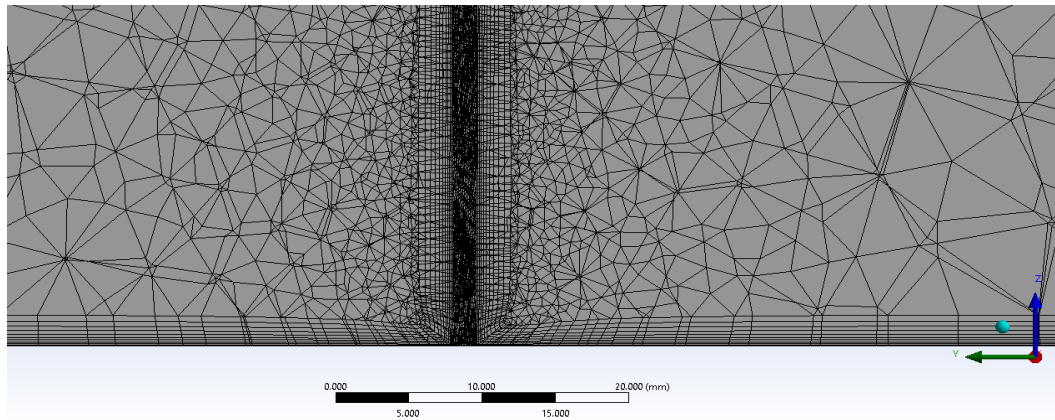


Figure 8.29 The mesh detail of the blade root

The mesh surrounding the blade shows the boundary layer, and the volume mesh has been intensified for better accuracy. The simulation mesh will use the 10 million elements mesh, and the result shows a good quality compared to the rest.

8.5.3 Simulation setting

The simulation in the current paper is a steady simulation, carried out by ANSYS fluent work bench 2020R2. The turbulence model used is the $k - \varepsilon - realizable$ with the standard wall function and Energy model. The mesh size is 10 million with refined mesh around the blade and vortex traveling space.

The interaction between the flow and wind tunnel boundary walls leads to complications in the simulation. Therefore, the model involved in the simulation

has much longer, wider, and higher boundary surfaces. The boundary setting of the model is shown in Figure 8.30.

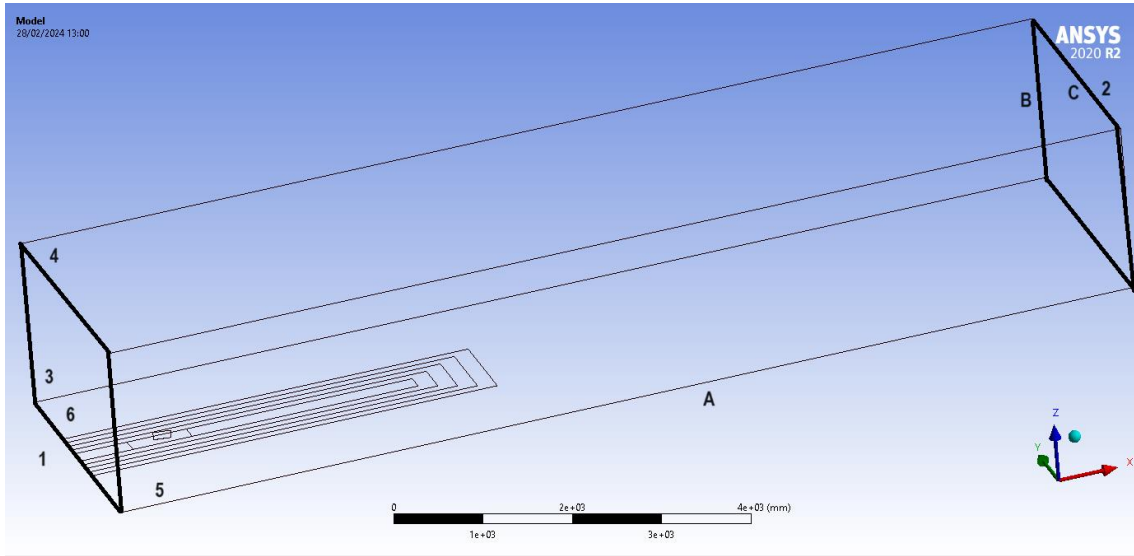


Figure 8.30 The model of the simulation

The length of the model denoted as A in Figure 8.30, is 12 M long. The height is B, which is 2 M. The width is C, which is 3 M. The air comes from the Surface 1 and goes out from the Surface 2. Both the inlet and outlet surfaces were highlighted. The Surface 6 is the bottom of the model and has been set as the solid surface. Surfaces 3,4,5 (left, right, and top) are set as pressure far field. The Mach number is 0.03, with the same direction of the incoming air. The inlet velocity profile of the Surface 1 is computed with the power law, Equation 8.4. The details of power law are in Appendix A.2.5.

$$\frac{u_{local}}{U_e} = \left(\frac{y}{\delta}\right)^{1/7} \quad (8.4)$$

A Pressure-based solver (PBS) is used due to the low-speed incompressible flow under investigation. The scheme of the pressure-velocity coupling is coupled, which solves pressure and momentum simultaneously. The Gradient of the solution variables are determined using the Least Squares Cell Based method. The interpolation scheme for the convection terms (momentum, density, and energy) were set as the Second-order Upwind methods. Turbulent kinetic energy

and turbulent dissipation rate were set as the first-order upwind method. The high-order term relaxation is on.

The solution is hybrid initialized, in which the Fluent gathers the condition automatically. The convergence is the default setting, which means the residual must be lower than 10^{-4} . The lift and drag on the blade are also considered to be convergent. There are a total of 15 cases after the mesh and model sensitivity check involved in the study, and not all cases are converged; cases 100mm and 180mm are not converged after 3000 steps, but the residuals, lift, and drag force are kept constant after 1000 steps.

8.6 Data processing

The current section focuses on data processing. The polynomial functions were employed to extend the pure experimental data, and more data points between original measurement points were obtained, improving the resolution rate of the plot. After the data were extended, it was further used in the circulation and vorticity calculations.

8.6.1 Background noise

The turbulent boundary layer contains various vortices that facilitate the transfer of momentum from the outer range to the bottom surface. Different locations within the boundary layer exhibit distinct background noise levels. The probe measured velocities (u , v , w) from 60 mm to 210 mm in the frequency analysis. At each height, the data was measured for 10 seconds at 1250hz. The noise reduction by spectral subtraction at 210 mm is shown in Figure 8.31.

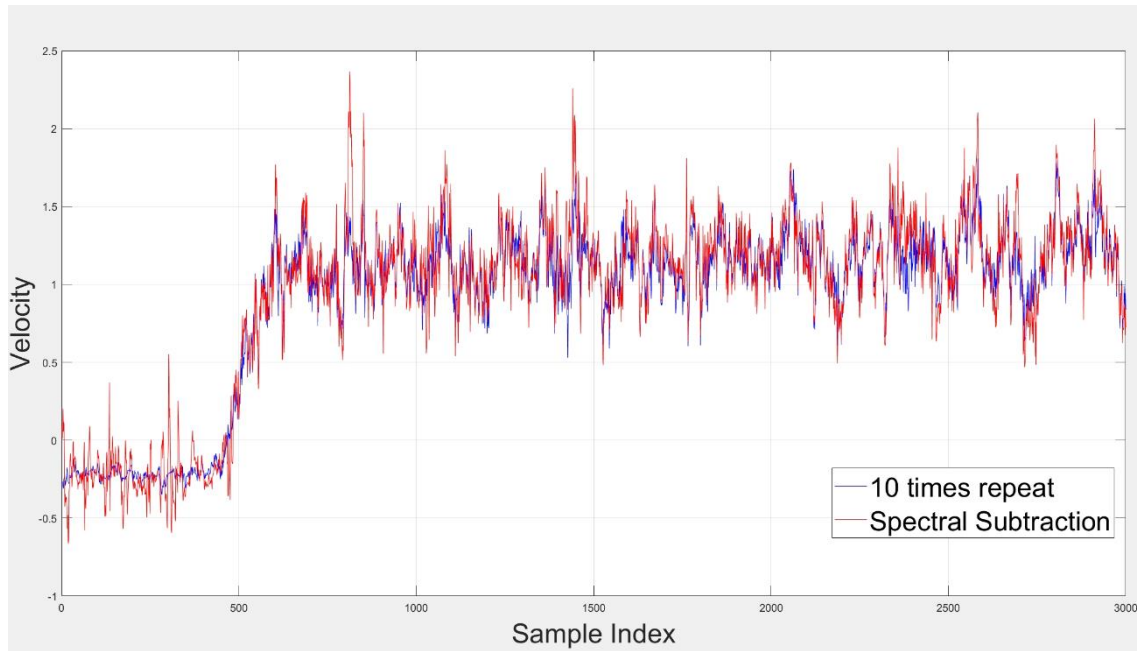


Figure 8.31 The noise reduction by spectral subtraction at the 210 mm location

The X-axis is the frequency in Hz. The Y-axis is the magnitude in m/s. Some of the peak frequency has been marked. The noise-reducing process is the subtraction of two spectrums for noisy data and background noise. The noise reduction by Wiener filter is shown in Figure 8.32.

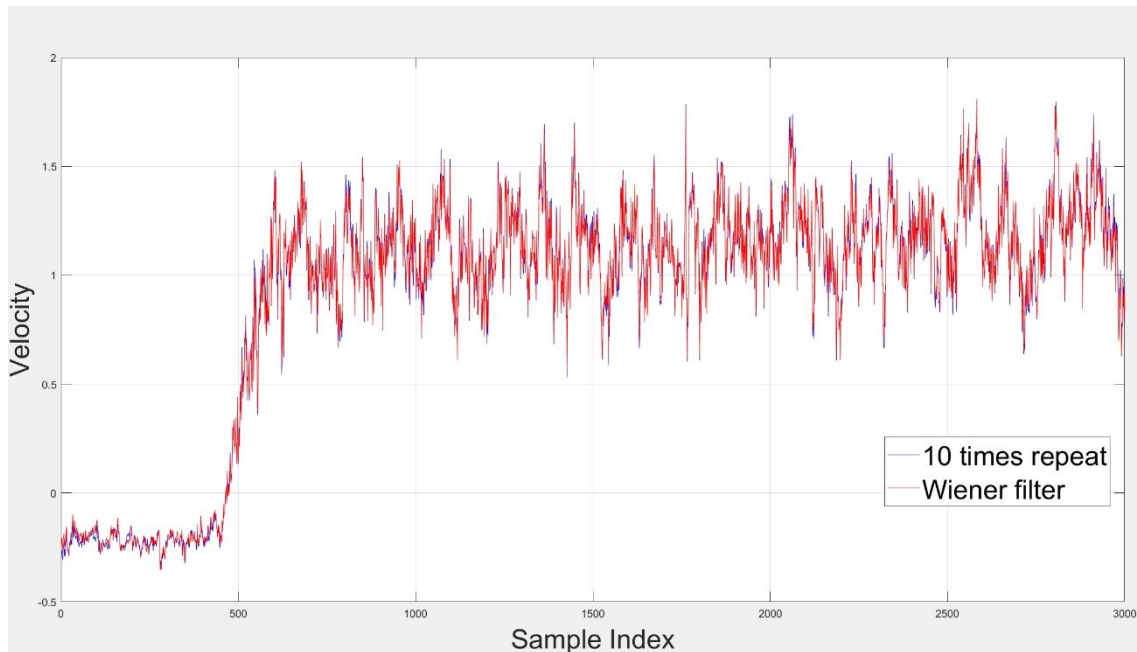


Figure 8.32 The noise reduction velocity at the 200 mm location

Figure 8.32 indicates the noise reduction process reduces the data's noise at a vertical 210 mm location from the bottom surface. The Wiener filter reduces the background noise by minimizing the mean square error between the original and cleaned signals. Noise reduction processes are applied to data processing. However, the experiment at single points was repeated 10 times; the repetition also reduced background noise, so the result from noise reduction and 10-time repeat are almost identical.

8.6.2 Polynomial function extension

The experimental data points were transferred to the polynomial equation, and then more points were produced to fill the gap; the process is shown in Figure 8.33. The 3-order polynomial functions extended the experimental data to increase the resolution of the results and make the plots looks better, as shown in Figure 8.34. The detail of the polynomial extension is in Appendix C.

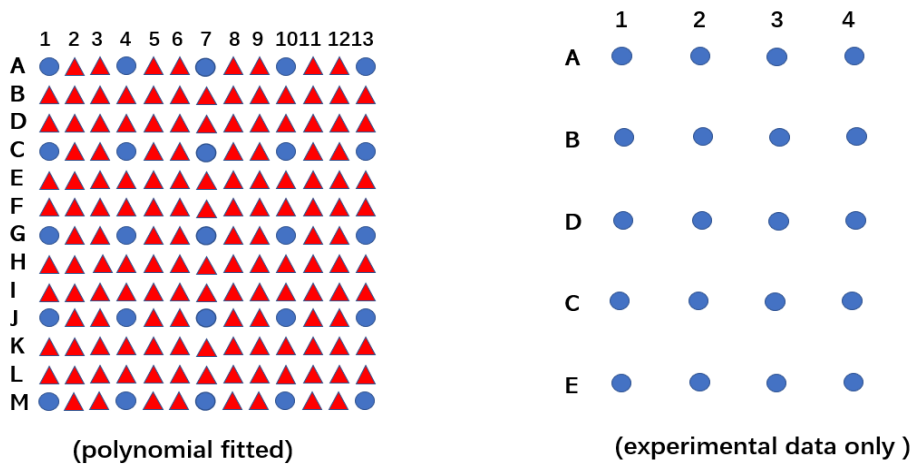


Figure 8.33 The data point matrix comparison

Circled data points: experimental measuring. Triangle data point: polynomial functions computed. The space in the left matrix is fitted by data computed from polynomial functions, and the right matrix is the experimental data with the large space between adjacent points.

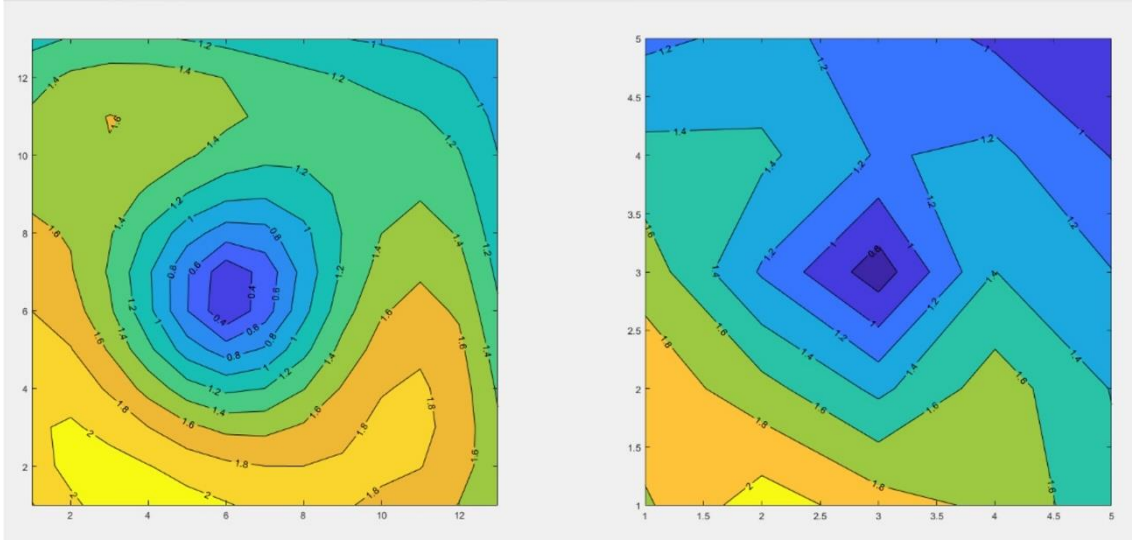


Figure 8.34 The secondary velocity of the experimental and polynomial vortex

The left part of the plot is the extended vortex; 169 points total, 25 points come from the experiment. The right part of the plot is the experimental vortex, and all data comes from the experiment.

8.6.3 Vorticity and circulation

The circulation was computed based on the vorticity distribution, which was the data point distribution in the recording area. The vorticity is calculated using Equation 8.5, as shown below. The polynomial functions were applied to improve the accuracy. After the extension, the shape of the vorticity area was closer to circular than the experimental condition. In contrast, the peak vorticity became smaller than the experimental data-only state, as shown in Figure 8.35.

$$\omega_x = \frac{\partial v}{\partial z} - \frac{\partial w}{\partial y} \quad (8.5)$$

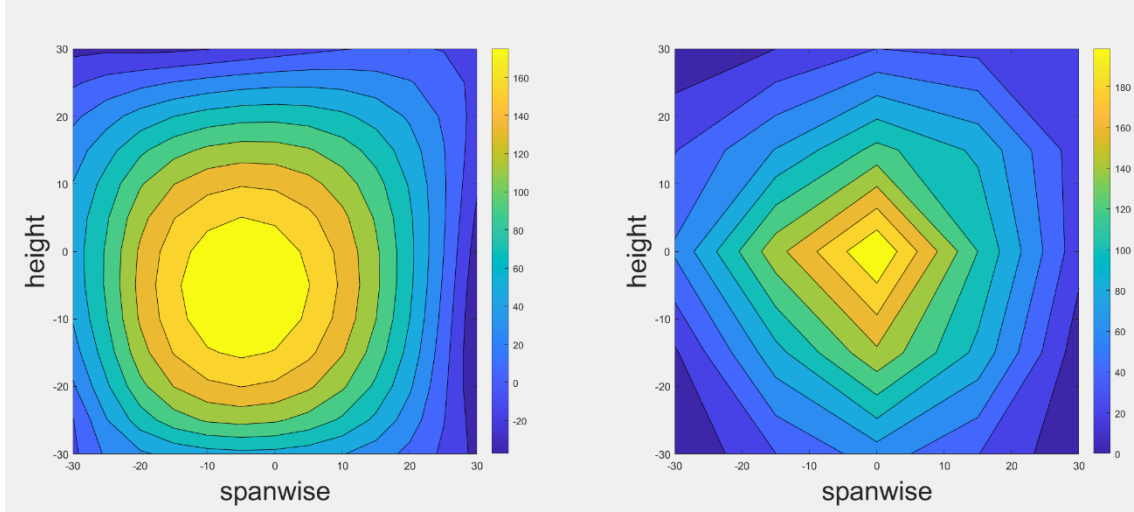


Figure 8.35 Peak vorticity of experiment results

The right part is the experiment data only. The Left-hand side is extended data according to the initial data.

Based on the two similar vorticity distributions. The circulations were obtained by integrating the area. The equation was as shown in Equation 8.6. The circulations were 0.3575 for pure experimental data and 0.3259 for the extended matrix.

$$\Gamma = \sum_{i=A}^M \sum_{k=1}^{13} \omega_{ik} ds \quad (8.6)$$

The vortex core location was considered the location of peak vorticity, which was the same as the tangential velocity profile.

8.6.4 Turbulence kinetic energy

The turbulence kinetic energy is relative to the fluctuations of the velocities. Therefore, the mean kinetic energy per unit mass is associated with eddies in a turbulent flow. The turbulence kinetic energy is related to momentum and heat transport. In the Phase II experiment, the turbulence kinetic energy was computed from both active motions and static vortex, and the equations are shown in Equation 8.7, Equation 8.8, and Equation 8.9.

$$k = \frac{1}{2} (\overline{(u')^2} + \overline{v^2} + \overline{(w')^2}) \quad (8.7)$$

$$\bar{u}' = \frac{1}{T} \int_0^T (u(t) - \bar{u}) dt = 0 \quad (8.8)$$

$$\bar{u}' = \frac{1}{T} \int_0^T (u(t) - \bar{u})^2 dt \geq 0 \quad (8.9)$$

The impulse response smoothing filter defined by Savitzky Golay is used to compute the mean velocity of the velocity components in Matlab. The filter was taken 3 orders for the polynomial functions, and the frame length was 31. The mean velocity computed by Savitzky Golay filter and velocity with fluctuations are shown in Figure 8.36.

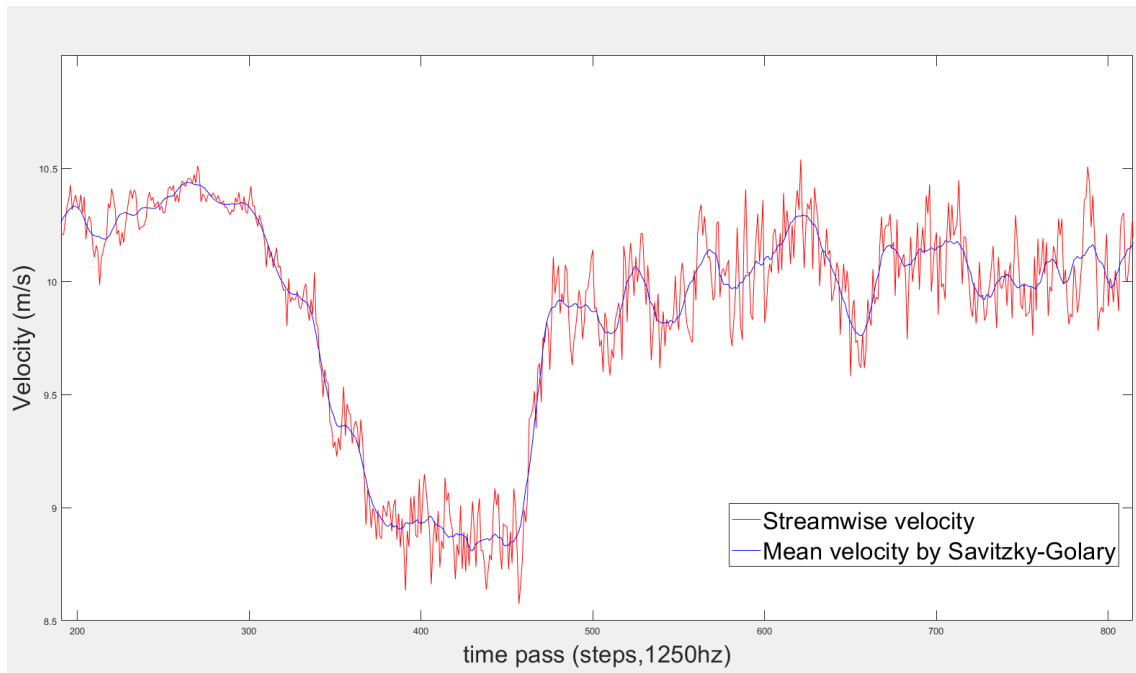


Figure 8.36 The velocity with the mean velocity

The red line represents the total velocity, including the mean velocity and fluctuations. The blue line was computed from the Savitzky Golay filter with 3 order polynomial, and 31 points were considered for computing one average point.

The velocity fluctuations were computed by the total velocity minus the mean velocity, and then the velocity fluctuations are used to calculate the turbulence kinetic energy. The frequency of the probe is 1250hz, and it is the best one in the lab to capture the fluctuations of dynamic processes. The background noise from the local boundary layer was measured and transferred to the frequency domain

to find the local resonance due to the boundary layer. The frequency peaks due to the boundary layer are reduced when the data process does not show a clear difference. The Turbulence kinetic energy contour plot of the static vortex, 200mm blade, are shown in Figure 8.37.

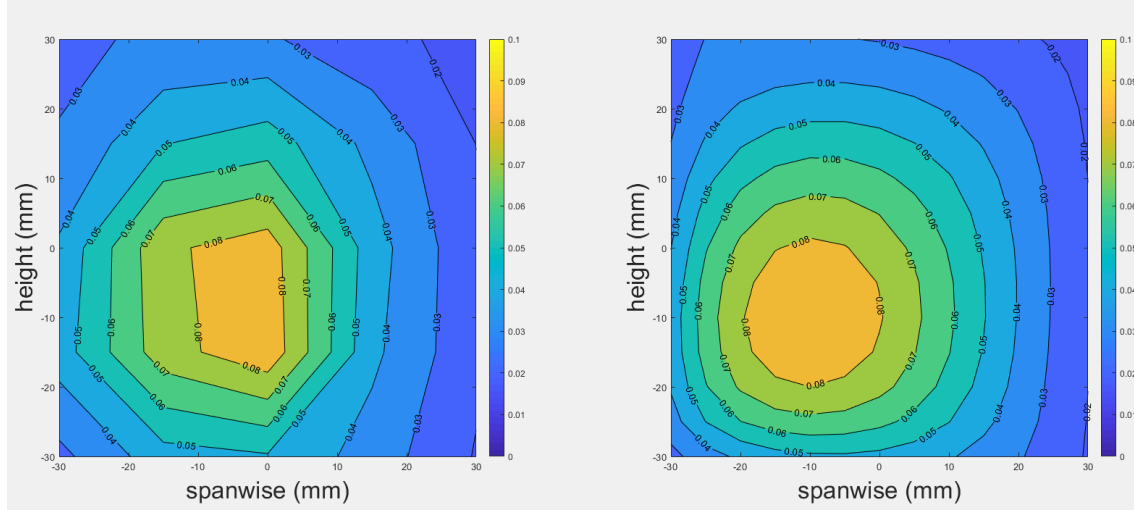


Figure 8.37 Turbulence kinetic energy contour plot of the static vortex, 200 mm

The left is the experimental result, and the right is the polynomial extended contour plot, units: $m^2 \cdot s^{-2}$.

8.7 Result

The results obtained from the experiment were analyzed from two perspectives: the time serial and nondimensional domains, specifically focusing on blade action and circulation activity in nondimensional domains. In blade action, which includes blade deflection and blade restoration, time-related data were transformed into nondimensional values by dividing the blade deflection or restoration times. For example, the circulation increasing period was divided by the blade deflection time to achieve a nondimensional representation. The active motion, which includes circulation increasing and decreasing motions is represented by process ratios. For instance, if the entire motion lasted for 100 seconds, a time step at 50 seconds would be at 50% of the motion's duration.

There were three vortices in the Phase II experiment, and the static locations are shown in Figure 8.38. The three boxes come from the experiment, and the

vortices were located on the left-hand side of the blade. These boxes are the measurement area by the probe.

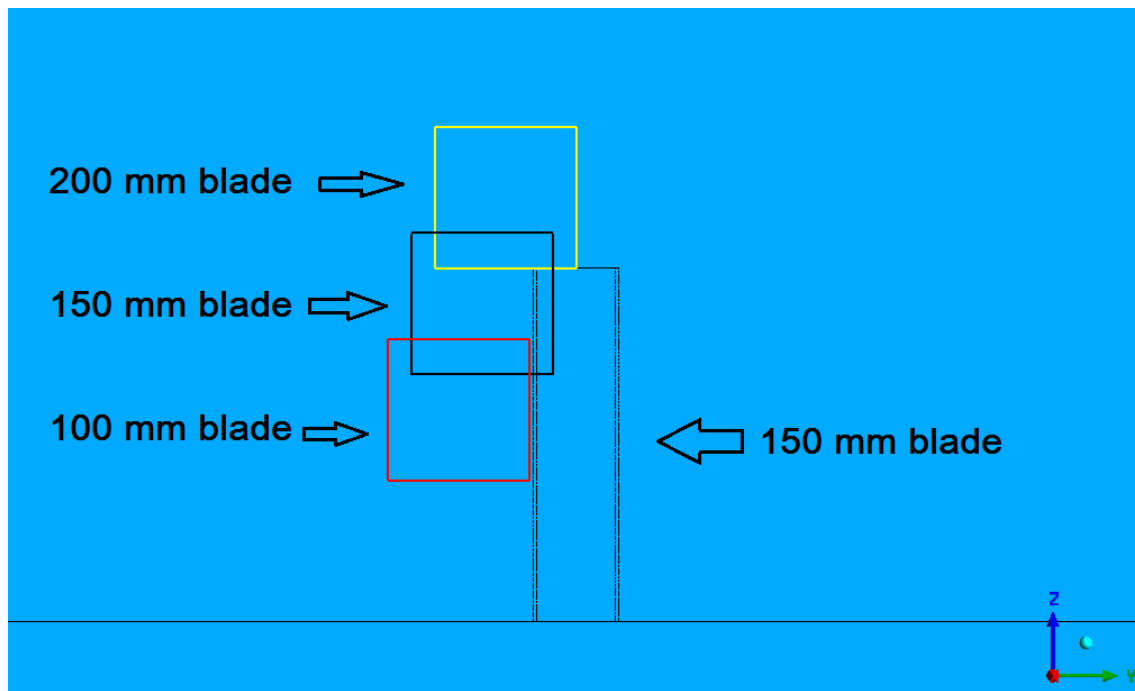


Figure 8.38 The locations of the vortices in the Phase II experiment

Figure 8.38 was plotted by CFD software. Three square boxes were the recording areas in the experiment. The rectangle in the center is the 150 mm blade, with a 1.5 mm thickness. Because the blade has a 10° angle of attack, the blade looks like a square in the plot. Upwind view to the wind tunnel.

The height of the vortex is closely related to the height of the blade. Specifically, the higher the blade, the higher the vortex. As the vortex's height decreases, its interaction with the surface causes it to move further to the left-hand side. Because of the selected angle of attack, all three vortices are positioned to the left of the blade, representing the negative y-direction due to the current angle of attack 10° .

8.7.1 Blade deflection and restoration

During the Phase 2 experiment, the average deflecting times and average restoring times of three cases were affected by the slight bending of the blade and mechanical wear. The repeated testing led to bending and wear, which in

turn may increase the deflection and restoration times. The result of deflecting time was as shown in Figure 8.39.

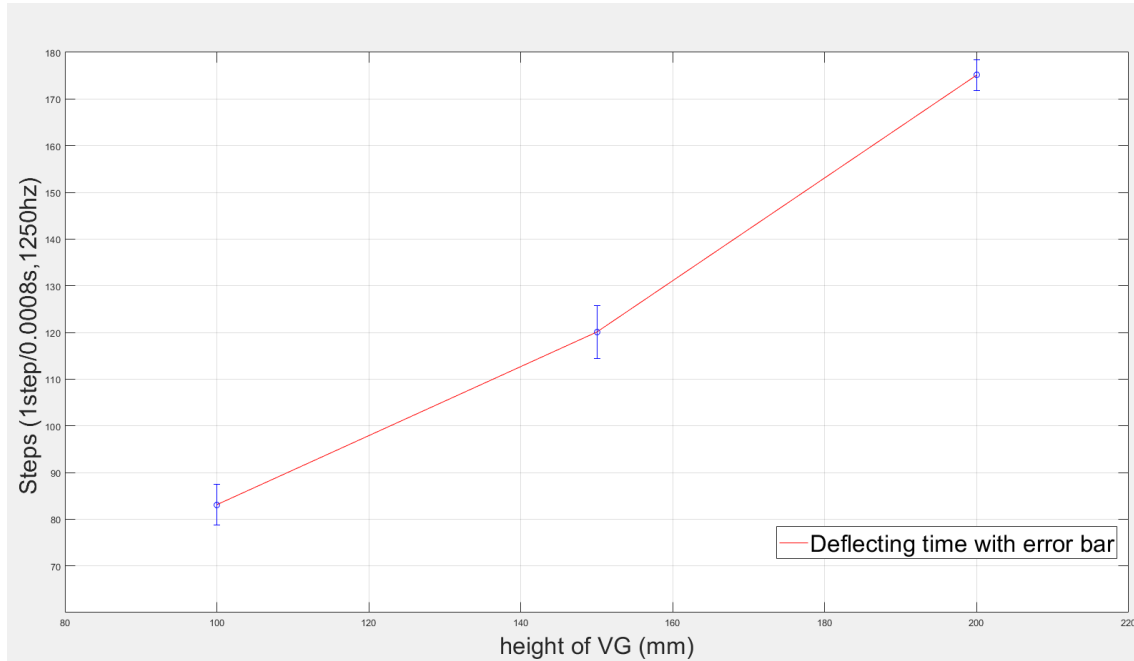


Figure 8.39 The deflecting time with time blade size variation

The X-axis of the plot is the height of the blade, and the Y-axis is the steps, which is the 0.0008 s per step.

Figure 8.39 shows the blade deflection time from the 100 mm blade to the 200 mm blade. The line of time changes was not fully linearized because of the different deflecting speeds. The sequence of tests of the three blades was 200 mm blade at first, followed by the 100 mm one, with the last one being 150 mm. The 200mm and 100mm experiments caused the VG blade wear and tear, leading to the largest error bar in 150 mm case. The error bar sizes from 100mm to 200mm were 9.6, 11.2, and 6.6 (unit: steps). The speed of deflecting was computed by $\frac{\text{height of the blade}}{\text{deflecting time}}$, which were 200mm: 1.3m/s, 150mm:1.1m/s, and 100mm:1.1m/s; the deflecting speed was uncontrollable due to the blade being powered by the rubber bands.

The blade bending and mechanical wear also affected the restoring motion, and the effects were larger than the deflecting motion. The result of the average restoring time shows in Figure 8.40.

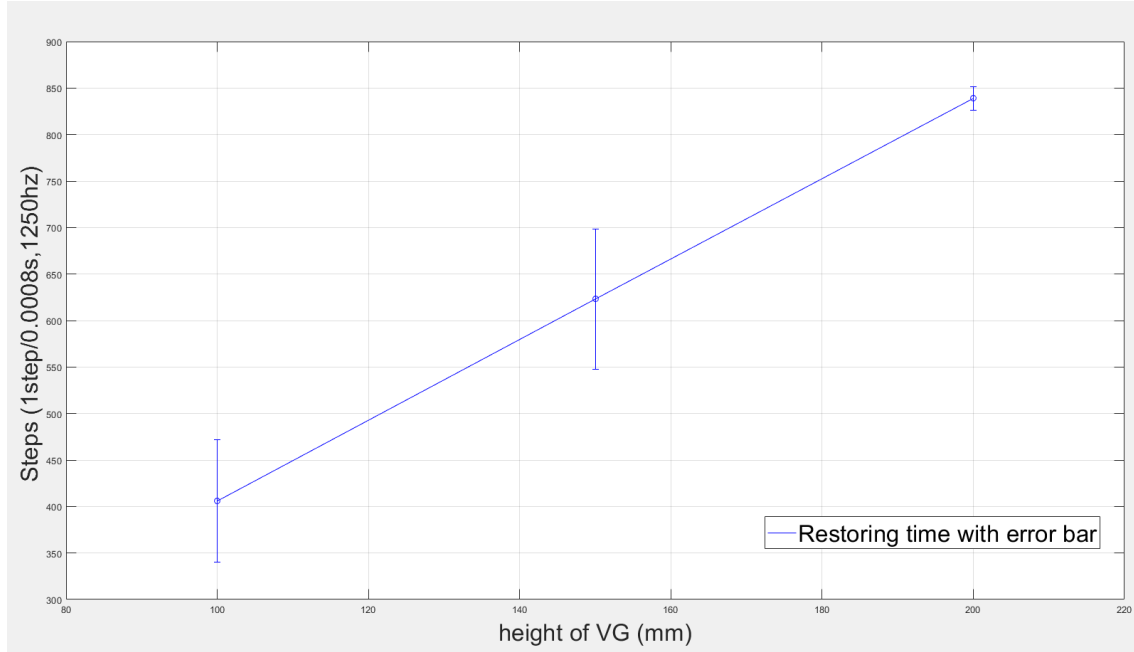


Figure 8.40 Restoring times with VG size variation

The plot shows the considerable error bars caused by mechanical wear and blade bending. At 100mm and 150mm conditions, the error bars range 5-6 times higher than the initial condition (200mm, right-hand side). The size of error bars from 100mm to 200mm is 132, 150, and 25 (unit: step). The speed of blade restoration is 0.123m/s, 0.16m/s, and 0.17m/s corresponding to 100mm, 150mm, and 200mm blades.

8.7.2 Circulation

The circulation indicates the strength of the vortex. It can be separated into static and dynamic motions in the Phase II experiment, the dynamic motions including deflection and restoration. Both experimental data and analytical data are compared in this section.

8.7.2.1 Static vortex circulation

The static circulation was obtained from the tangential velocity matrix, which was extended by the polynomial function; the circulations were nearly the analytical condition after extension.

The space between two experimental data points at 200 mm blade conditions was 15mm as the initial test. After the primary analysis on 200mm case, the space was reduced to 10mm at 150mm and 100mm blade conditions to increase the accuracy. By comparing the circulations based on different distances between two experimental data, the minimum data points in each column and row for the polynomial extension method in this study was 3 (located at both ends of the line and the middle point). Circulations of pure experimental data only, polynomial fitting data, and analytical data are shown in Figure 8.41.

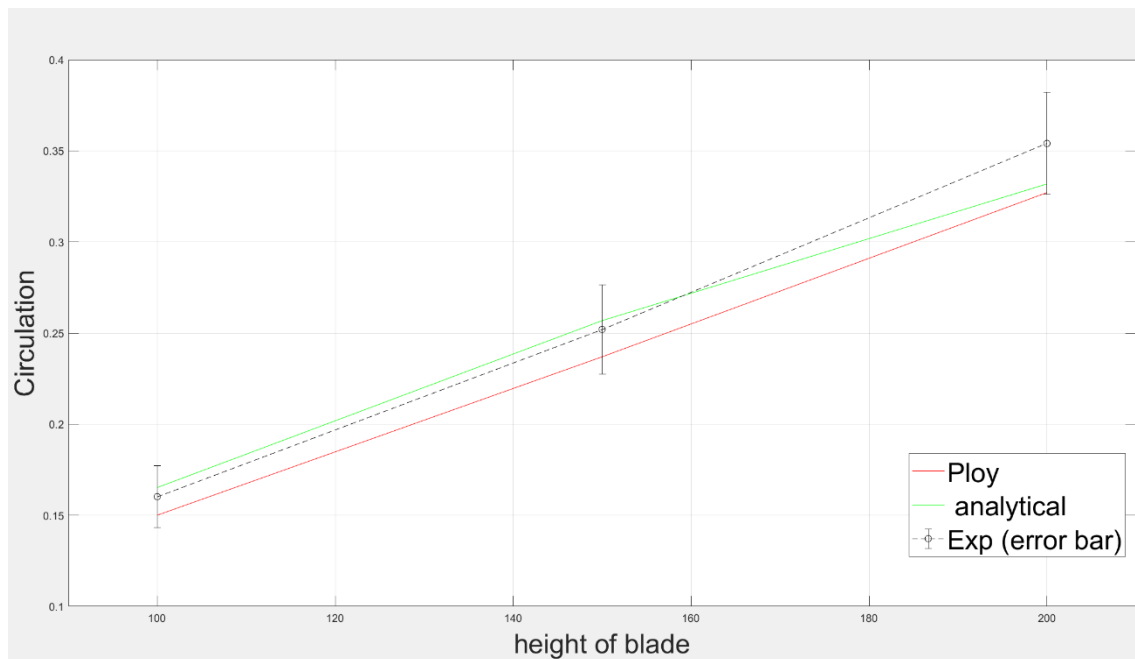


Figure 8.41 The static circulations with blade height variation.

The three different data groups are plotted in different colors: the red line is the polynomial fitted data, the blue line is the experiment data, and the analytical data is green.

The result shows that the analytical circulations were close to both polynomial fitted and experimental circulations, but it seems the analytical model

overestimates the experimental results consistently in the 150 and 100 mm cases. At the 200 mm cases, both polynomial and analytical data underestimate the real case.

The larger space between two measuring points in the 200mm case than the 150 and 100 mm cases could lead to a polynomial extension error. The function computes the points between experimental data, as the space increases, the error increases. The polynomial function uses the smooth velocity variation to replace the real velocity gradient, which could smooth the vortices and lead to an underestimate.

The analytical method is a faster way to compute the circulation but tends to overestimate the vortex. The current method employs the theoretical approach with experimental regression parameters. The assumption in the theoretical approach simplifies the real condition and results in the omission of certain objects. The regression parameters limited the accuracy due to the different blade geometry and experimental conditions. The varying viscosity ranges, boundary layer thickness, and secondary vortex may all lead to the error, but they are not accounted for in the model. All those simplifications and limitations lead to errors in real cases.

The 200mm blade thickness is similar to the boundary layer thickness. At the 200mm location, the free streams are involved in the vortex-forming process on the blade tip; this may be beyond the range of current analytic methods. This leads to the misestimation of the analytical model.

The increase in the difference between interpolation data and experimental data at the 200mm condition is caused by the fewer measuring points within the vortex area. There are 7*7 measuring locations in the 100 mm and 150mm cases, but only 5*5 in the 200mm cases. All cases were expanded to a 13*13 matrix through interpolation. The reduction in measuring locations resulted in increased errors. Nevertheless, the interpolation result for the 200mm blade still falls within the error bar of experimental data, rendering it reliable. The analytical model seems to predict the interpolation in 200 mm cases, but the combination of two errors causes it.

8.7.2.2 Active circulation

The probe was located within the static vortex location to record the vortex forming at the static position. The circulations of active motion that come from the extended tangential velocity matrix are shown in Figure 8.42.

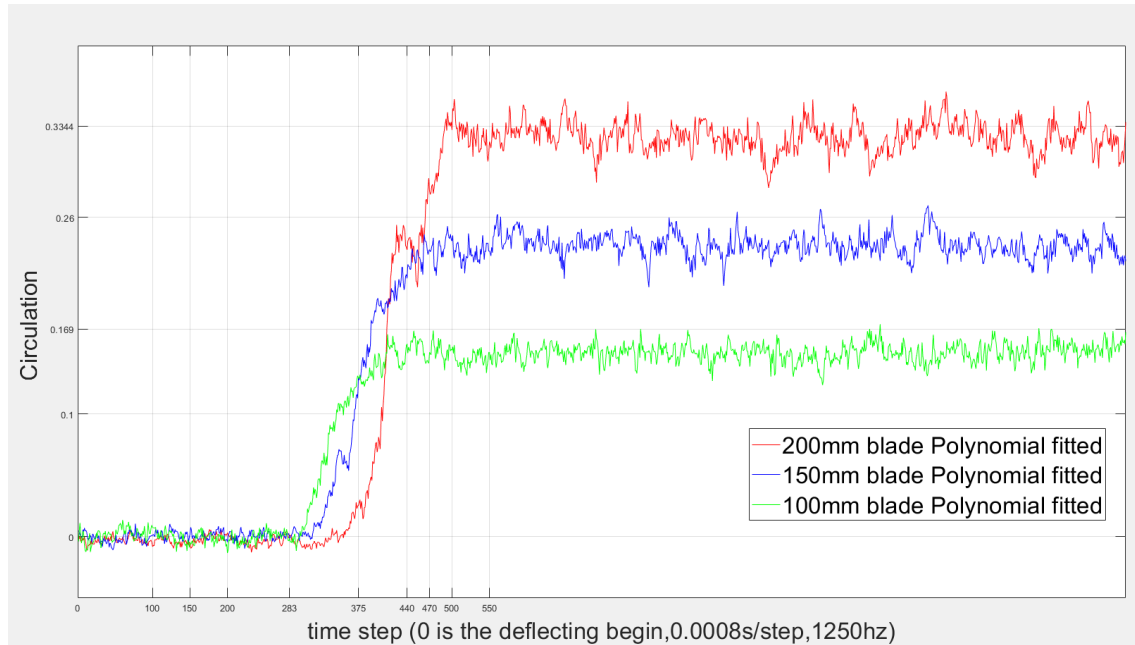


Figure 8.42 Circulation of vortex forming with blade size vibration

The solid lines on the Y-axis are the analytical circulations, which are 0, 0.169, 0.26, and 0.3344. The X-axis is the time passed. The red line is the circulation of the 200 mm blade, the blue line is for the 150 mm blade, and the green line is for the 100 mm blade. The angle of attack is 10° , the airspeed is 10m/s.

Figure 8.42 shows how the circulations change against time. The beginning point was when the blade began to deflect (0 on the X-axis). The circulations remained zeros at the beginning and then went up. The order of the increasing circulation was 100 mm at first, followed by 150 mm and the last is 200 mm.

The formation time difference is linked to the blade heights. The formation time includes the blade deflection time, vortex forming time, and vortex traveling time. The difference in blade height leads to different deflection times and changes in vortex traveling distances. The amplitudes of the three circulations show a

reasonable difference. The streamwise distances of the blade and testing locations were the same, but the responding times were different.

The circulation was transferred to ratio form to indicate the changes clearly, and the X-axis remains the time steps. The equation of transfer is shown in Equation 8.10. The results show the vortex generated by the shorter blade forms faster than the larger blader. The result shows in Figure 8.43.

$$\text{ratio of circulation} = \frac{\text{whole range circulation changes}}{\text{static circulation}} \quad (8.10)$$

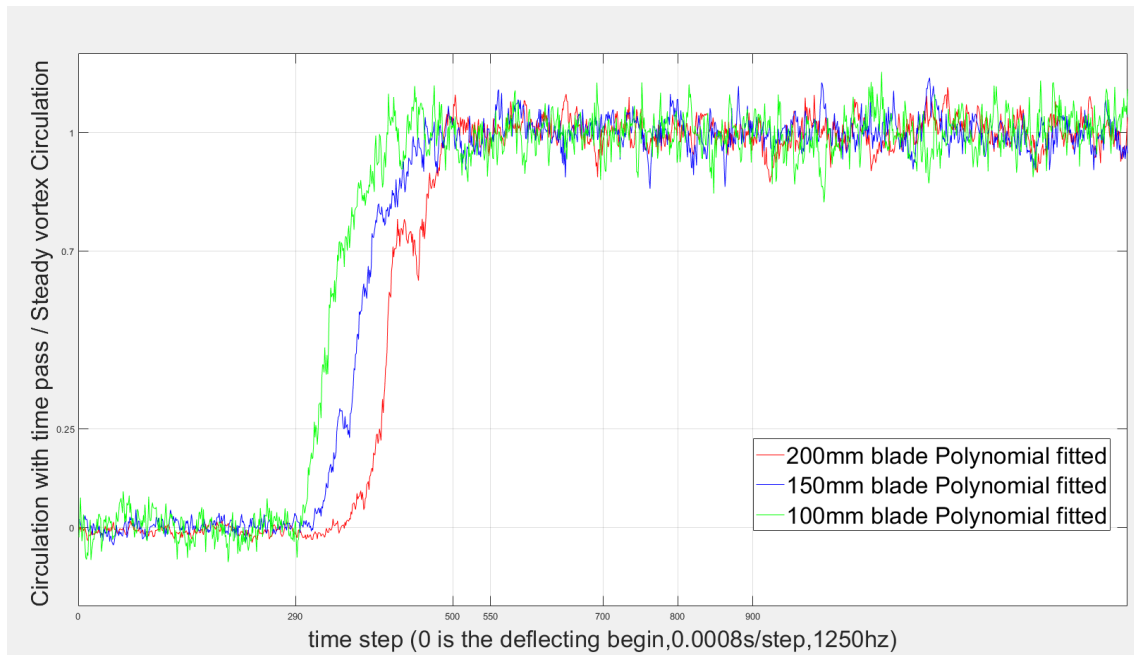


Figure 8.43 The circulation ratios variation of three blades

Different cases are plotted in different color. The Y-axis is the circulation ratio, and the X-axis is the time steps. The angle of attack is 10° , the air speed is 10m/s.

To convert the dimensional circulation variation to a nondimensional variation, the X-axis (time steps) needs to be non-dimensional. The active process of circulation variation is extracted from the whole process. The key point indicating the beginning of the active process is the first data point above the error bar of the steady circulation before the significant increase. The point indicating the dynamics process finished was the first point that reached the steady condition

after the increase. The results of both types of key points at deflecting motion are shown in Figure 8.44.

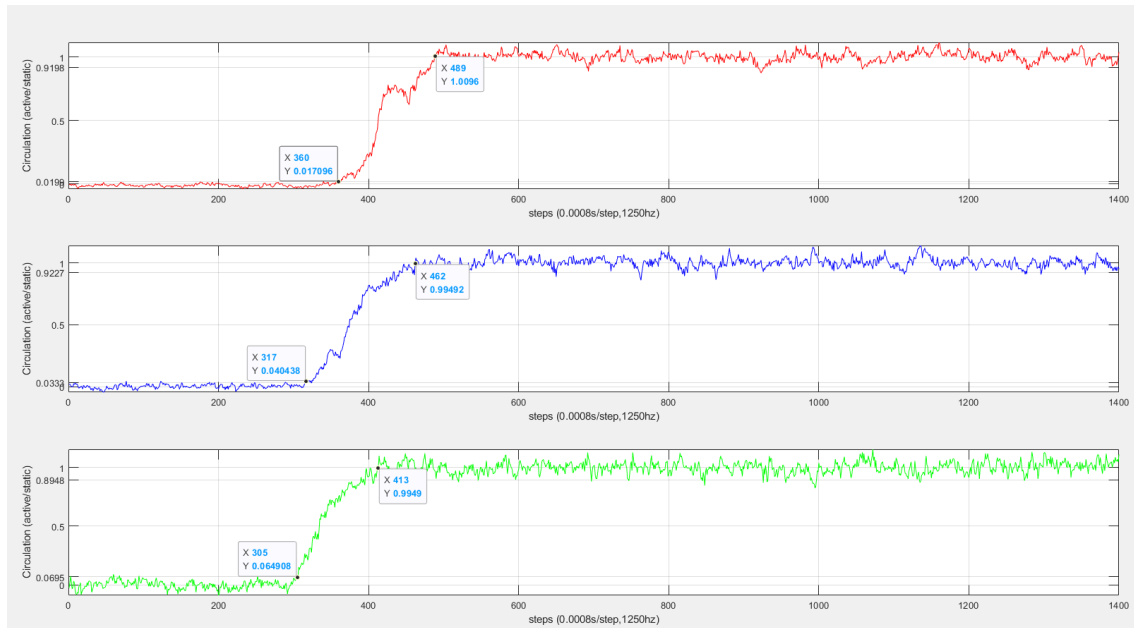


Figure 8.44 Key points at deflecting motions

Figure 8.44 shows the key points of three cases. All three plots' Y-axis is the circulation ratio (active circulation / static vortex circulation). The X-axis is the time domain.

All three conditions have been plotted separately. Both types of key points indicate the beginning and ending have been marked. The time requirements of the three blades are shown in Table 1. The active range is the circulation over zero to the static vortex level, describing the vortex formation inside the measuring area. The active ranges were selected and related to the blade deflecting times for the nondimensional study, the equation in Equation 8.11.

	Beginning	Ending	Total steps(seconds)
100mm	305	413	108(0.086s)
150mm	317	462	145(0.116s)

200mm	463	589	129(0.103s)
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Table 1 Time requirements of three-blade deflection

The result was selected from the average under the multiple repeat test, and the difference is clear with the clean wind condition and static vortex condition. The blade deflection process and vortex traveling process both affect the circulation increase part. The 150 mm has the longest time because the blade's mechanism is worn and stillly jammed during the experiment. The order of the experiment is 200 mm first, then is 100mm, the last one is 150mm. Case 100 mm and 200 mm show a reasonable time increase due to the longer blade and deflection time. The numbers within the beginning and the ending columns indicate the steps behind the beginning of deflection.

Active range in circulation is the circulation increase from zero to a static level. The blade active time is the blade deflection time from the bottom surface to the fully deflected. The active period is the circulation increase/decrease motion relative to the blade deflection time, and this is from the nondimensional study of the vortex formation, show in Equation 8.11.

$$Active\ period = \frac{active\ range\ in\ circulation}{blade\ active\ time} \quad (8.11)$$

The entire nondimensional vortex-forming plot is shown in Figure 8.45. The plot shows the circulation increasing at 200mm in the case "faster" than the other two shorter blades, where the circulation reached a steady level even faster than the time of blade deflection. A similar "faster response" was recorded by SHIZAWA [69]. Both the 150mm and 200mm conditions exhibited a "U" turn in the circulation-increasing process. This phenomenon is caused by the movement or oscillations of the vortex, which lead a portion of the vortex to exit the recording area briefly, resulting in a drop in circulation. In 200mm conditions, the U-turn appeared at 0.7 of circulation and 0.3 of 150mm conditions. It should be noted that there were three stages in the circulation, which increased for all three blades. The three stages were from 0 to 0.3 circulation, from 0.3 to 0.7, and 0.7 to 1. The

two oscillations were located at the stage connection parts, the red line is at 0.7 of the circulation ratio, and the blue line is at 0.25 to 0.3 of the circulation ratio.

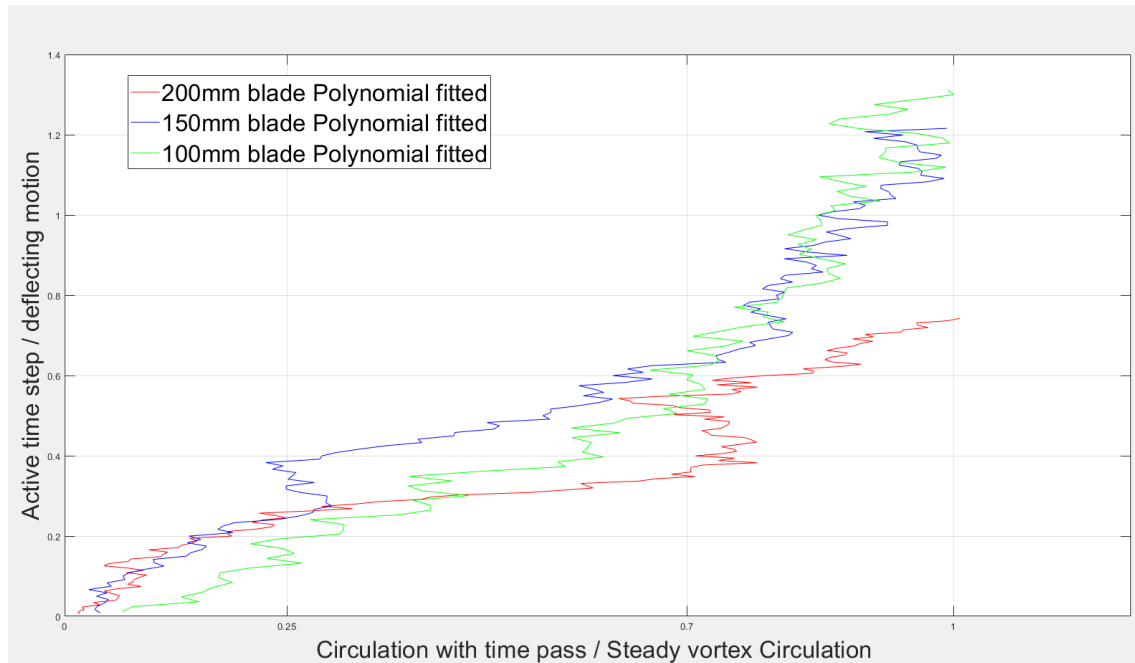


Figure 8.45 Circulation variation of three blades non-dimensional form

Figure 8.45 represents the relation between circulation strength with blade deflection. The y-axis is the $\frac{\text{circulation increasing time}}{\text{blade deflecting time}}$, which related the circulation variation time with the blade deflection time. The X-axis is the ratio of circulation, and 1 means the 100% circulation of the static vortex. The stages are separated by the solid bar on the X-axis at 0.3 (30%), 0.7 (70%) of the circulation.

The trend lines were applied to the data to clearly show the three stages of motion. The first-order polynomial function obtained the trend lines of three stages. The first stage is below 0.3, and the second stage is from 0.3 to 0.7; the final stage is above 0.7, as shown in Figure 8.46.

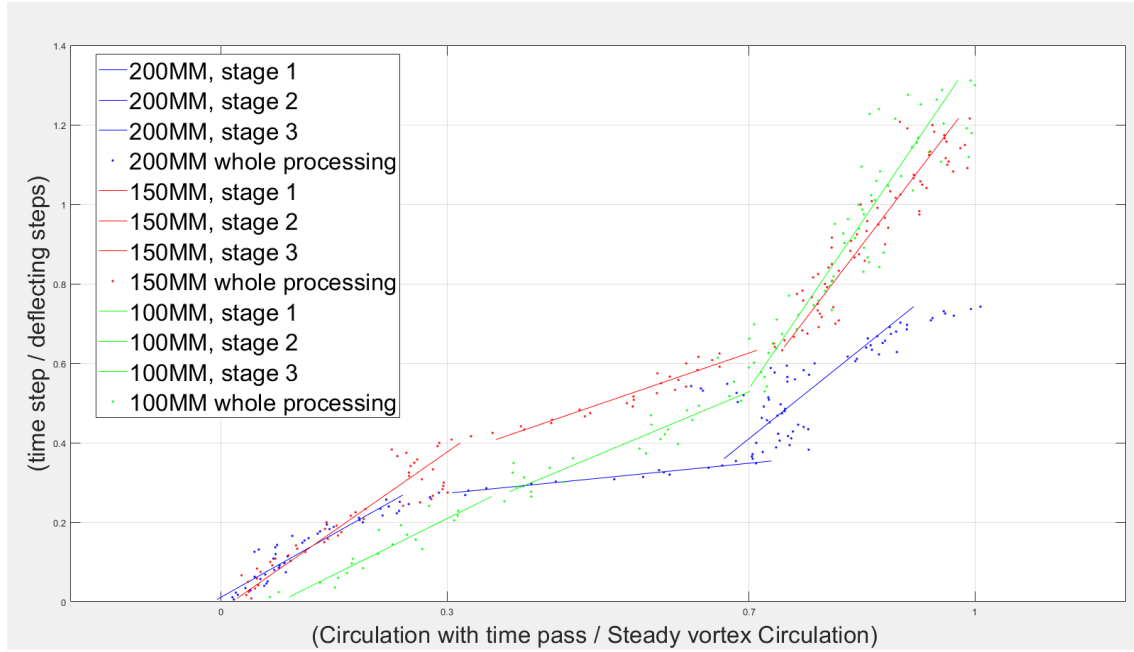


Figure 8.46 The circulation gradients of three blades in deflection

The scatter points are experimental data. The solid lines are the trendlines, which clearly indicate the stages of the vortex forming. The same experimental cases are plotted with the same color. The X-axis is the process ratio (time pass), the Y-axis is the circulation ratio (strength).

In the beginning, the circulation increased slowly, while entering the second stage, it showed the fastest increase in speed. Finally, the circulation improved with the slowest speed at the final stage. The three stages so far exhibited universality across all three cases and were not affected by the current deflecting speeds, regardless of whether the circulation increasing time was shorter or longer than the blade deflecting time. The non-dimensional active process divides the circulation process into three parts, which is similar to the deflection, as shown in Figure 8.47.

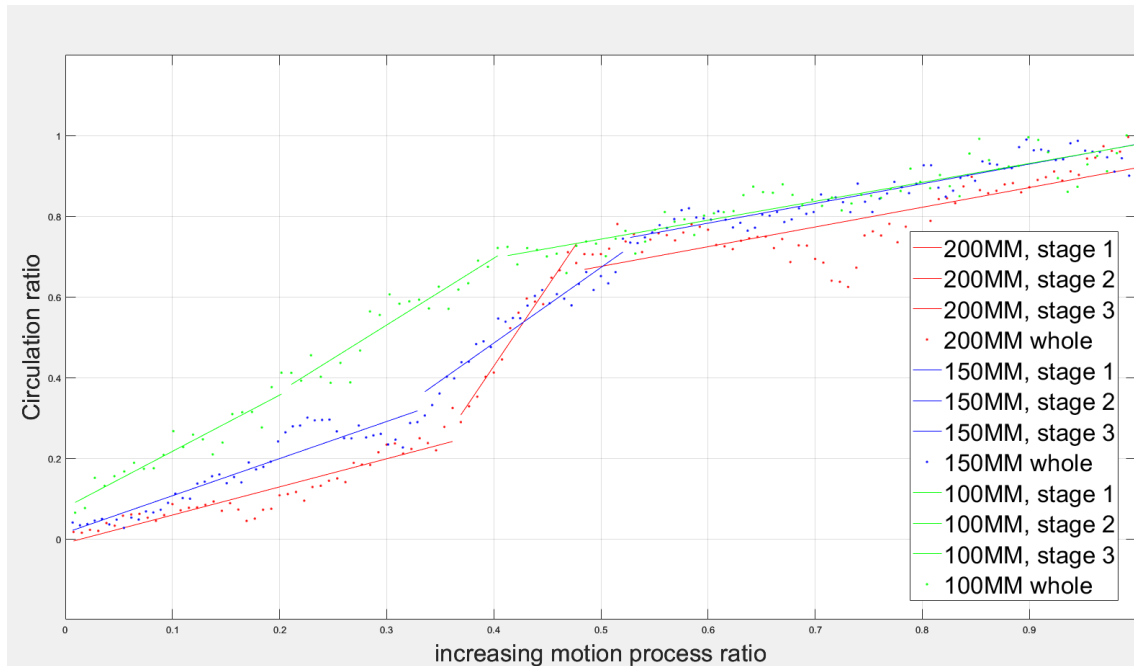


Figure 8.47 The circulation Gradients of three blades in active process.

The colorful points within the plot are experimental data. The solid lines are the trendlines. The same experimental cases are plotted with the same color. The X-axis is the process ratio or progress ratio of the process (time pass), the ratio represents the progress of the active process, 0 is the beginning of the process, 0.5 is 50% progress, and 1 is the finish of the process. Y-axis is the circulation ratio (strength).

The three stages of the active motion are similar to Figure 8.46, but all motions are scaled the same, both on the Y and X-axis. The middle stage also seems to be affected by the blade's height. The intermediate stages of the three cases differ in gradients, with the 200 mm has the highest gradient, followed by the 150 mm case and then 100 mm. The final stages of all three cases are similar; they take half of the time, and the strength is around 70%. The deflection and active motion circulation show a similar result: the clear three stages increase. The difference between stages one and two is not as clear in the 100 mm case as in the 150 mm and 200 mm.

Both analytical and static experimental data compile the quasi-steady motions to predict the active motion. The quasi-steady motion was separated from active

motion into different static stages and compiled. The experimental and analytical prediction results using three blades of experimental data are plotted in Figure 8.48.

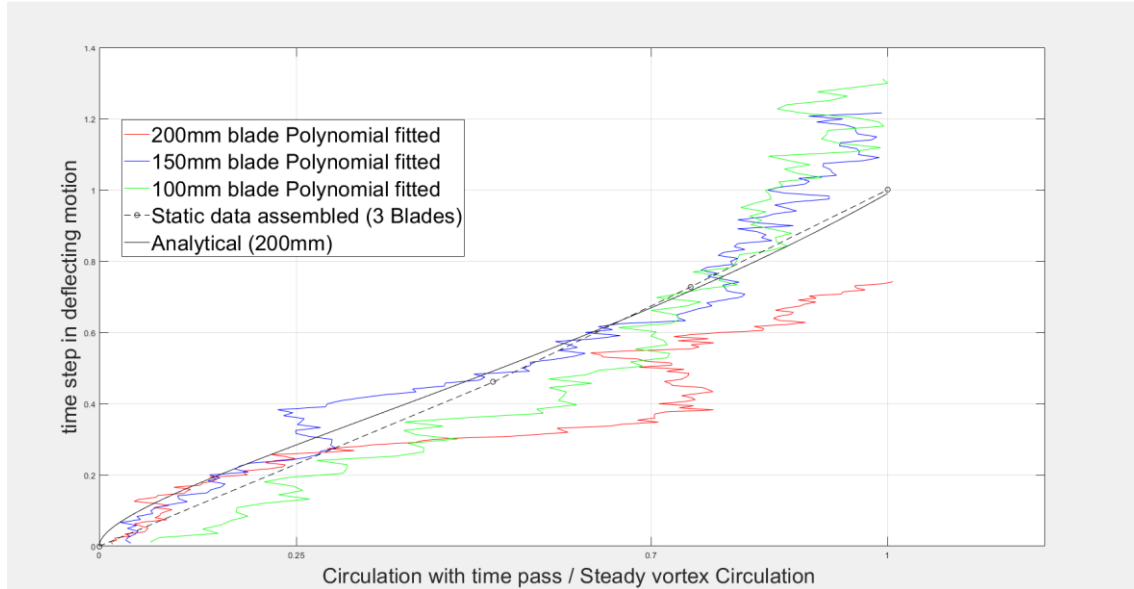


Figure 8.48 Circulation variations of active and assembled prediction

Three points make the dashed line “—” from the steady circulation of three cases, the data points marked by “o.” The solid black line is computed from the height of the blade by the analytical method. The Y-axis is nondimensionalized by the blade deflection, and ‘1’ represents the blade fully deflected. The X-axis is the nondimensional strength of the vortex.

Figure 8.48 shows the difference between quasi-steady circulation variations with the active experimental results. The curves of the solid line show that the circulation did not increase linearly with the boundary and blade height changes. The three stages were unclear. The initial stages between active circulations and analysis plots seem similar, but the middle and final stages differ. All three blades with nondimension circulation were plotted in Figure 8.49 to thoroughly examine the possibility of analytical prediction.

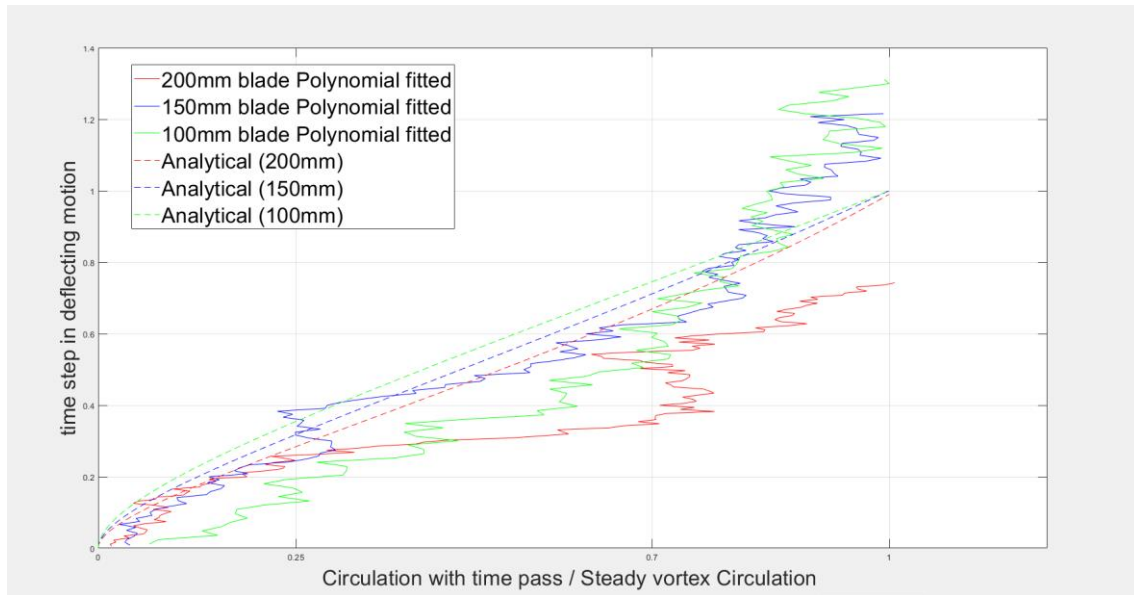


Figure 8.49 The experimental active circulation with analytical predictions

The solid lines are from experimental data. The broken lines are from analytical prediction. The same height of the blade is plot in the same color.

Figure 8.49 shows that the analytical prediction only fits the initial stages, which were between 0 to 30% of the circulations. In the middle stage(0.3 to 0.7) the analytical prediction was slower than the experimental data, while in the final stage(0.7 to 1), the prediction was faster than the experimental data. Figure 8.48 and Figure 8.49 show that, the analytical method and static experimental data cannot predict active circulation under deflecting motion. The result shows that the increase in circulation caused blade deflection, which can not simply simulate the vortex formation recorded in the area. The experimental data, including the vortex movements and growth, were recorded in a fixed location. The vortex forming is a dynamic process, but the analytical model and experimental prediction are all based on static data, which can not predict the dynamics of the vortex.

The restoration of the blade was also subjected to time analysis. The restoration time was longer compared to the deflection time, and both processes were affected by wear and tear. The circulation ratio versus time was as shown in Figure 8.50.

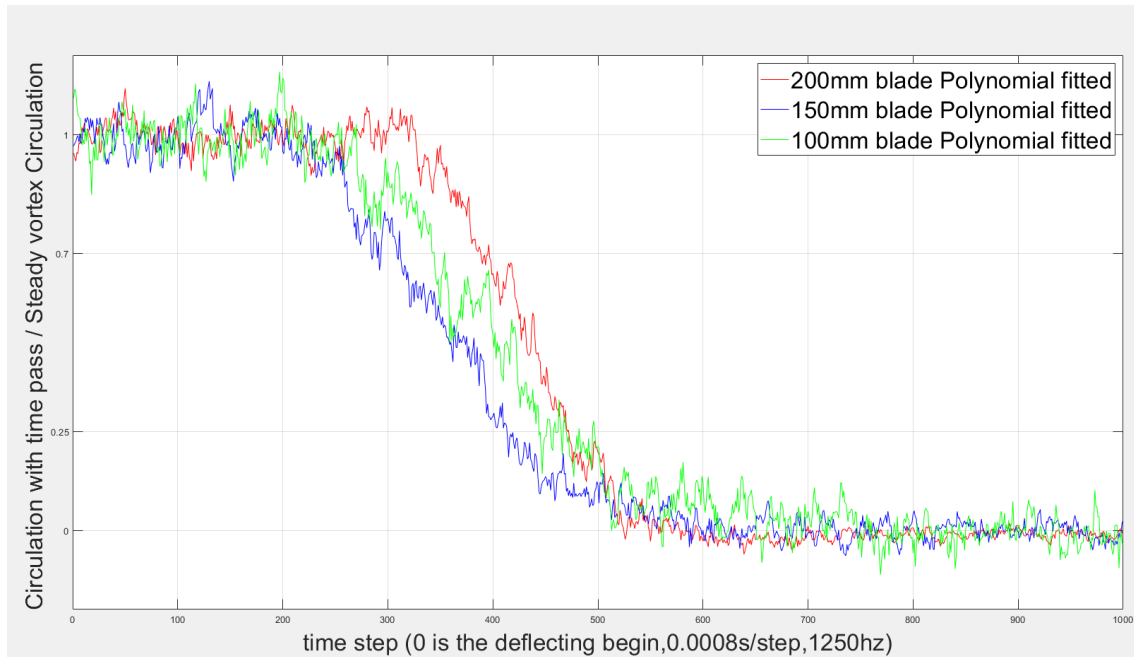


Figure 8.50 The circulation variation of the three-blade restoring condition.

The circulation has been transferred to the ratio. The Red line is the 200 mm case, the Blue line is the 150 mm case, and the green line is the 100 mm case. The angle of attack is 10° , the airspeed is 10m/s.

The restoring plots show the different slope gradients of circulation drops. The sharpest slope corresponds to the highest blade, then is the 100 mm and the 150 mm. The sequence of the gradient is the same as the sequence of experiments, which may imply that mechanical wear and blade bending have affected the data, causing the blade to be restored at different speeds during each run. In all cases, there are two parts in the circulation dropping. In the beginning, the circulation dropped faster than that appeared between 500 and 700 steps.

The slopes were transferred to nondimensional plots to show the circulation variation clearly under restoration. The two key points selected from the restoring processing were the beginning of the circulation drop point, the first one that crosses the error bar, and the finished point, which was the first one that crossed 0, as shown in Figure 8.51.

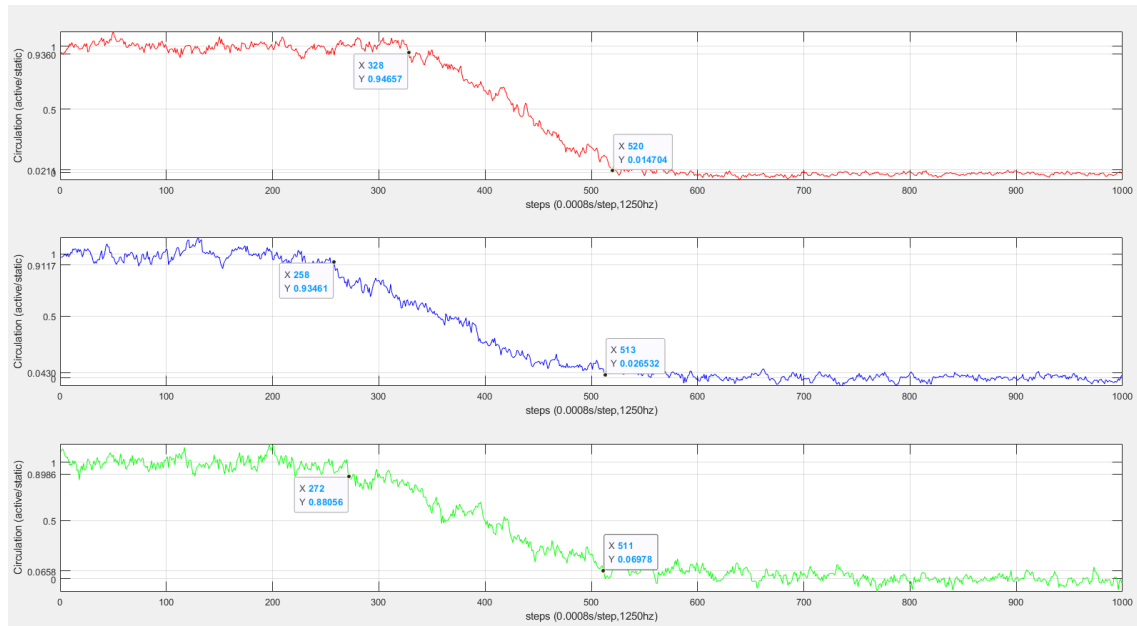


Figure 8.51 Key points of the three blades at restoring action

The Y axis of all three plots is the nondimensional circulation, and the X axis is the time steps. Two key points were marked on the plots. The upper plot is a 200 mm blade, the middle is a 150 mm blade, and the bottom is a 100 mm blade.

After selecting the restoring process from the whole procedure, the time axis was transferred to represent one restoring motion (the time of circulation decreasing divided by the time of blade restoration). The Y-axis represents the circulation ratio from 0 to 1, and 1 indicates the static level of circulation, as shown in Figure 8.52.

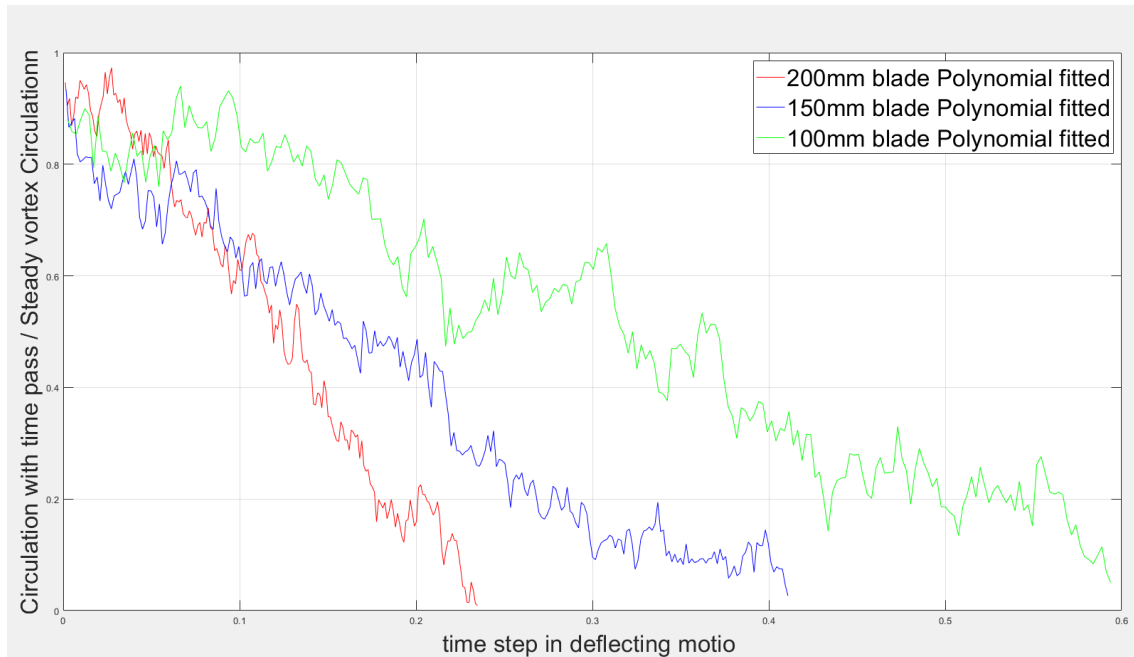


Figure 8.52 The circulation variation of three blades in restoring motion

The changes in the circulation of blade restoration were picked up and converted to the nondimensional domain, as measured by strength and time passed. The time steps have transferred to nondimensional by dividing the restoration time.

The nondimensional plots show the highest blade has the shortest circulation response time; the circulation becomes zero after the blade restores 25%. As the blade height became shorter, the time required for the circulation dropping got longer. In all cases, the circulation drops were faster than when the blade was fully restored. The nondimensional circulation drop shows the time needed for the drop is related to the blade size; the higher the blade, the shorter the time.

The predicted data from the analytic method was plotted with the experimental one, as shown in Figure 8.53.

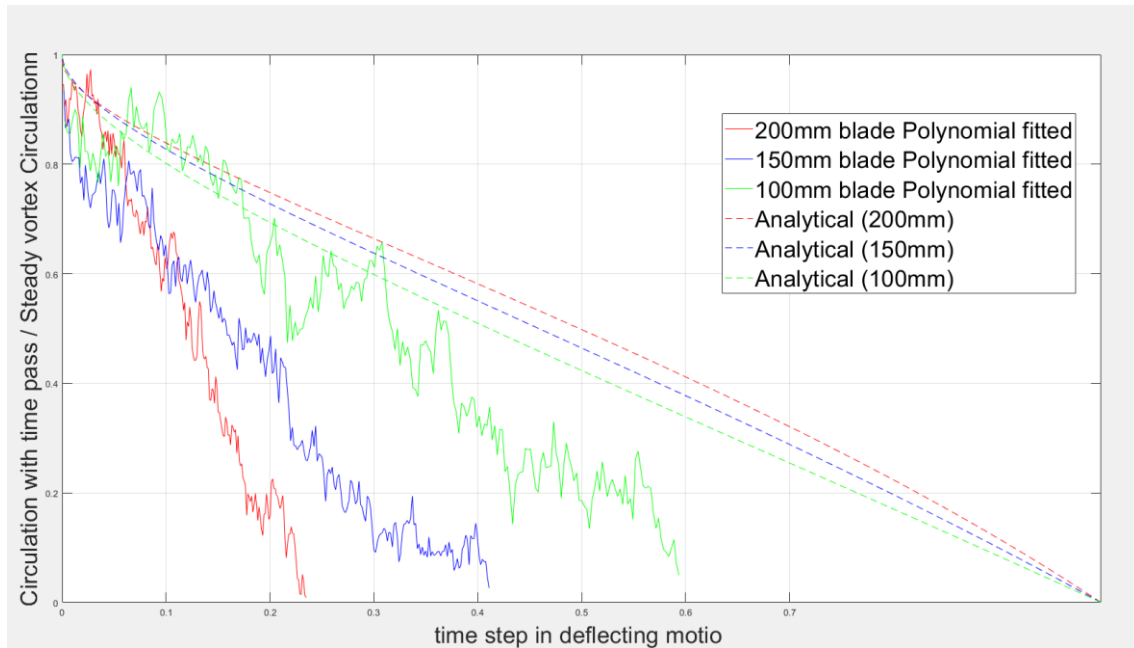


Figure 8.53 The experimental circulation variation with prediction in restoring motion

The angle of attack is 10° , wind speed 10m/s. The blades of the same size are plotted in the same color. The experimental data is solid, and the dashed lines are the analytical results.

Figure 8.53 shows that the restoration prediction was not possible with the current analytical method. The reason the prediction is not consistent with the experimental data is similar to that of the previous blade deflection simulation in the current chapter. The current methods can not simulate the vortex movements. The vortex moves out of the recording area, leading to the circulation decrease to zero. The analytical method did not simulate the vortex in the recording area but the vortex downstream.

The blade deflection and the vortex formation are dynamic processes, while the analytical model of the vortex was based only on the static data instead of the recording data. To better understand the behavior of the vortex forming within the area, for example, the vortex moving into the recording area or a vortex forming in the area. Further analysis of the vortex motion, such as the vorticity and velocity contour plots, is needed.

8.7.3 Peak vorticity

The peak vorticity is one of the key parameters of the vortex. It indicates the concentration of the vortex. In the deflection condition, both circulation and peak vorticity increase in all three cases were plotted, as shown in Figure 8.54.

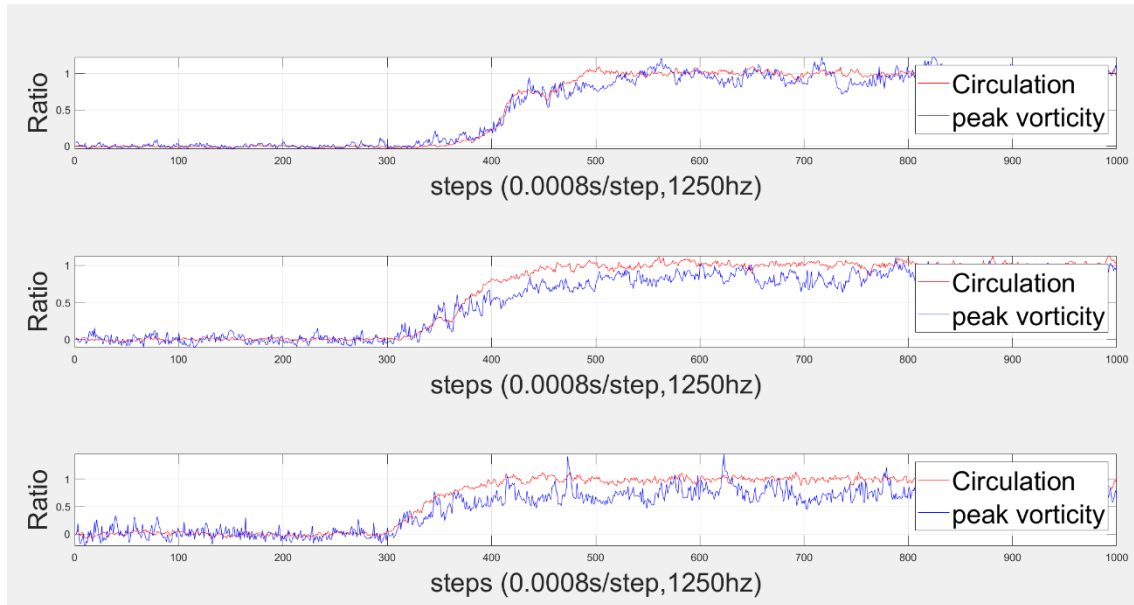


Figure 8.54 The ratio of circulation and peak vorticity of deflection

Figure 8.54 shows the 200mm blade case, the middle plot is the 150 mm blade case, and the bottom is the 100 mm blade. The blue lines represent the delta peak vorticities ratio, and the red lines represent the circulation ratio from the no-vortex to the static vortex condition. The Y-axis of all three plots is the strength ratio, and the X-axis is the time domain..

The peak vorticities and circulations in all three cases are positively related. As the strength of the vortex increases, the peak vorticity also increases. The gradients of the peak vorticity also showed some differences compared to the circulation gradients. The increased motion of peak vorticity was selected from the entire process. The starting points are the first points that cross the peak vorticity's error bar under clean wind conditions, and the ending points are the first points that reach the static vortex condition. Those points are shown in Figure 8.55.

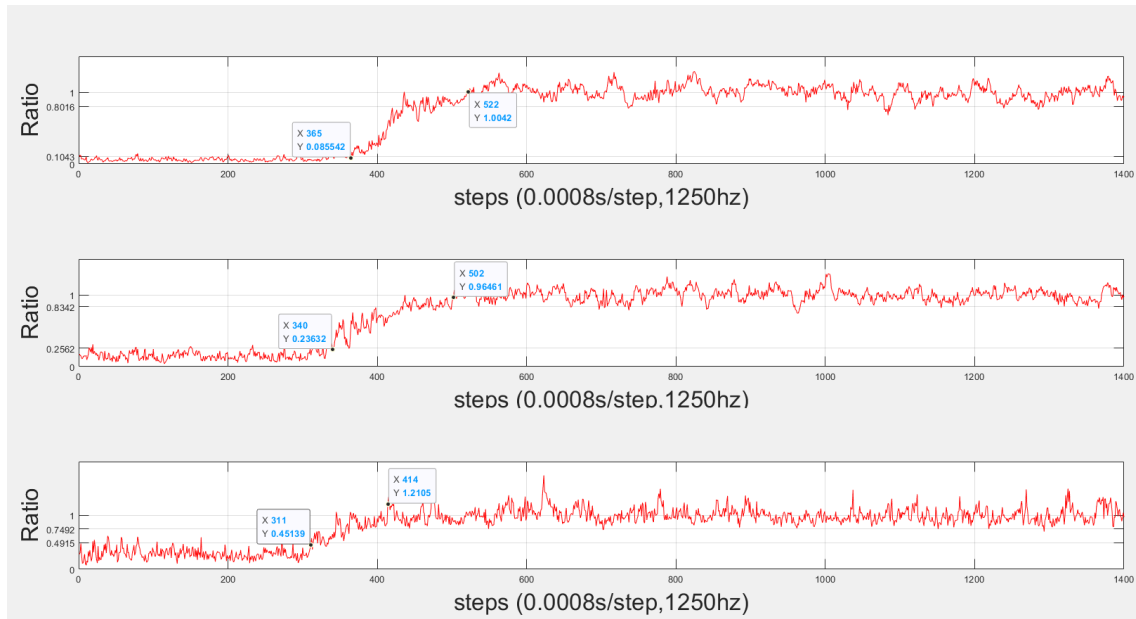


Figure 8.55 The ratio of circulation and peak vorticity of deflection

Figure 8.55 shows the 200mm blade case, the middle plot is the 150 mm blade case, and the bottom one is the 100 mm blade. The vorticity increase part's beginning and ending points (increase motion) were marked.

The increased motions of peak vorticity were selected from the whole motion, and both strength and time domains were transferred to nondimensional. The result is shown in Figure 8.56.

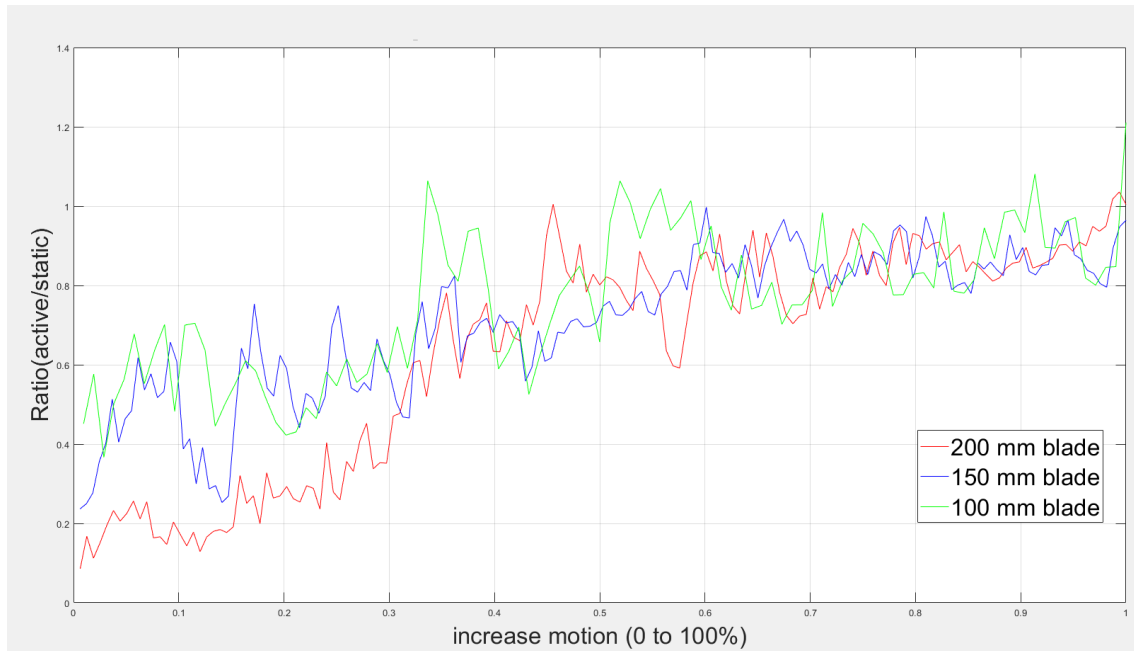


Figure 8.56 The peak vorticity increases in all three cases

The red line is the 200 mm blade, the blue line is the 150 mm blade, and the green is the 100 mm blade. The X-axis is the ratio of motion, which indicates the progress of the vorticity-increasing motion. 0 is the beginning, 0.5 is the half of the process, and 1 is the finish of the vorticity increase. The Y-axis is the ratio of strength, which is from no vorticity to the static level, 0 to 1.

The X-axis in Figure 8.56 was computed from the time steps of the increased motion divided by the time taken of the motion, which transforms the motion into nondimensional time phases. The turbulence of the boundary layer causes the non-zero beginning of the peak vorticities. The plot illustrates the similarity of all peak vorticities; the initial and middle stages oscillated and exhibited high gradient increases. All lines smoothed after reaching 50% of the motion and increased at a lower speed. The motion and development of the vortex cause the increase in similarities.

The deflection speeds of the three cases differed; cases 200 mm had the fastest deflection speed, while cases 100 mm and 150 mm had similar speeds. The peak vorticities during deflection were shown in Figure 8.57. the X-axis was transferred to the deflecting motion.

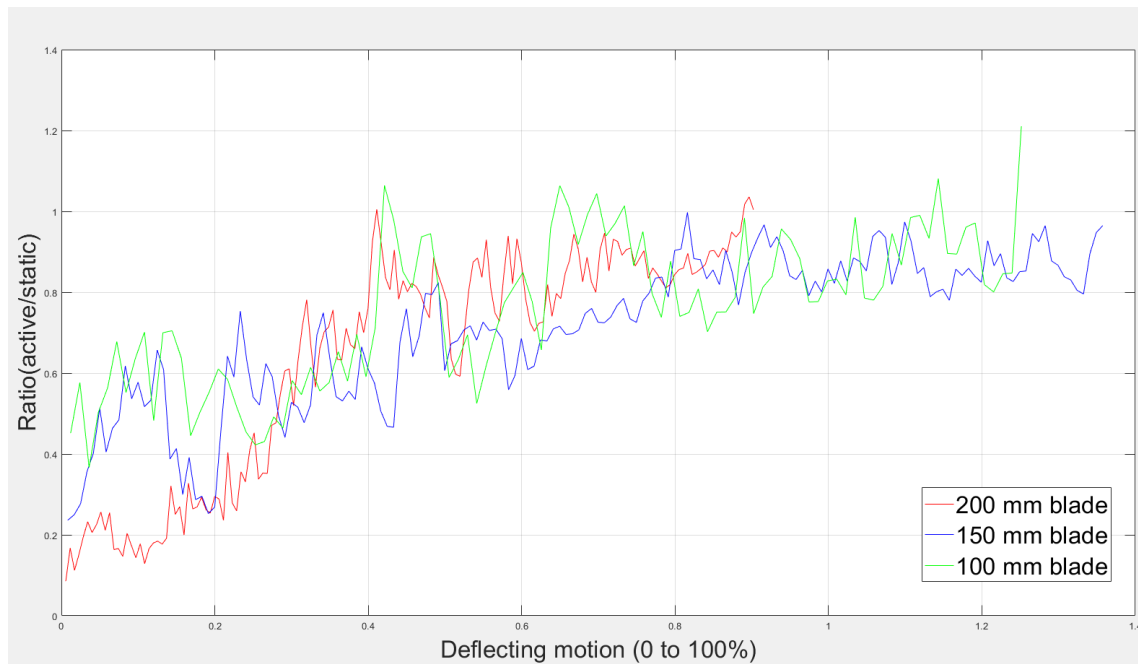


Figure 8.57 The ratio of peak vorticities in active motion

The X-axis is the deflecting motion. The Y-axis is the ratio of vorticity. The peak vorticity response time showed a pattern similar to circulation. The peak vorticity at 200 mm case reached the steady motion faster than the blade was fully deflected. In the cases 150 mm and 100 mm, the increasing process took longer to reach steady motion than the fully deflected blade.

The peak vorticity at initial restoration shows a late response, even an increase. This behavior is most clear at 200 mm and 150 mm, while in 100 mm cases, it is not as clear as the taller blades. The peak vorticity and circulation in the restoration of the blade were shown in Figure 8.58.

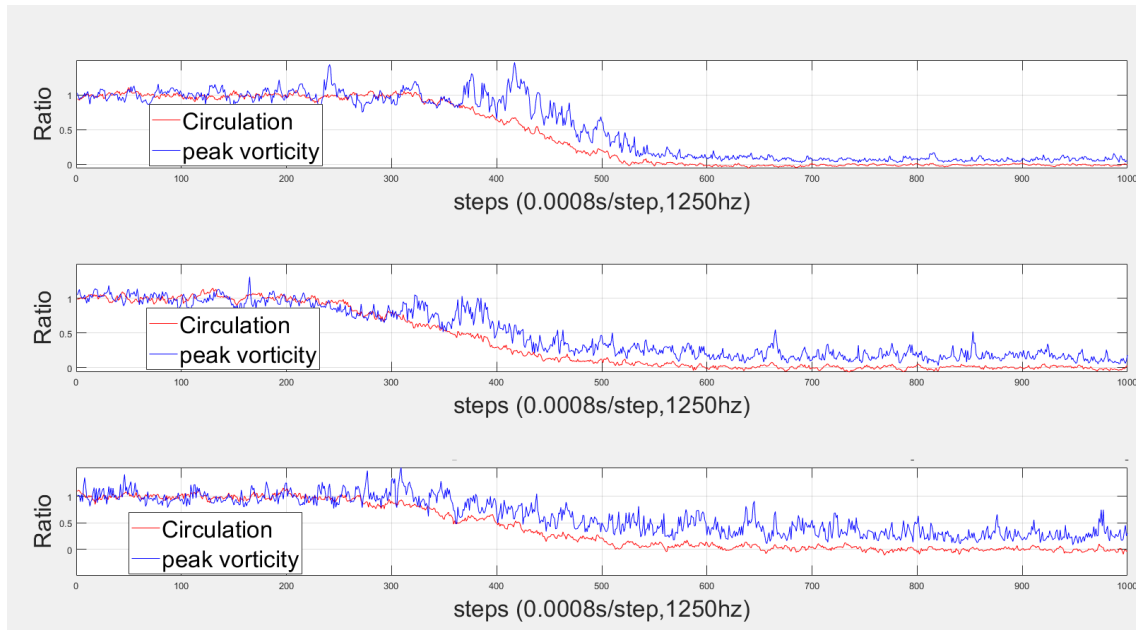


Figure 8.58. The ratio of the circulation and peak vorticity of restoration.

The Y-axis is the strength of both circulation and peak vorticity compared to the static condition. The X-axis is the time passed in steps. The peak vorticity in all three cases dropped as the circulation decreased. In the cases of the 200 mm and 150 mm blades, the peak vorticity had a strong oscillation (overshoot) and a late response after the circulation began to decrease. As the blade height was reduced, the oscillation weakened. In the 100 mm case, the oscillation became indiscernible. In the case of 100 mm, the peak vorticity seemed to take longer to decrease than in the other two cases.

The active motion of peak vorticity was picked up from the entire motion. The presence of noise in the data made both the beginning and ending points hard to identify. The key points are shown in Figure 8.59.

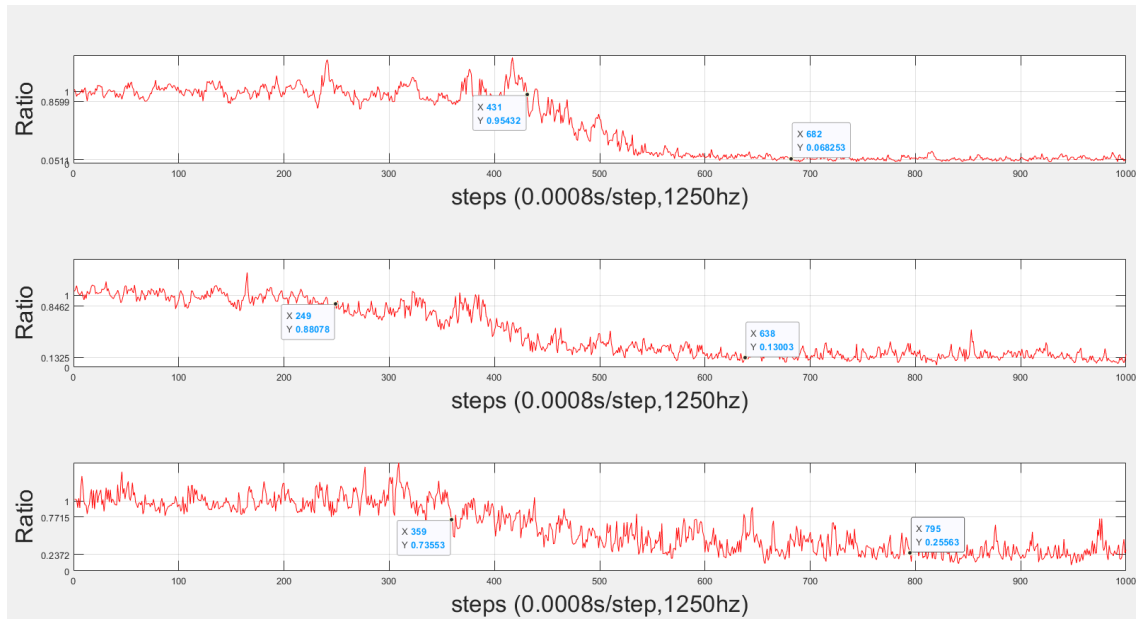


Figure 8.59 The ratio of peak vorticity in restoration

The upper plot depicts the 200 mm blade case. The middle plot is the 150 mm, and the bottom plot is the 100 mm case.

The active motions of the peak vorticity drop took longer than those in the circulation case. The nondimensional active motion is shown in Figure 8.60. The time steps were converted to the ratio of the dropping motion process.

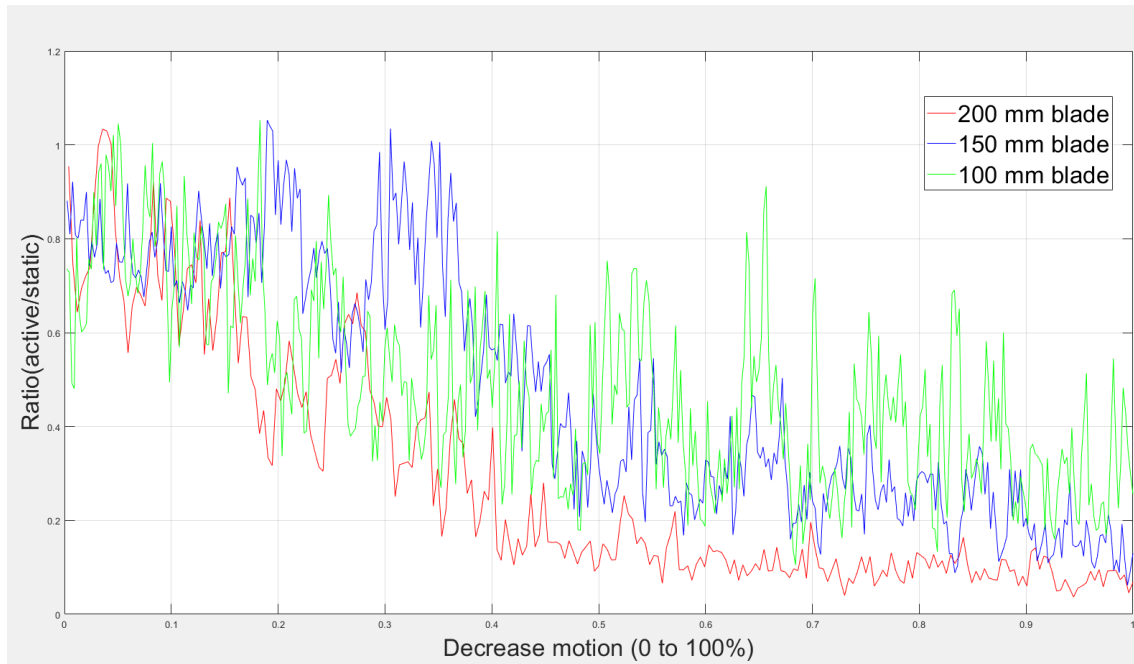


Figure 8.60 Ratio of peak vorticities in active motion

The X-axis is the decreased motion of the peak vorticity. The Y-axis is the ratio of vorticity.

The peak vorticity oscillated at the initial decrease stage in both 150 mm and 200 mm. There were two stages of the peak vorticity drops in both 150 mm and 200 mm cases (blue and red lines in Figure 8.60). The peak vorticity began to fall slower in the latter half of the whole motion. The blade restoration with peak vorticity drops is shown in Figure 8.61.

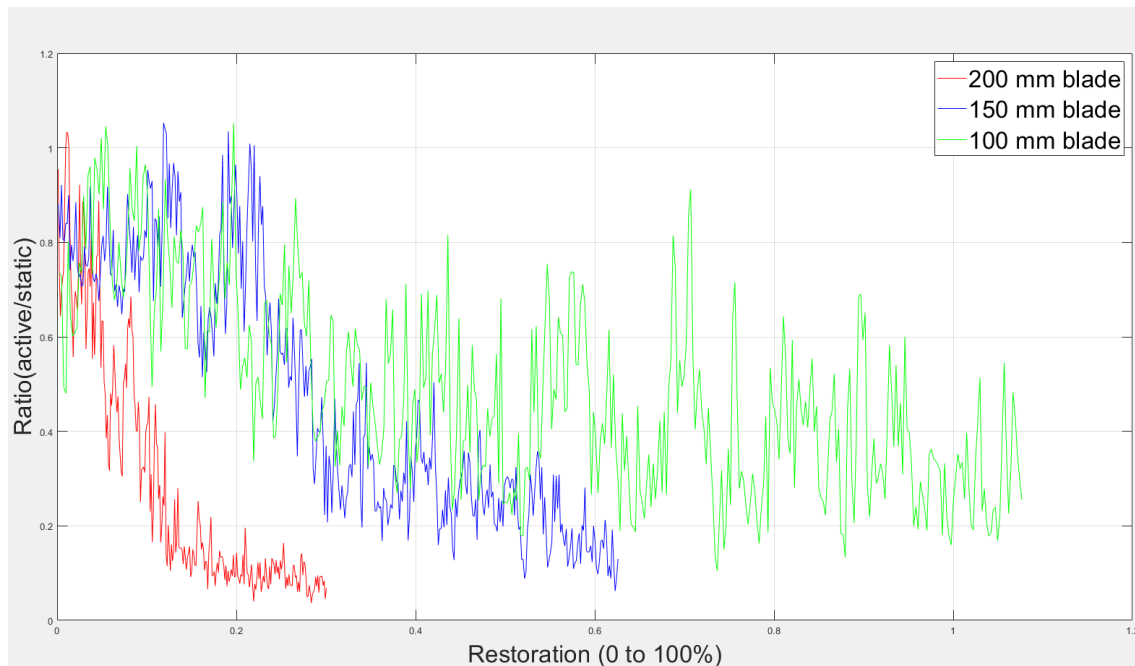


Figure 8.61 The ratio of peak vorticity in restoration

The X-axis is the nondimensional time pass of the blade restoration. The Y-axis is the strength ratio.

The strength in 200 mm and 150 mm cases vanished before the blade was fully restored and had an oscillation at the initial decrease stage. The peak vorticity at 100 mm fully decreased after the blade was restored, and had a stronger noise than the rest of the cases. The result shows that the 200mm blade has the peak vorticity-dropping process, and the 200mm blade has a faster restoration speed.

The faster-dropping motion of the taller blade is due to being involved two time periods in the computation of motions. The first time period is when the blade goes down to the bottom surface from being deflected; a taller blade takes a longer time. The second period is the vorticity drop to zero; the drop is affected by the time the vortex moves out of the recording area, and the size of the areas are the same.

8.7.4 Vorticity Contours

The vorticity counterplot is one of the clearest ways to show the vortex's location and structure in the current project. The vorticity comes from the difference in

velocity within the vortex. The experimental and polynomial vorticity of the 200 mm blades are as shown in Figure 8.62 and Figure 8.63. The contour of 150 mm and 100mm are included in Appendix C.

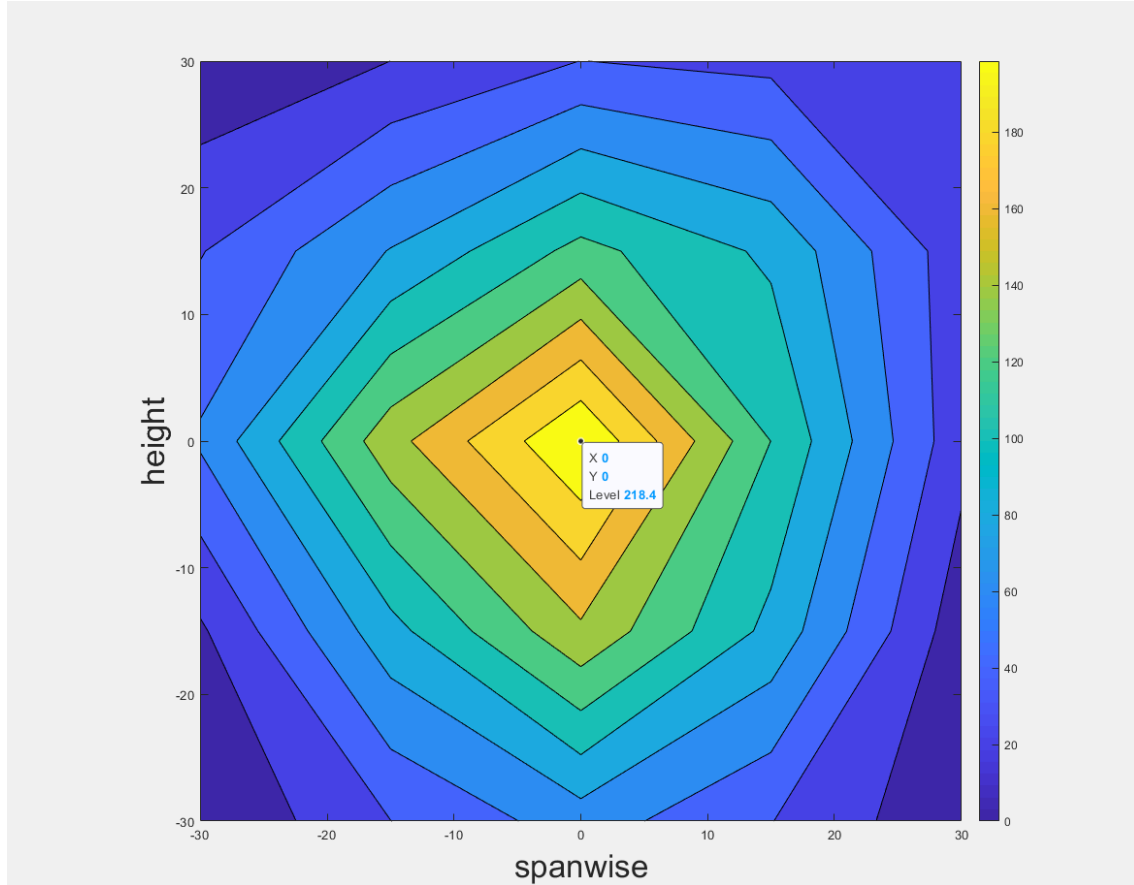


Figure 8.62. The vorticity contour plots of 200mm blade.

The spanwise is Y-direction, vertical is Z-direction. The peak vorticity have been marked within the plots, units: s^{-1} . The vortex is in an averaged static condition from experimental data.

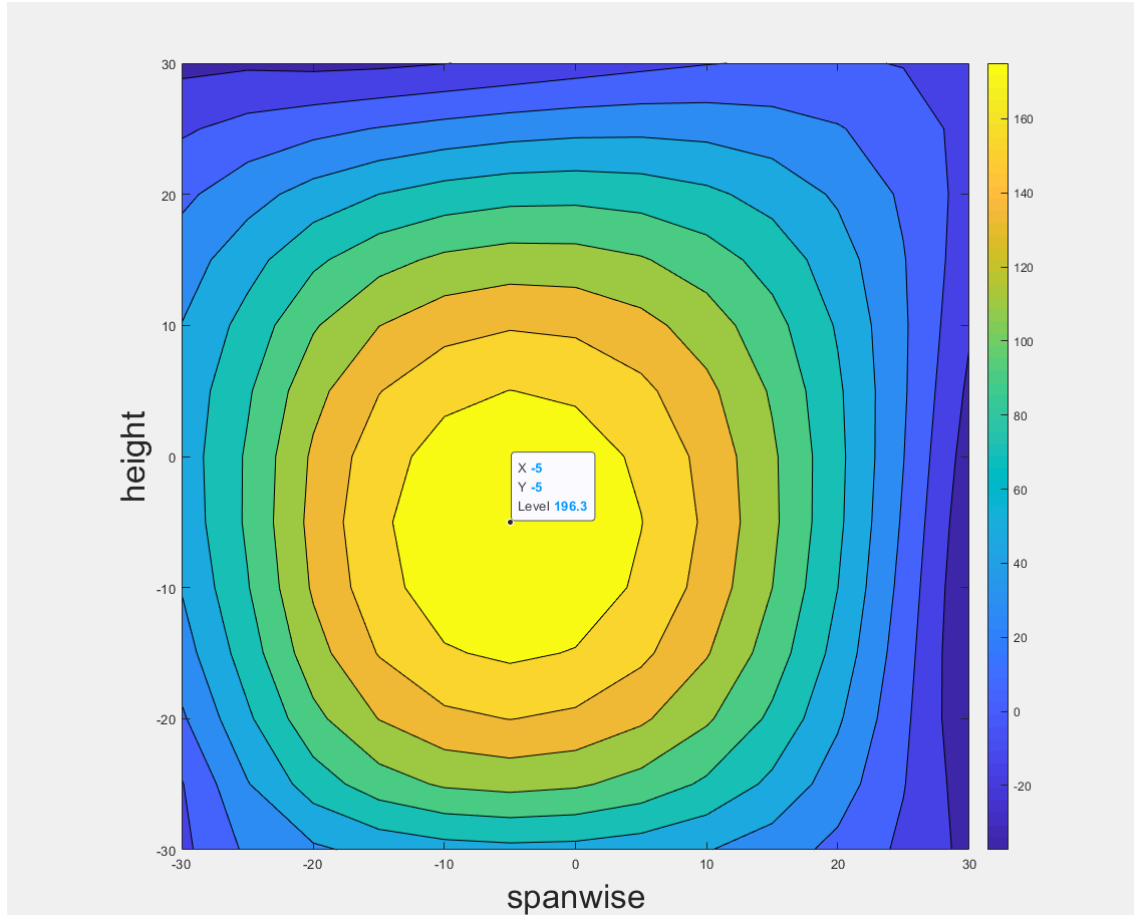


Figure 8.63. The vorticity contour plots of all three cases.

The peak vorticity has been marked within the plots, units: s^{-1} . The spanwise is Y-direction, vertical is Z-direction. The vortex is in an average static condition. The polynomial function has emphasized the vortex based on experimental data.

From the plots of the vorticities in Figure 6.60, the shape of the static vortex was distinct. The peak vorticities were marked in each condition. The peak vorticities were different between pure experimental data and polynomial-fitted data due to the order of the polynomial functions.

The vorticity contours also show three parts similar to the three-stage circulation increase, but the contour plots display limited connection due to the limited numbers. Stage one is the wake in the recording area. In stage two, the vortex enters the recording area. In stage three, the dynamic vortex reaches the static vortex position and then grows to the static strength. The vorticity contours with blade deflection for 200mm blades are shown in Figure 8.64.

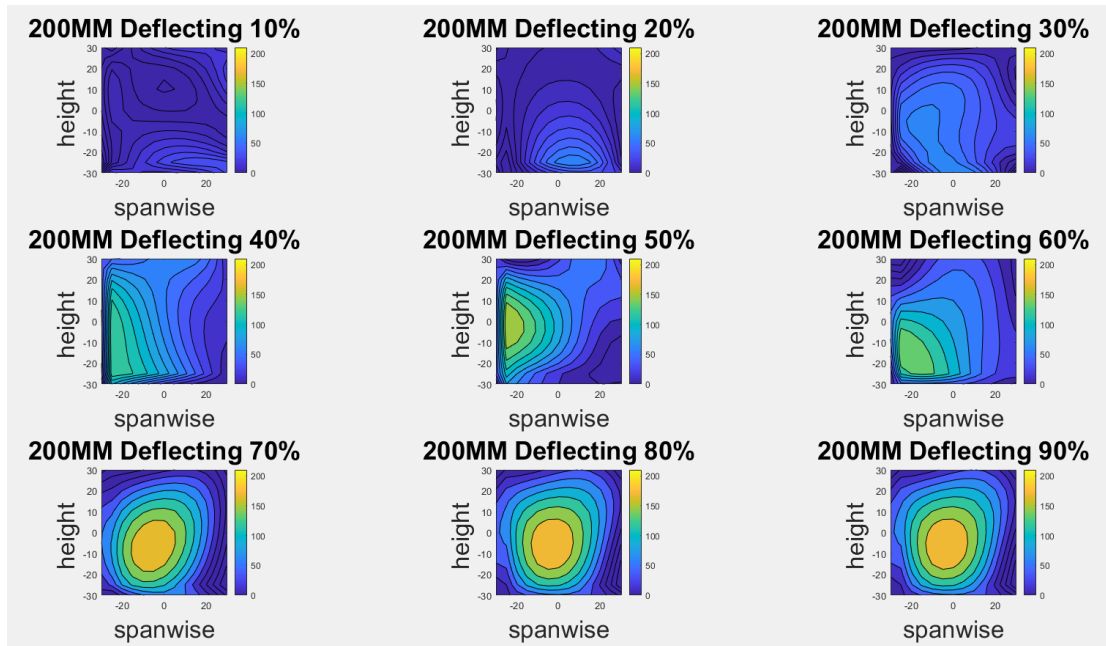


Figure 8.64 Vorticity of the deflecting 200mm blade

The spanwise is Y-direction, vertical is Z-direction. The percentage is about the circulation increasing motion.

Figure 8.64 shows “vortex forming” within the recording area under deflecting motion. The bright color shows the high vorticity area and the vortex's shape.

The vortex appears at the bottom of the measuring area and then covers the whole area at 30% of circulation increase motion and is located at the left-hand side until 70% of deflection. The shape of the vortex at deflection between 40% to 60% was not clear due to the unsteady active motion. Appendix C contains the contour plot of the 150 mm and 100 mm.

Despite various changes and challenges, such as blade height alterations (200,150,100 mm), rubber band decay, equipment fatigue, and increased friction, the deflection motion involving three blades exhibited some consistent behavior. At the beginning of all three stages, a low vorticity area appeared at the bottom of the recording area. In the middle stages of the cases 150 mm and 200 mm, the shape of vorticity covered half or more than half of the area, and the middle vorticity area in each plot was located on the left-hand side. At the final stage, the vortex is in the static position with a similar static size, but the strength continues

to increase. Due to the weakness of the vortex generated by the 100 mm blade, the vorticity shape was not clear enough to show more information about the middle and final stages.

A similar plotting method of cross-sectional velocity was applied to the restoring motion. Still, the percentage of circulation drops was selected as the X-axis due to the short nondimensional period. The stages and circulation drop were shown in Figure 8.65. The vorticity variation of the 200mm case is shown in Figure 8.66.

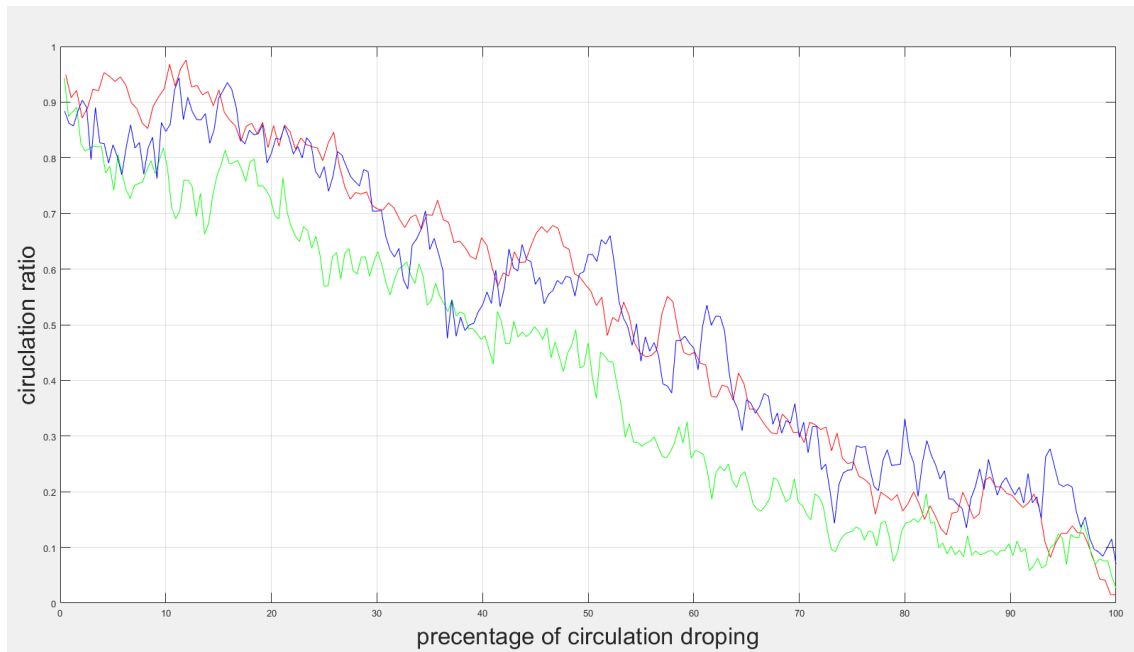


Figure 8.65 Circulation variation with the ratio of the process of decreasing

The X-axis is the percentage of the circulation dropping processing. On the X-axis, each ratio is marked by a grid. The circulations of the three blades were transferred to nondimensional conditions by dividing the steady vortex circulation.

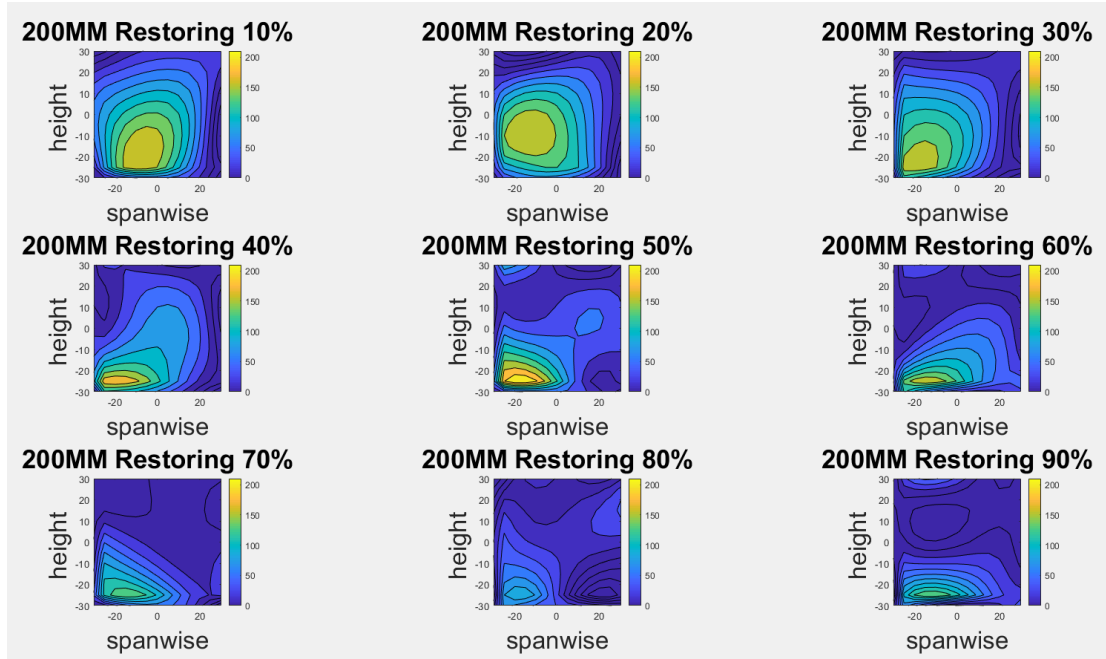


Figure 8.66 The vorticity variation of the 200mm blade restoring

The spanwise is Y-direction, vertical is Z-direction. The vorticity variation within the restoring motion has been separated into nine stages. The space between each stage is 10%. Within the plots, the bright color is the high vorticity area.

Figure 8.66 shows the vorticity area variation during a 200mm blade restoration. The vorticity circle moved to the bottom left corner in the first stage. At the middle stages, from 40% to 60% restoration, the high vorticity (indicated by bright colors) only exists at the bottom left-hand corner. The high vorticity area disappeared from 70% to 90% restoration; only the middle strengthened area stayed in the bottom left corner.

From the vorticity plot of the deflection, the vortex with the lower vorticity entered the measuring area at the bottom left corner, and grew in size and strength, then became a steady vortex. During the restoring motion of the blade (200 mm blade), the vorticity circle went to the bottom left-hand corner, where the circle first appeared, then became weaker and disappeared. Additionally, in the cases of the 150mm and 100mm blades, the vorticity circle first appears in the bottom's middle stages and later exits from the bottom region after completing its motion.

8.7.5 Spanwise tangential velocity

The tangential velocities were calculated to better understand the vortex forming mechanics. The spanwise location was chosen at the center of the recording area with the horizontal direction, which was the center of the vortex, as shown in Figure 8.67.

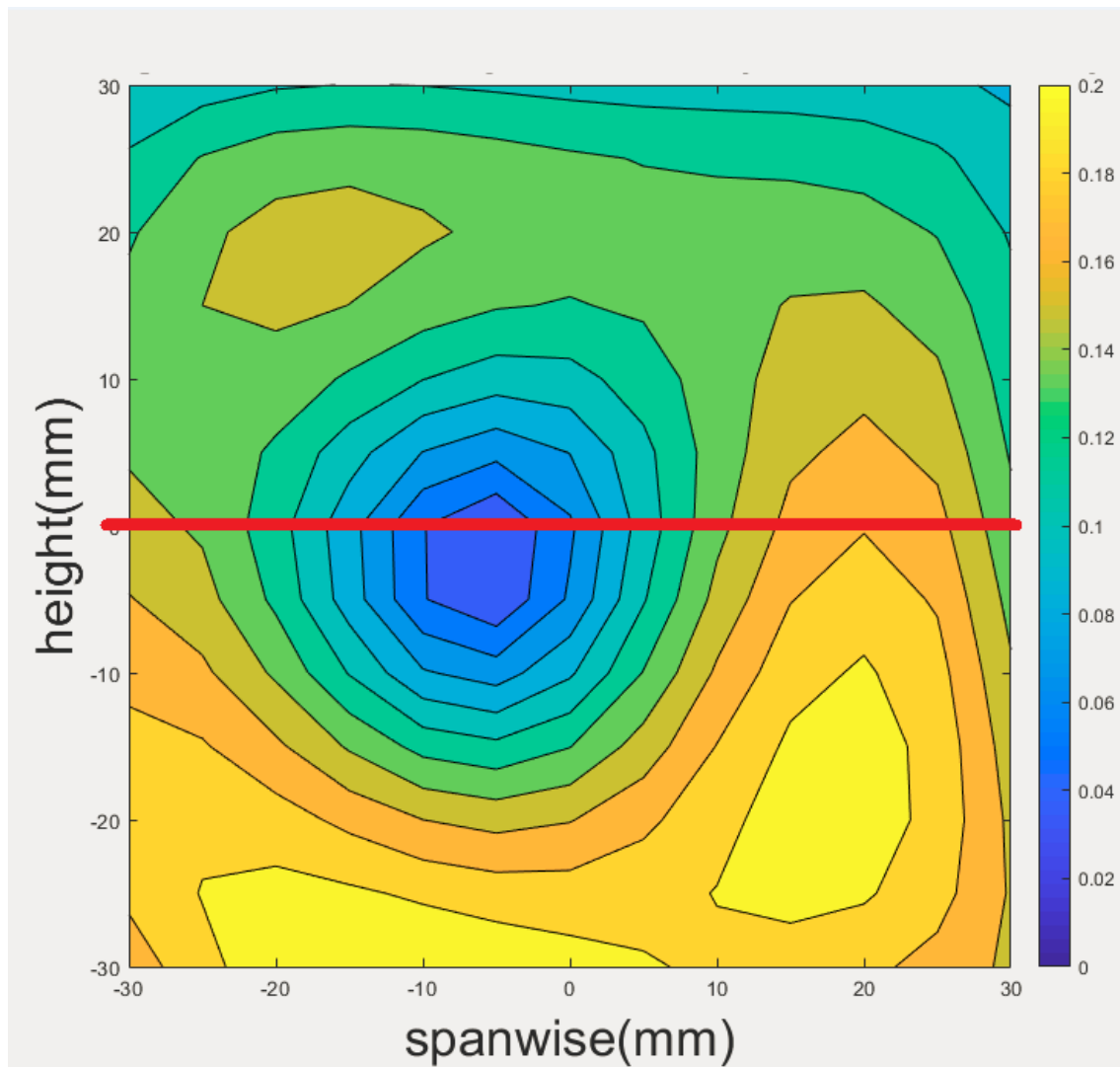


Figure 8.67 The location of the spanwise tangential velocity

The plot is the vorticity counter of the 200 mm blade condition. The red line has marked the center of the vortex.

The static spanwise tangential velocities were computed from the average velocity. The results of all three cases are shown in Figure 8.68 and Figure 8.69.

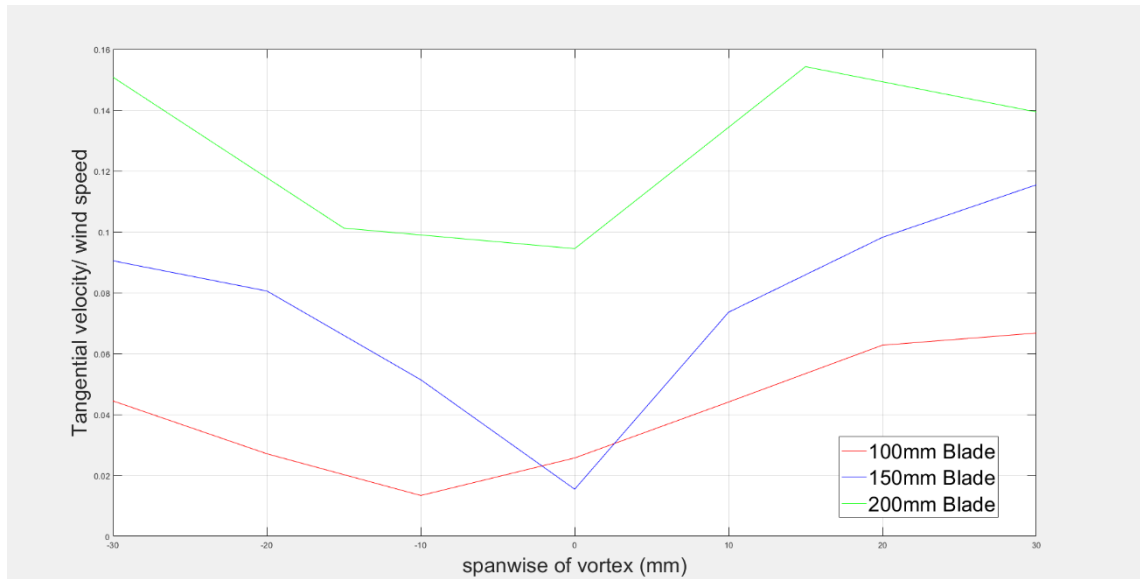


Figure 8.68 Experimental tangential static velocities with the blade height variations

The X-axis is the spanwise diameter of the recording area. The Y-axis is the velocity ratio of the radius velocity, which was computed from tangential velocity divided by wind speed.

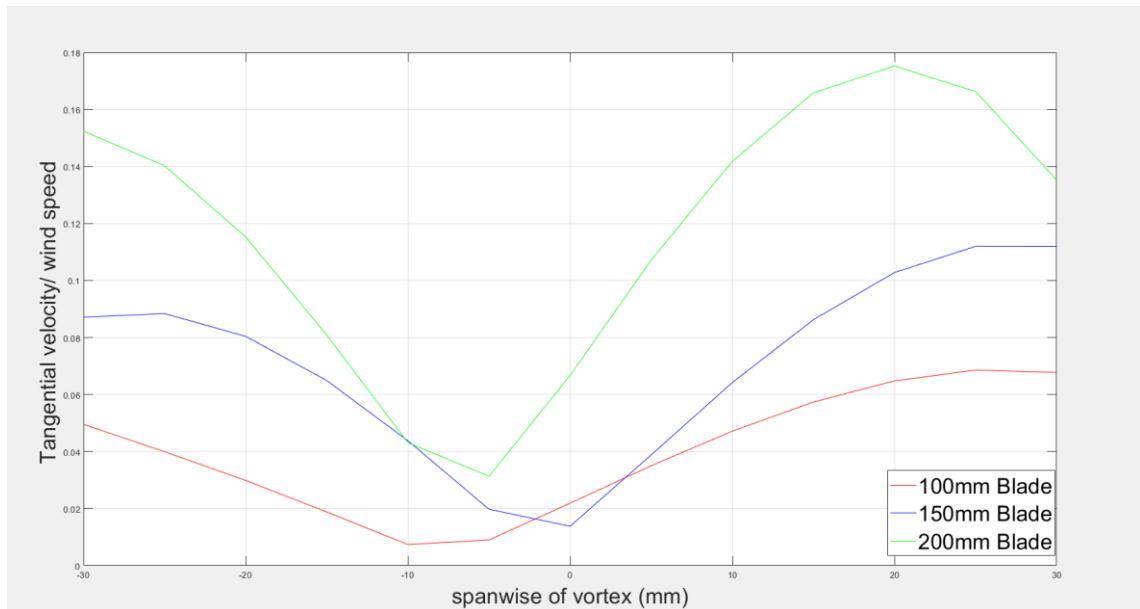


Figure 8.69 Polynomial fitted tangential static velocities with the blade height variations

The X-axis is the spanwise diameter of the recording area. The Y-axis is the velocity ratio of the radius velocity. The velocity ratio is computed from tangential velocity divided by wind speed.

Figure 8.68 and Figure 8.69 both showed the typical tangential velocity at the vortex cross-section. The height of the blades corresponds to the magnitude of tangential velocities. The 200mm blade had the highest tangential velocity, followed by the 150 mm, and 100 mm.

The flow structure inside the recording area was simplified to the maximum and minimum velocities and locations. The tangential velocity was plotted against time based on the circulation-forming process, which could help show the vortex-forming process more straightforwardly. The speeds and locations at the maximum and minimum velocities (as marked in red and black in Figure 8.70) were selected from the tangential velocity on the horizontal center of the vortex, as shown in Figure 8.70.

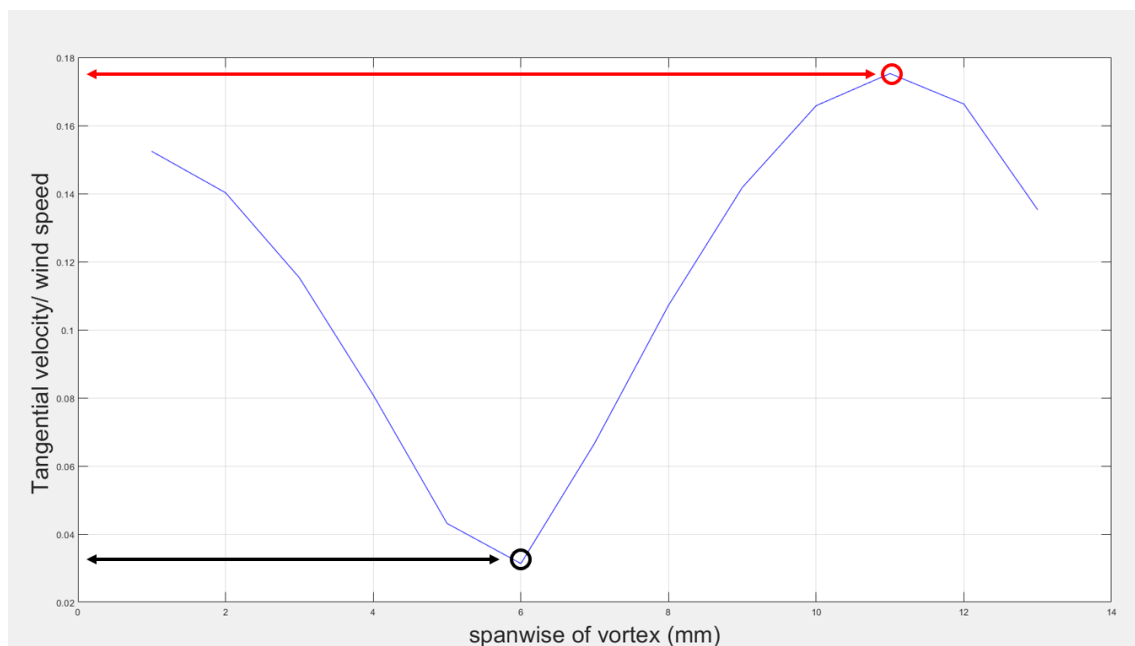


Figure 8.70 The definition of the Max and Min speeds and locations within spanwise radius velocity

Circles mark the maximum speed and the minimum speed. The two locations were the distance between two peak points and the 0 on X-axis.

Both the maximum and minimum tangential data of velocities and their corresponding locations of velocities were plotted to indicate the variation of the vortex structure. The results of the case 100 mm are as shown in Figure 8.71.

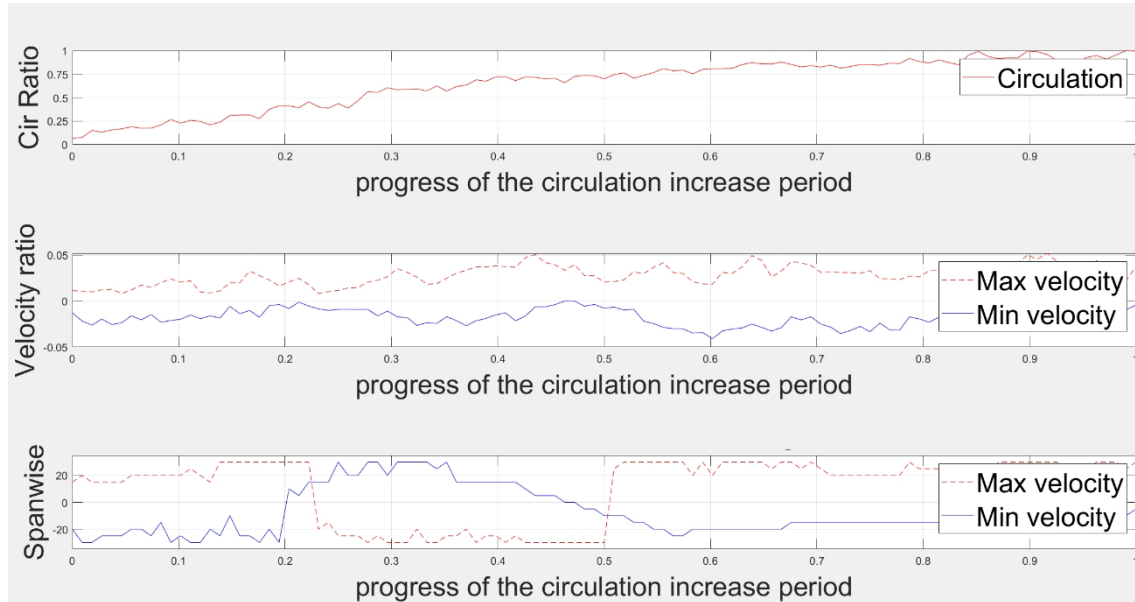


Figure 8.71 The Max & Min tangential velocities with corresponding locations vary within the vortex forming

The experiment is under the 100mm blade condition. The top plot depicts the circulation variations, and the middle one displays the maximum and minimum points of the radial velocity with time passing (the positive and negative values indicate the higher or lower than the average tangential velocity at the vortex core; it is only for indication the maximum and minimum velocity). The bottom plot illustrates the variations of two key points over time, where -30 represents the left-hand side of the recording area, and 30 represents the right-hand side of the recording area.

Figure 8.71 depicts the cross-section structure variations against time. The circulation increases smoothly. Still, both maximum and minimum radius velocities also increase with oscillations. The biggest oscillations occur at 50% of circulation increasing motion (0.5 on the X-axis). However, the shock of velocities did not cause any circulation changes. At 0 on the X-axis, the circulation increases, and both key velocities also increase. However, at the beginning of

the active processing, the two points switch locations 3 times within two positions (location -30 and location 30 in the Y axis of the bottom plot in Figure 8.71, -30 is the first point on the left-hand side of the vortex in spanwise, 30 is a first right-hand side point, the unite is mm). The changes are clearly visible at the bottom plot. The plots of the 150 mm and 200 mm cases in nondimensional form and all three cases in the time domain are included in Appendix C.

The locations of the two points show the flow structure of the vortex forming within the recording area. In the beginning, the wake appears to cover the recording area fully, and both maximum and minimum speeds increase at both the left and right ends of the area (locations -30 and 30 in the bottom plot of Figure 8.71). As the circulation increases, the flow structure changes in the measuring area due to the vortex moving in and leading to locations of both maximum and minimum velocity changes. This is shown in the red line and blue line crossing each other twice in the bottom plot in Figure 8.71.

The tangential velocity studied the restoration of the blade. Due to the short nondimensional motion of circulation drop, the spanwise radius velocities were plotted against time only. The sections of the restoring motion are as shown in Figure 8.72. The sections in Figure 8.72 cover both static and active parts. The two static parts at the beginning and the end represent the static vortex condition and the clean field. The active part represents the circulation decrease.

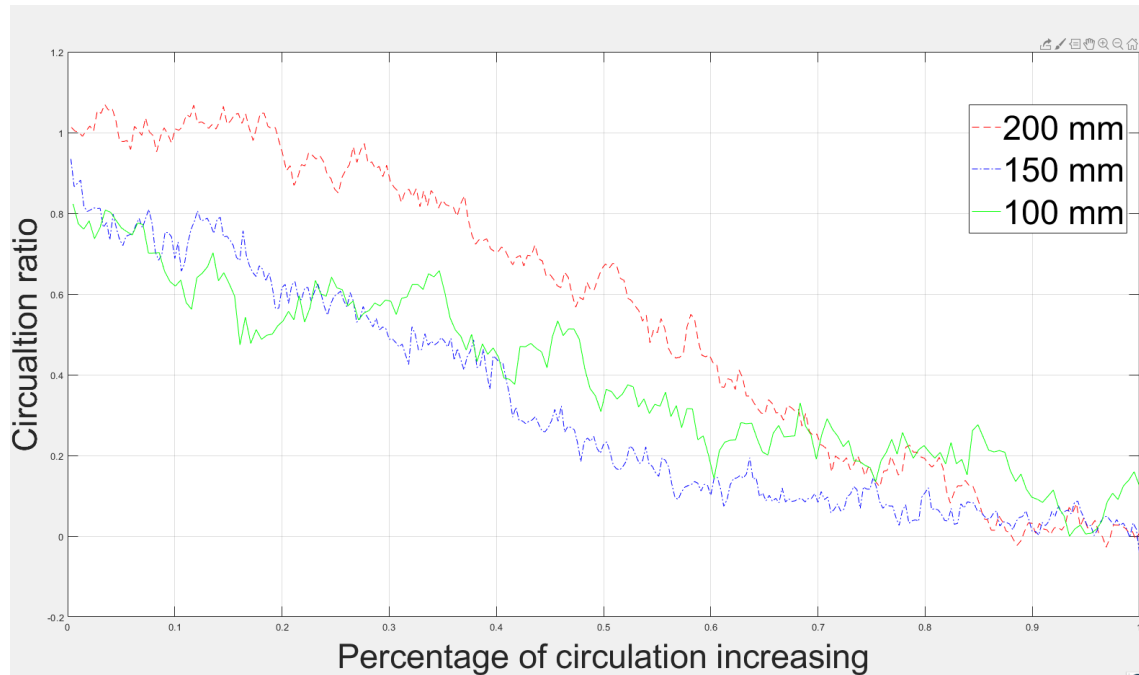


Figure 8.72 Nondimensional circulation decreasing and tangential velocities selected sections

In the restoration process, the vortex movement in the recording area is two parts. In the initial stage, the vortex vanishes smoothly, but the weak part of the vortex remains in the area. At stage two, the weak of the vortex vanishes. The results of the 200mm blade are shown in Figure 8.73.

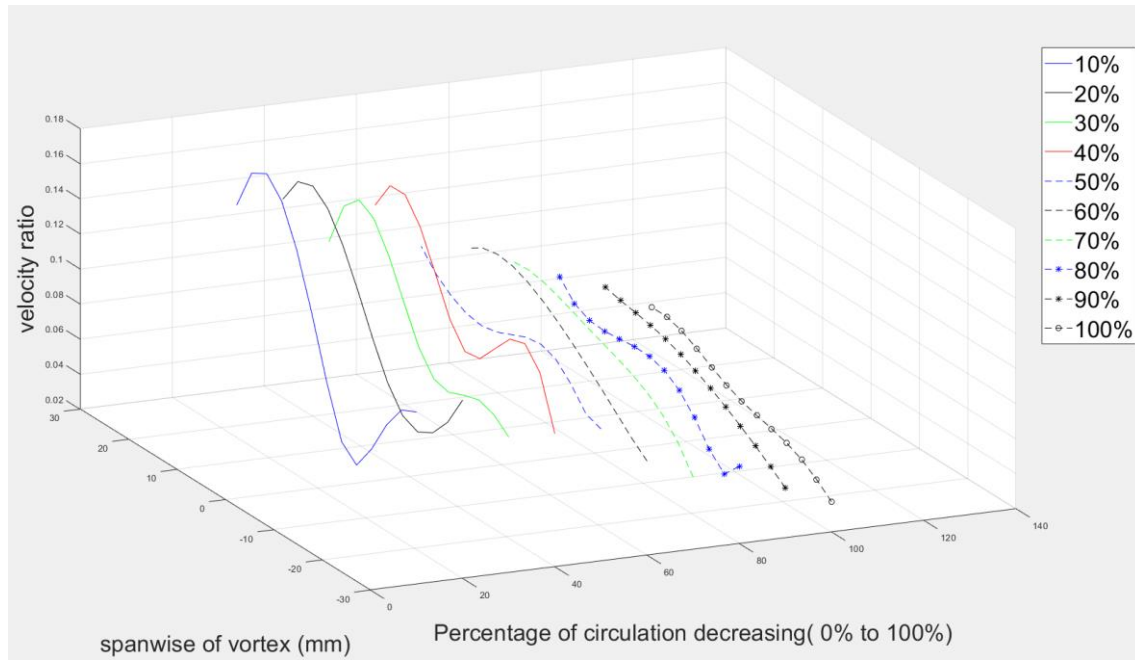


Figure 8.73 Tangential velocities of deflection 100mm blade condition

The tangential velocity at the spanwise location has been plotted with different line types under restoring motion. The x-axis of the plot is the time steps. The Y-axis is the spanwise cross-section of the vortex. The Z-axis is the velocity ratio of the radius velocity, which is computed by $\frac{\text{radius velocity}}{\text{free stream velocity}}$. The legend value is the ratio of the progress of the circulation decrease; 10% means the initial circulation decrease, and 100% is the circulation decrease to zero.

From Figure 8.73, the vortex vanishing was represented by the radius velocities. Unlike the deflecting motion, the restoration was relatively smooth. From the decrease in the vortex, the shape of the tangential velocity curves became a straight line of around 80% to 90%, and the vortex became weakest, which was similar to the circulation plot. The tangential velocity ratio also moves downside after the circulation vanishes, which is caused by the wake of the vortex; the detailed plots are in Appendix C.

Based on the theory and both vorticity and tangential velocity contours, blade restoration leads the vortex to move out of the recording area. The vortex will cross the recording area as the vortex moves. The tangential velocity of the vertical cross-section was plotted to check the vertical movements of the vortex.

The vertical-wise radial velocity shows a similar two-stage decay like that of the circulation and vorticity contour analysis. The vertical velocity distribution indicates the vortex moves downward; after the vortex moves out, all radius velocities are similar and decrease at the same speeds. The vertical case section tangential velocity for 200 mm is shown in Figure 8.74.

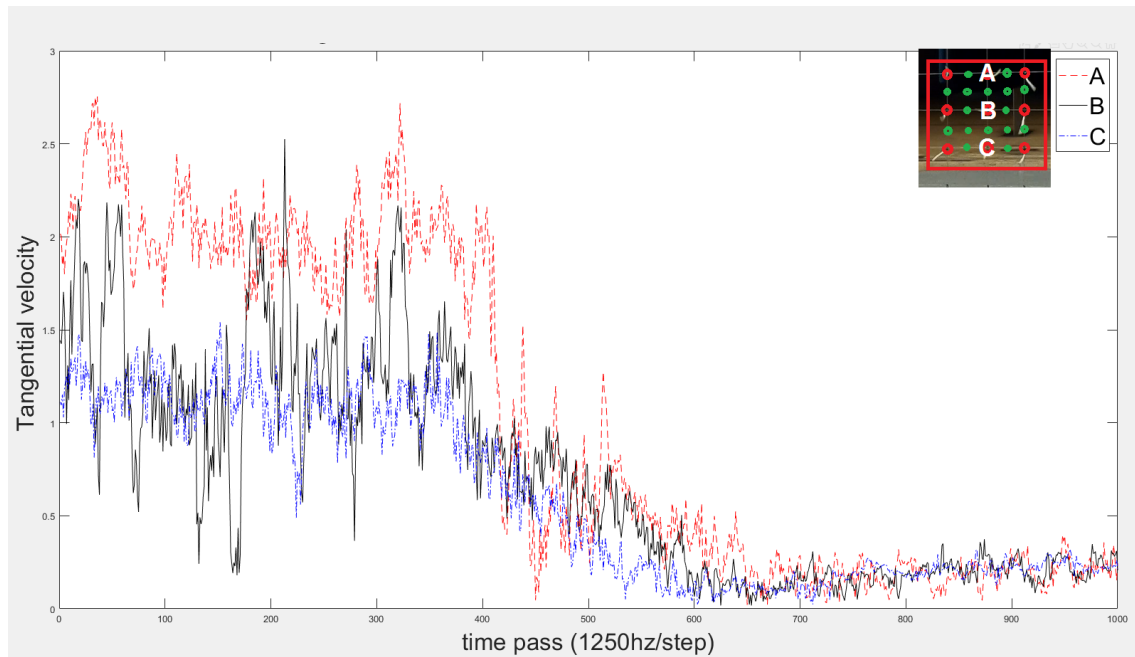


Figure 8.74 The vertical section tangential velocity with time passed

Point A: the top location in the vortex. Point B: vortex core location, solid line. Point C: bottom location, broken line. The X axis is the time steps, and the Y axis is the tangential velocity (m/s) that varies as time passes.

Figure 8.74 shows how the tangential velocities at the vertical section changed with the blade restoring at 200 mm condition. At time step 328, the circulation began to decrease, and all the velocities also began to decrease. The tangential velocities decreased smoothly, and the velocity at the top of the vortex (location A) decreased faster at the beginning, during which stage the structure of the vortex vanished. Then, the top points decreased at a speed similar to the rest of the points in time, steps 400 to 630. The tangential velocity with the decreasing percentage of the circulation is shown in Figure 8.75. The cases 150mm and 100mm show similar results in Appendix C.

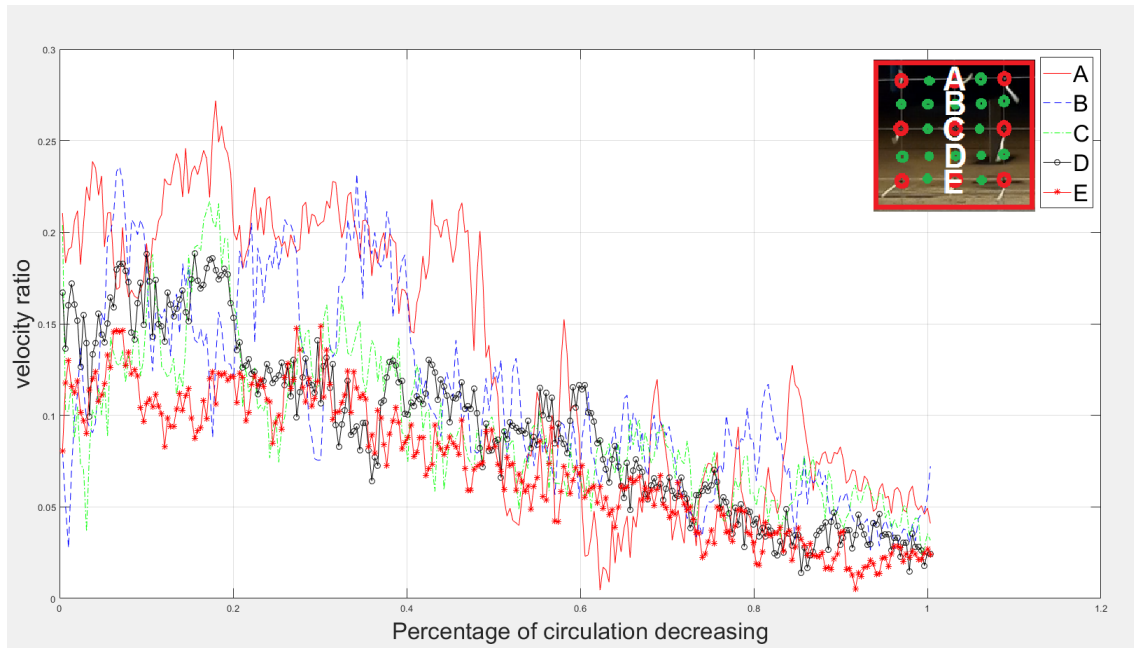


Figure 8.75 Tangential velocity variation with the circulation decreasing

Solid line: Location A, top of vortex. — —: Location B, upper of the vortex. — · —: location C, vortex core. —o—: Location D, the lower part of the vortex. —*—: Location E, the bottom of the vortex. The X-axis is the percentage of the circulation decreasing motion without considering the blade restoring speed.

8.7.6 Velocity contours of vortex

The velocity contour shows the structure of the vortex. In the static condition, the vortex was shown by the streamwise and tangential velocity contours, while in the deflection and restoration, only tangential velocity contours were involved. The two velocity contours of the static vortex are shown in Figure 8.76; the pure experimental data contours are in Appendix C. The ratio of freestream airspeed plotted the contours of the tangential velocity.

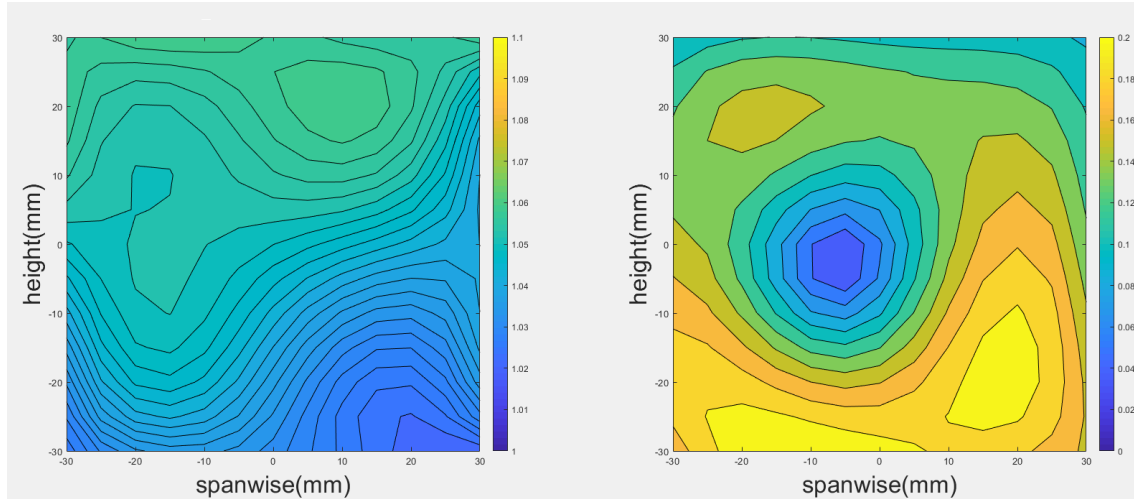


Figure 8.76 Velocity contours of the static vortex (200mm blade)

The spanwise is Y-direction, and the vertical is Z-direction. The left plot is the streamwise velocity ratio contour, and the right plot is the tangential velocity ratio contour. The velocities are represented by the ratio of the airspeed, 10m/s.

The higher speed area in the tangential velocity contours is the lower speed area in the streamwise contour. Figure 8.76 shows that the tangential velocity better represents the vortex than the streamwise one. The tangential velocity contour was thus selected to show the vortex.

Based on the vortex movements and strength, there are some differences in the current result compared to the quasi-steady condition. The tangential contours show the vortex movement variations with strength in deflection. During the deflection, the vortex first appeared in the middle of the area and remained there for the rest of the process. The height of the vortex did not change much, but the circulation increased from 48% to 96%, as shown in Figure 8.77.

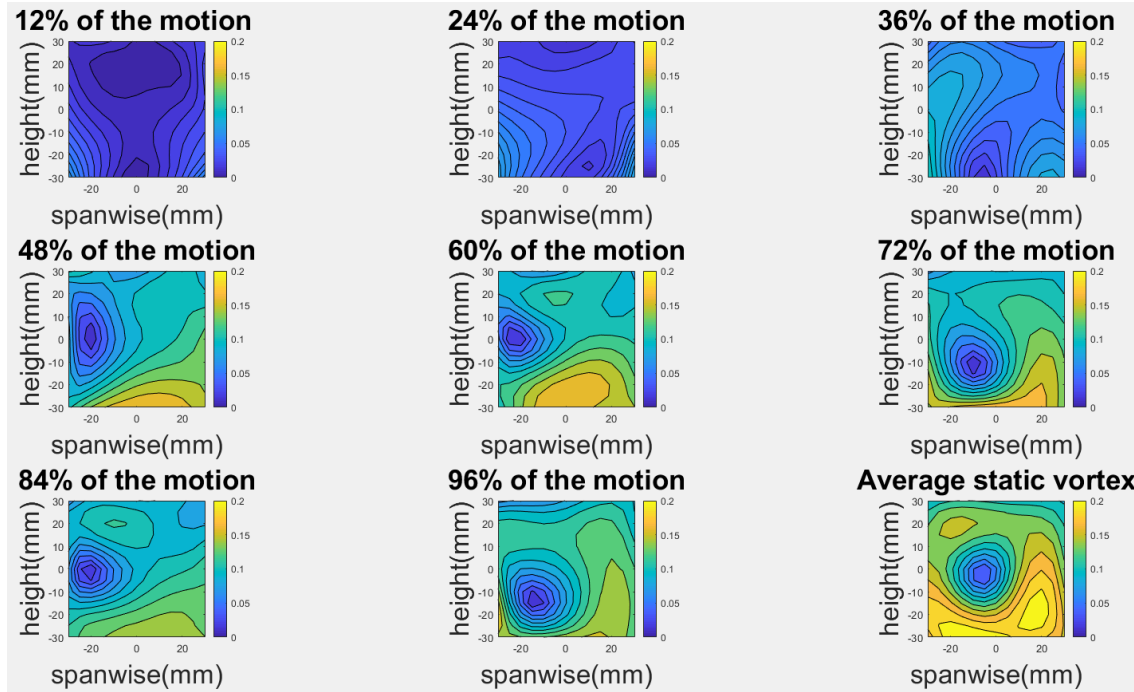


Figure 8.77 The variation of the tangential velocity contour of the 200 mm blade in deflection

The spanwise is Y-direction, and the vertical is Z-direction. The percentage in the subtitles indicates the circulation ratio to the static circulations. The data points were extended by function. The whole active deflection process was regarded as the circulation variation period. The time scale of the active motion was nondimensionalized to the percentage of the circulation increasing motion.

Figure 8.77 shows the variation of the tangential velocity contours in the deflection of 200 mm. The shape of the vortex core is clear since 48% of the deflection, the contours show the lower tangential velocity in the middle of the vortex and increase as the radius increases. The high-velocity area was always on the bottom of the vortex because the flow accelerated at the bottom of the vortex. The acceleration is because the part of the vortex at the bottom has been pressed due to the ground effects, area reduction, and velocity increase. The contours show the vortex went to the recording area from the left-hand side, and the entrance on the spanwise location is not steady. The last contour is the average contour of the static vortex.

After 48% of deflection, the motion of the contours variation is all similar across the three cases. Appendix C contains the contour plots for case 150 mm and 100 mm during deflection.

The contours during the blade restoration of the three cases are not as clear as those during the deflection. The contours in all three cases indicate that the faster drop in circulation in the area is related to the vortex moving out, not the vortex decay; this process is clearer in cases of 150 mm, as shown in Figure 8.78. Below are the contours for the 150 mm blade plot, cases 200 mm and 100 mm, in Appendix C.

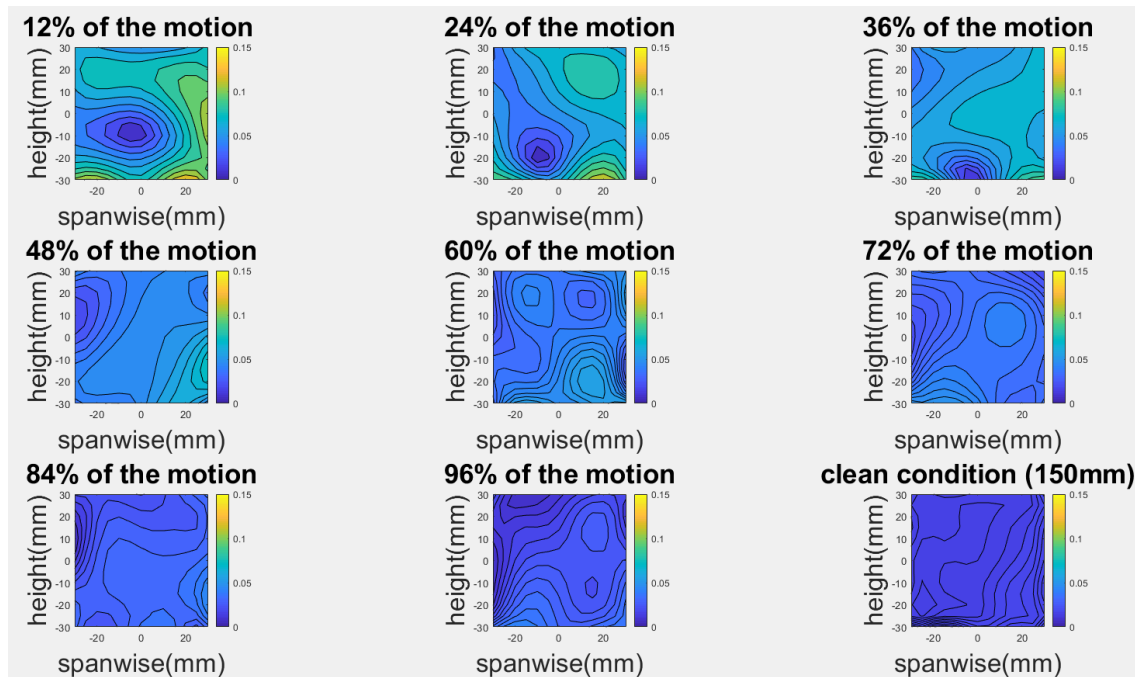


Figure 8.78 The tangential velocity contour of the 150 mm blade restoration

The spanwise is Y-direction, vertical is Z-direction. The percentage in the subtitles indicates the circulation ratio to the static circulations.

The contours of the 150 mm blade in restoration show the clear vortex shape at 12%, and the processing of the vortex moves to the bottom and leaves the recording area clear.

The tangential velocity contours of the three cases exhibit two stages of the circulation increase. In the first stage (0-36% of circulation), the circulation

increase is not caused by the vortex directly but by the wake of the vortex. In stage two, the vortex enters the recording area. The vortex's locations are not steady but remain nearly at the same height in the area. At the final stage (after 48%), the vortex remained in the same position and grew stronger. During restoration, the result mirrors that of vorticity and spanwise velocity distribution; the vortex leaves the area during the initial restoration (circulation drops process) from the bottom, but the wake of the vortex remains in the area for the rest of the circulation drops process.

8.8 Computational fluid dynamics result of Phase II

The experiment involved active motion, and the key processing was the blade deflecting and restoration. The experiment results show that the vortex-forming process consists of three parts in the recording area, and the final stage does not have a quasi-steady state in deflection because the vortex grows in the same position. The simulation focused on the Phase II experiment, aiming to represent the vortex-forming comprising steady states for comparison with dynamic forming.

The static vortex was simulated in CFD. The simulation software used in the current study is ANSYS FLUENT 2020 R2. The deflection and restoration were separated into several static stages, forming a very slow motion. The slow motion serves as the reference for the vortex-forming study. The spacing between the stage blades was 10mm, as shown in Table 2. Based on the previous study, the circulation increase shows a similarity across all three cases, so only one active motion was simulated. The model and details of the mesh are in Appendix C.4.

	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
h_{vg} (mm)	60	70	80	90	100	110	120	130	140	150

Table 2 The stages of experimental simulations.

The top row shows the stages in the quasi-steady simulation, the height of the blade is in the bottom row, and the unit of the bottom row is in mm.

The total size of the mesh was from 150 mm, case 7 million to 10 million, and the model of turbulence was $k - \varepsilon - Realistic$ with stander wall treatment obtained from the model and the mesh sensitive checks.

The quasi-steady simulated both deflection and restoration. The height difference between the two simulation modes is 10mm. A total of 10 blades, from 60 mm to 150 mm, are involved in the simulation.

8.8.1 Result

The location of the static vortex was an important result of the experiment. The vortex location was obtained from the CFD, and the locations of the simulated vortex and recording areas were as shown in Figure 8.79.

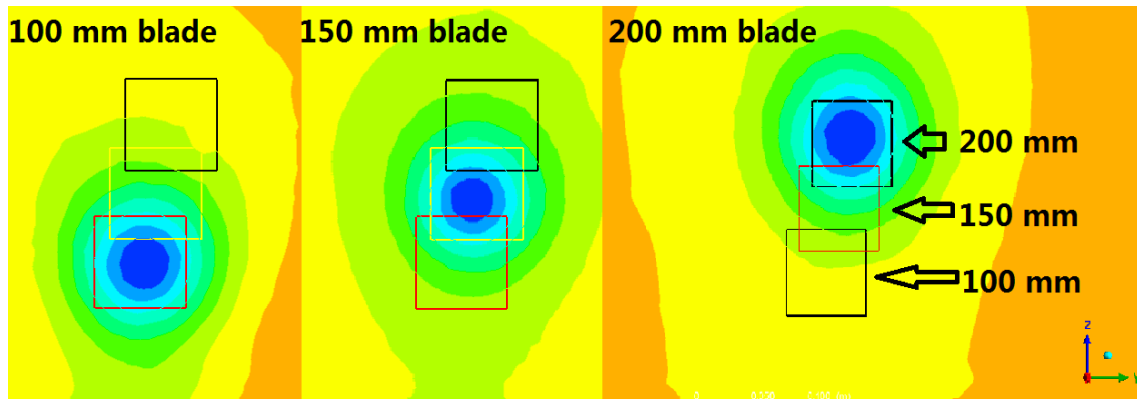


Figure 8.79 The locations of the vortex from the experiment

The top square box is the location of the vortex in the 200 mm case. The middle square box is associated with the 150 mm case. The bottom square box is associated with the 100 mm case.

Figure 8.79 shows the location of the static vortex was well predicted by the CFD method. The squares in the upper plots were the recording areas in the Phase II experiment, and the blue color indicated the vortex. It shows the locations of the static vortex predicted by the CFD.

The tangential velocity is one of the key parameters of the vortex. The simulation shows a good similarity with experimental data. The simulated result of tangential velocity with experimental data is shown in Figure 8.80.

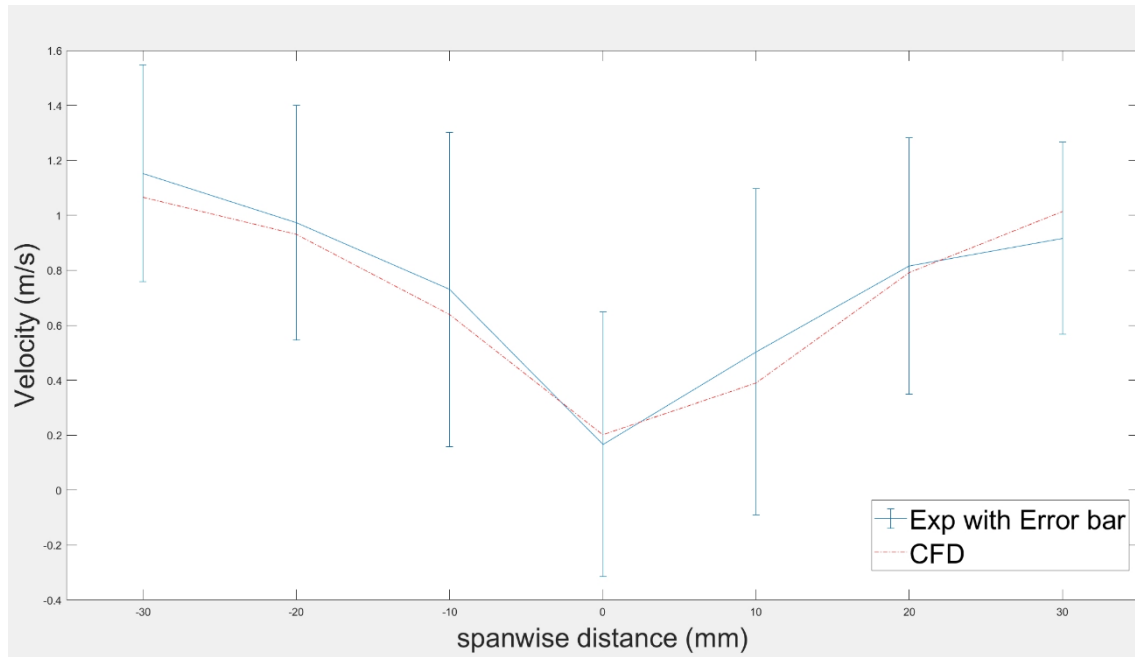


Figure 8.80 The tangential velocity of simulation results with experimental data under static conditions (150mm case)

A broken line with data points: experimental data. A broken line without data points: CFD. The number and locations of CFD data points were the same as the experimental data.

The tangential velocity and vortex core location comparisons show a good similarity; the circulation difference is higher than the analysis with the experiment. The circulation of the CFD vortex at 150 mm is only 0.2505 m^2/s , but the experimental data is 0.3257 m^2/s , and the analysis result is 0.3344 m^2/s .

The local pressure contour represents the vortices in the simulation. The vortex movements in the quasi-steady simulation indicate the vortex moving continually, both vertically and spanwise, as the height of the blade increases, as shown in Figure 8.81.

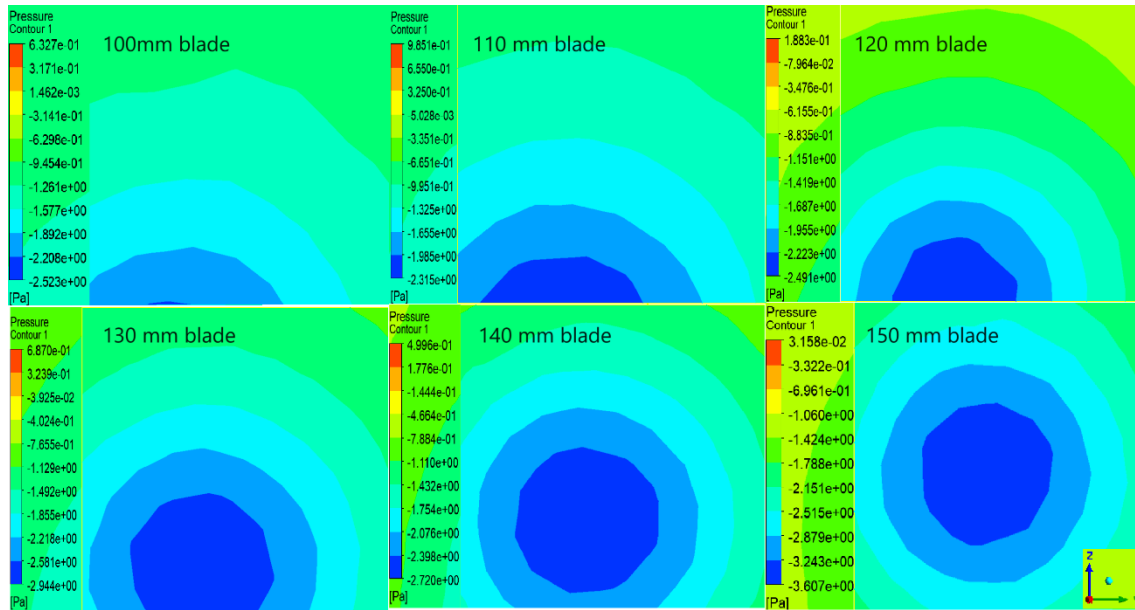


Figure 8.81 The vortex movements in quasi-steady simulation

The plot involved vortex movements from 100 mm to 150 mm. The vortices are represented by the local pressure contours from the ANSYS CFD-post.

The location variation shows the vortex movement is different from the experimental data, and the vortex-forming process is not a quasi-steady motion. The circulation variation of the vortices from the simulation was transferred to the non-dimensional and compared with experimental data, shown in Figure 8.82.

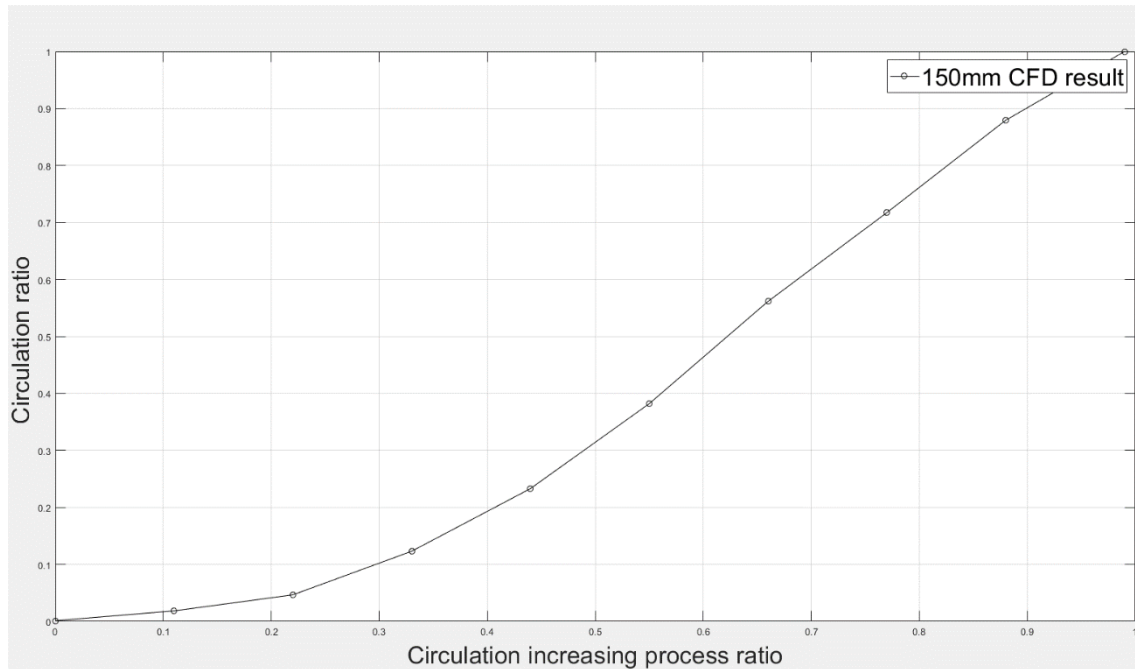


Figure 8.82 The circulation increases with the steady made-up simulation

The plot's Y-axis is the circulation ratio, computed by the whole process divided by static vortex circulation (circulation at 150mm condition). The X-axis is the ratio of the process, which is from 60mm to 150mm, and the process is separated into 9 points.

Figure 8.82 shows the circulation increased based on the CFD simulation. The lowest height that can affect the flow in the recording area occurs when the blade is deflected to 60 mm, represented by the plot's second point. The first appearance of the vortex core is at 100 mm; the vortex's wake causes the early phase of the circulation to increase. The slope of the circulation is caused by the vortex movement (vortex area increase in the recording area) and also by the circulation increase of the static vortex. The comparison of the static-made-up moving motion and experimental data shows that the simulation is not fitted. The comparison plot is in Figure 8.83. Only the non-dimensional active process (circulation increasing with the ratio of the increasing progress) was compared.

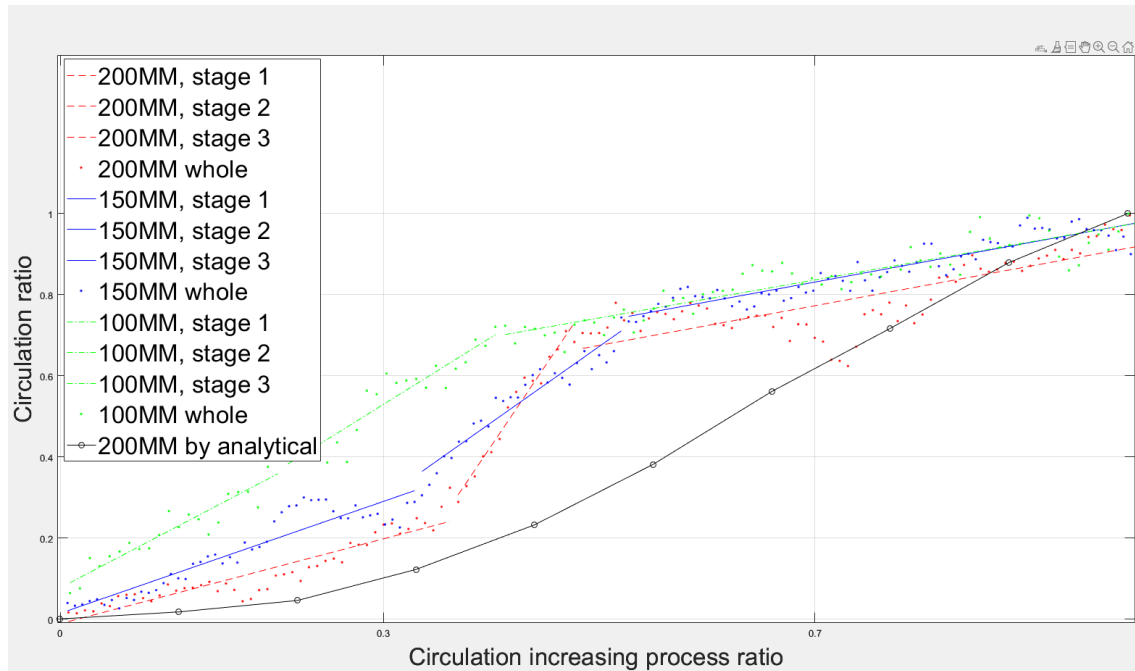


Figure 8.83 Comparison of the experimental circulations with the simulation result

Solid line: 150mm case. — —: 200 mm case, — · —: 100 mm case. —o —:CFD results. The Y-axis is the ratio of the circulation. The 1 on the Y-axis represents the final stage of the strength of circulation in the steady-state. The X-axis is the ratio of the circulation increasing process without considering the blade deflecting speed and size.

The CFD simulation shows the location of the vortex can be predicted accurately. Tangential velocity at the vortex core spanwise is close to experimental data, while the circulation simulation is not fitted. The quasi-steady simulation can not predict the dynamic process in the experiment.

9 Discussion

The experimental results show that the development of the vortex downstream was not linear, even when the blade deflects linearly. The nonlinearity is evident in the three deflection stages: stage one represents the wake of the vortex, stage two indicates the vortex entering the area, and the final stage involves the vortex developing further at the static vortex location. The restoration process has two stages: the vortex moves out with a lateral movement, and the wake of the vortex remains in the area until the circulation drops to zero. This chapter compares and analyzes the results from both phases of the vortex-forming process in more detail.

The experimental data from both the Weybridge wind tunnel and ABLT wind tunnel can be divided into two parts: the active part, where the vortex formed, and the static part, where the vortex stayed. The analysis was mostly based on the phase two experiment.

9.1 Static vortex

The static vortexes in phase II experiments were compared with the results predicted by the simulation and empirical model. The comparison of the results showed that the empirical method and CFD could well compute the strength and location of the static vortex.

The angle of attack was fixed at 10° in all three cases of the phase II experiment. The only variable was the height of the blade. The height of the blade affects the vortex's location and leads to an increase in circulation. The increase in the relative height caused the initial circulation increase (h_{VG}/δ), the increase in actual physical size, and the shorter relative distance. The shorter relative distance affected the circulation at the recording location as there was a smaller decay. The results of the circulation obtained from the experiment (2 m downstream of the VG), the analytical method are shown in Table 3.

	100 mm	150 mm	200 mm
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Experimental	0.1602	0.2520	0.3565
Analytical	0.1652	0.2568	0.3318

Table 3. Static vortex circulation comparison (units: m^2/s)

The upper table concludes the circulations obtained from both experiment and analytical results. The analytical method is introduced in Chapter 2.

The circulation of the static vortices from the analytical equation was close to the experimental data. The difference between prediction and experimental data were changed from overestimate to underestimate. The difference became smaller as the height of the blade increased, and the relative downstream distance became shorter, leading to less vortex decay close to the initial circulation. The model is based on the experimental data used to compute the initial circulation; the data was recorded at 1 h downstream of the blade, which has less decay.

The empirical model used in the current study is a regression of the experimental data. This model is not based on theoretical principles but on observations. The limited data and experimental conditions cannot represent the entire range of the real condition, such as the boundary layer in the empirical model is lower than the current experimental conditions. The 200mm blade is close to the boundary layer thickness. This led to the free stream air rolling into the vortex formation beyond the analytic model's application range.

The model is based on the simplification of the real condition to make the formula possible to apply. The simplification also led to a missing factor, which caused the prediction's inaccuracy.

9.2 Blade deflection

The key part of the current study focuses on the blade motion and active motion of circulation. The initial vortex (starting vortex), nonlinear response, and three stages of the vortex formation are discussed in this chapter.

The deflection process occurs inside the boundary layer. The air speed and size of the blade affect the vortex forming. The Reynolds number can represent both of the effects. The local velocity at the tip of the blade and the blade height are involved in calculating the Reynolds number. The Reynolds number variation inside the boundary layer is shown in Figure 9.1.

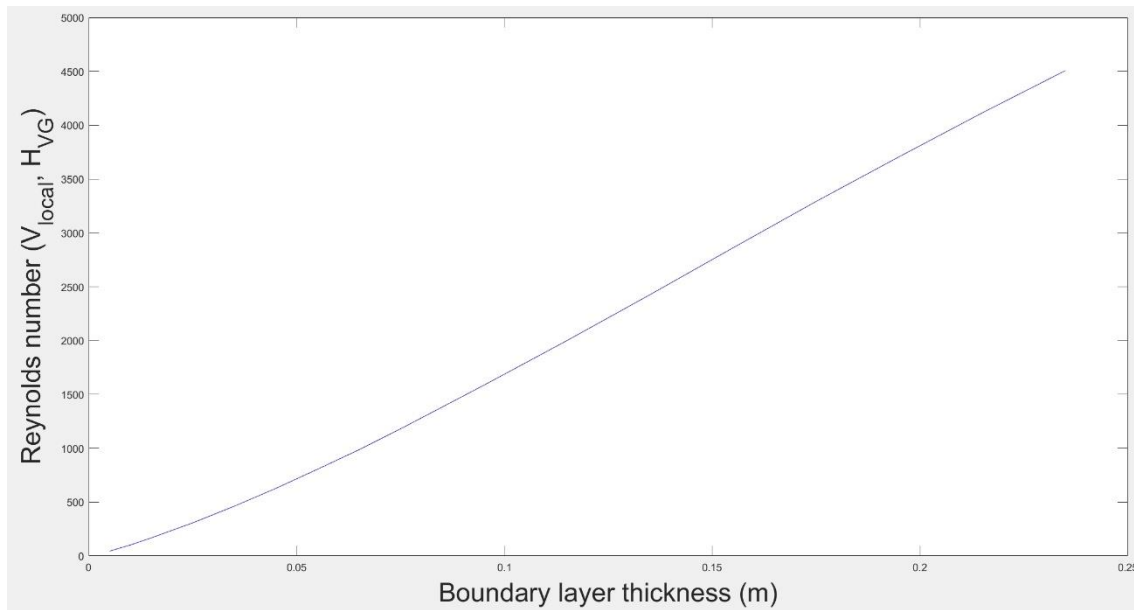


Figure 9.1 The Local Reynolds number variation in the boundary layer

The local Reynolds number indicates that both the local speed and the size of the blade have a linear effect on the vortex-forming process. The circulation of static vortices from the experiment increases linearly under the current condition.

9.2.1 initial vortex

The two different strength indicators (circulation and static pressure) were transferred to the non-dimensional ratio by dividing the static vortex strength. The time steps in both experiments were transferred to seconds from frequencies.

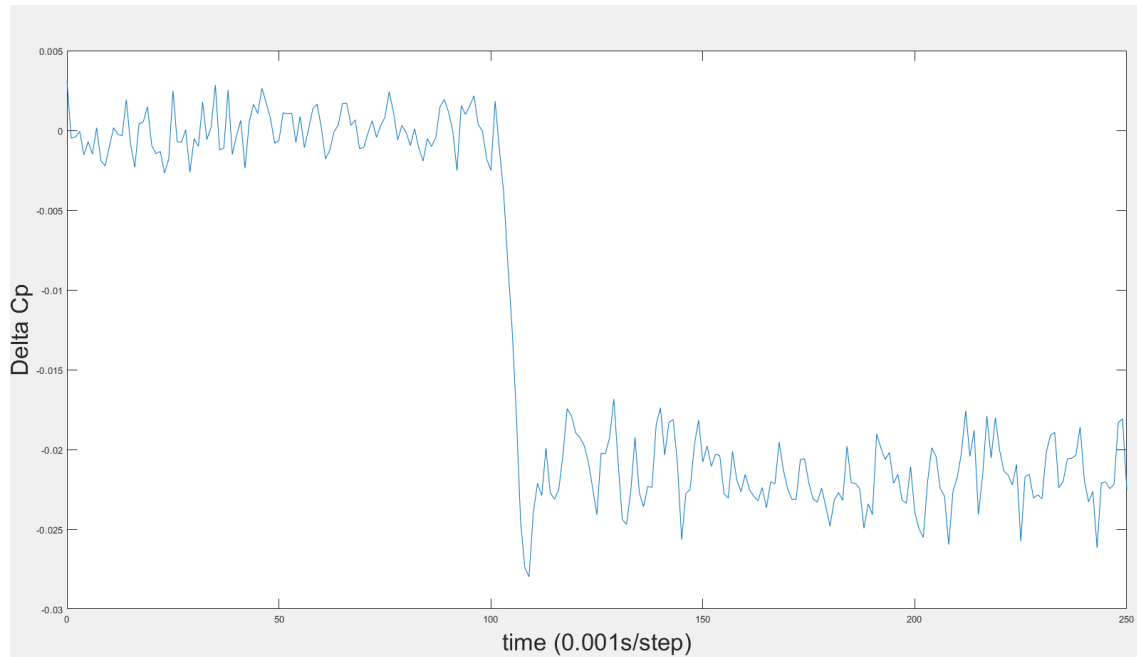


Figure 9.2 The vortex formed with 7MM at phase I

The results are from the phase I experiment, stage two, 30° . The different colors indicate the different heights of the blade. The Y-axis is the ratio of the surface static pressure coefficient, and the X-axis is the time-pass (unite: second).

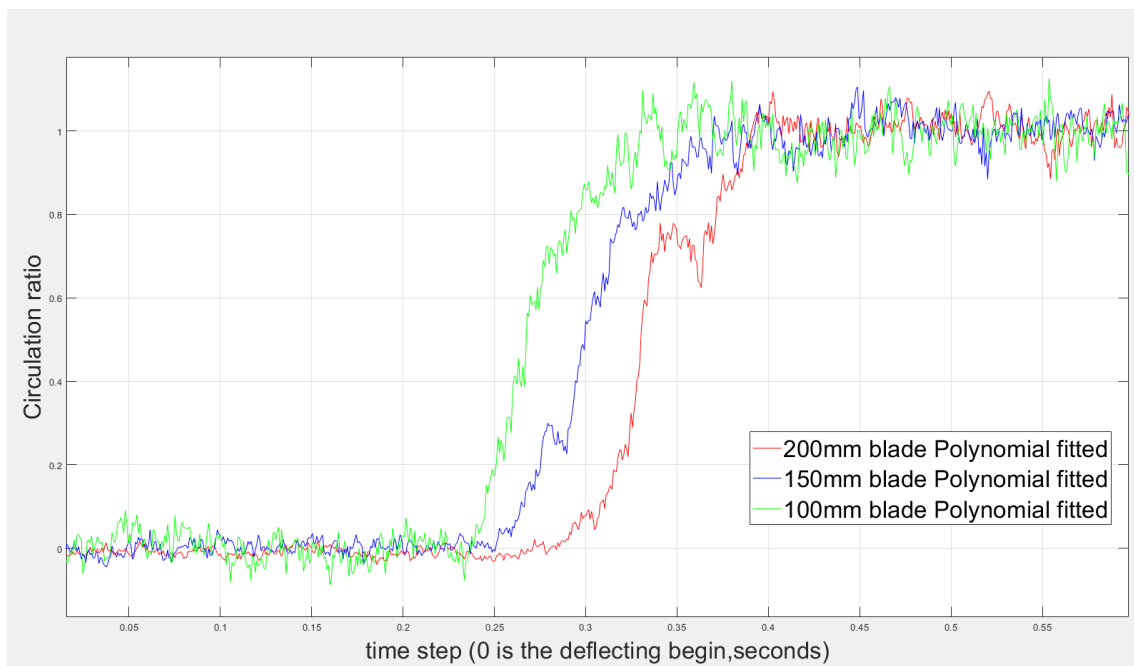


Figure 9.3. The circulation ratio changes against time pass, Phase II

The y-axis is the circulation ratio. The x-axis is the time steps in seconds.

The angle of attack in Phase I was selected to be 30° . Both angles of attack in Phase I of Phase II were the optimal angle, close to the maximum strength condition. The main difference between the two vortex-forming plots was the "overshoot" and stages of the strength increase slope. Phase I's plots showed clearer overshoots than results from Phase II. The Phase II results showed the three stages of the vortex-forming slopes. The overshoot and strength changes showed that Phase I and II vortex-forming processes had different behaviors.

The possible reason is that the starting vortex and static vortex were not in the same position, spanwise or vertically, as shown in Figure 9.4. From the tuft test in Phase II, the initial vortex moved to the upper-pressure side (left-hand side) first from the bottom, and then the static vortex formed at the recording area. SHIZAWA also found a similar situation [69]. The starting vortex and static vortex were not in the same spanwise position. However, the starting vortex and the static vortex were on the same spanwise location in phase I results, and the same condition was also recorded by Barth [65] Barth also indicates the starting vortex has a higher position than the static vortex. The motion of the higher position starting vortex across the recording area was not recorded. All the previous studies involved have a small blade, but the current experiment involved a 100 mm to 200 mm blade, the starting vortex may formed and shed in the early stage of the deflection. So, the small recording area may not be suitable for catching the starting vortex because the starting vortex may be at the same location.

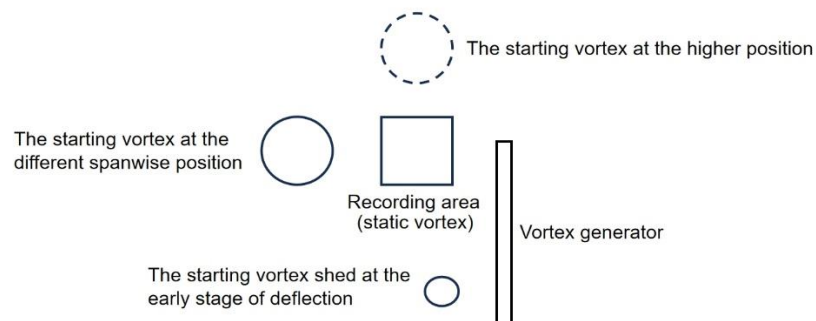


Figure 9.4 The locations of the starting vortex

The difference between the two references and the Phase II experiment in the project was the deflection speed, the blade's shape, size, and relative downstream distance. The blade in Phase I and references are delta-shape, a square shape in Phase II. The Kutta condition theory also supported the speed reason of the starting vortex presence: the blade suddenly appears in the flow, and the flow cannot form a steady circulation on the blade, leading to the high circulation vortex at the trailing edge, the speed reason also support by Barth.

The frequency represents the deflection speed in Osborn and Barth's works. The lowest frequency to produce a starting vortex is 30 hz in Osborn's experiment and 112 hz in Barth's work. The deflection speed and airspeed ratio indicate the relative deflection speed in reference works and Phase II, as shown in Table 4.

	Phase II	Osborn	Barth
$\frac{\text{deflection speed}}{\text{air speed}}$	0.15	0.0217	0.0178

Table 4 The ratio of deflection speed

The deflection ratio in Table 4 shows the relative deflection speed in Phase II is nearly ten times higher than the ratios in reference, but the starting vortex was not recorded.

The relative size effects and shape differences should be considered. The vortex generator's size in the reference was smaller than 10mm, but in Phase II, the size is from 100mm to 200mm. Additionally, the shape of the vortex generator in the reference study was delta-shaped, while in Phase II, it was square.

Another possible reason could be that the downstream distance is too far to travel through because of the rapid decay of the starting vortex. The nearest distance is for the 200 mm blade, which is 10 h downstream. In Phase II, the angle of attack is only 10° . The starting vortex is weak if the starting vortex is generated. The 10 h distance is far beyond the capability of weak starting the vortex to travel.

To conclude, even though there are several possible reasons, the long downstream distance is impossible for the starting vortex to travel. Therefore, the starting vortex is not present in the study.

9.2.2 Vortex forming

The vortex-forming process obtained from phase II can be divided into wake formation, vortex movement, and vortex growth. Despite the variations in deflecting speeds and forming speeds, the results from Phase II show evident similarities.

The height of the blade was the only variable in the Phase II experiment. The height effect was related to nondimensional distance, local velocity (submerged inside the boundary layer), and initial circulation. The non-dimensional distance enormously impacts the vortex decay, as demonstrated in stage two of Phase I and other studies [56]. The relative distances in phase II were 10 h, 13.3 h, and 20 h, and the aspect ratios were 1, 0.75, and 0.5. The results showed that the circulation increasing (vortex forming) slopes were similar in all dimensions; the three stages increasing is constant.

9.2.2.1 The Nonlinear Response of Vortex-Forming

In the phase II vortex forming process, the three stages of the circulation increase were shown to be consistent in all three cases in phase II. Stage one was from 0 to 30%, stage two was from 30% to 70%, and the final stage was 70% to steady motion.

The movements of both maximum and minimum velocities represented the same vortex movements in the recording area. The locations of both velocity points over time in three cases are shown in Figure 9.5. At a similar percentage, the maximum and minimum velocities and relative locations showed that the flow structure inside the recording area changed, with the wake of the vortex, the vortex moving in, and the vortex growing. The peak point rotating three times and the three stages represented the vortex movements associated with the circulation increase.

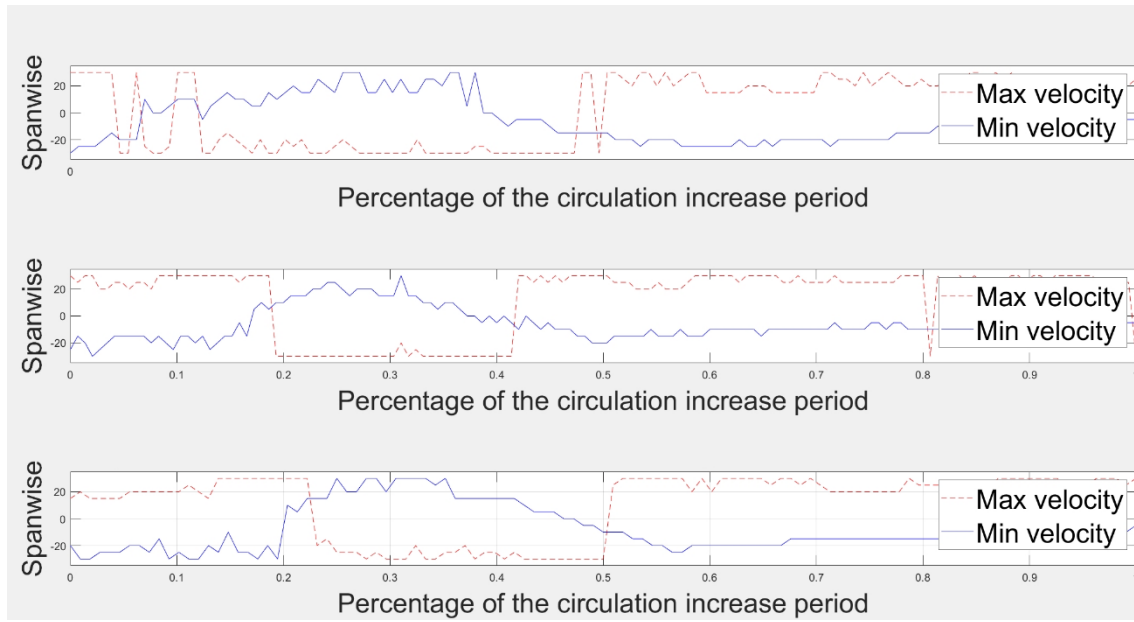


Figure 9.5 The route of maximum and minimum velocities in Y-axis with increasing circulation motion

The zero at spanwise is the vortex core location. Solid line: location of maximum velocity. Broken line: location of minimum velocity. The spanwise is the location in the recording area. 0 means the vortex core, -30 is the left-hand side, 30 is the right-hand side.

Figure 9.5 indicates the similar vortex movement inside the recording area of all three cases. The tangential and vorticity contour in the blade deflection period were plotted to show the structure of the vortex of all three cases. Both types of contour (tangential velocity and vorticity) of the case 200 mm, 150 mm, and the 100 mm were shown in Figure 9.6.

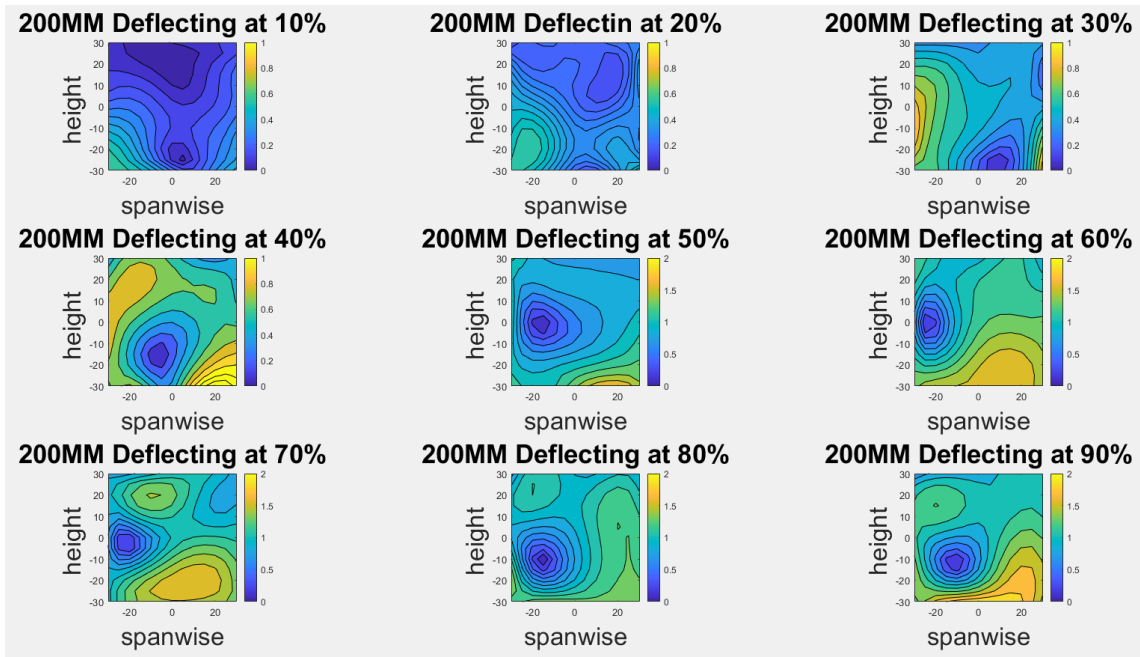


Figure 9.6 Tangential velocity contour of the 200 mm blade in 3 switches

The spanwise is Y-direction, vertical is Z-direction.

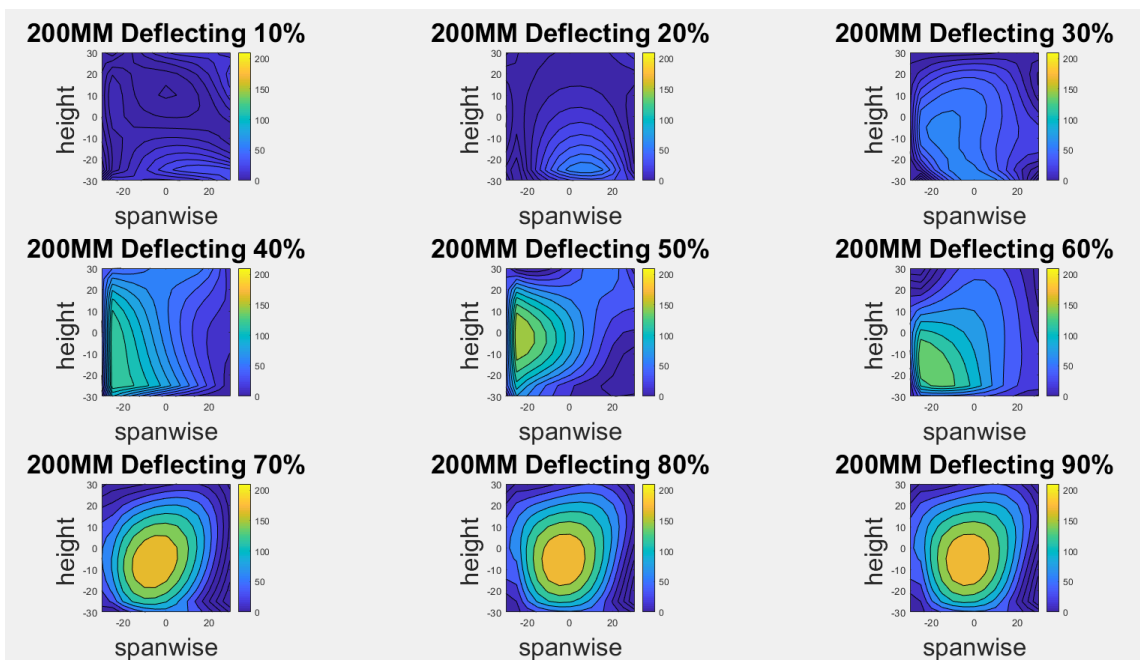


Figure 9.7 The vorticity contours of 200 mm blade case in 3 switches

The spanwise is Y-direction, vertical is Z-direction.

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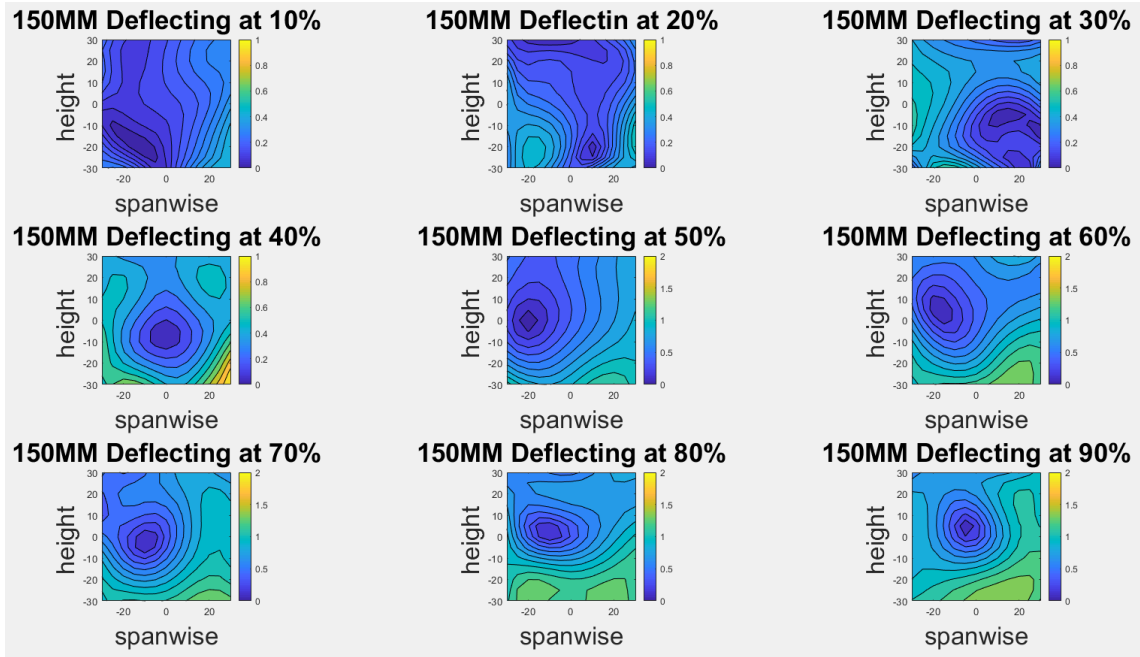


Figure 9.8 Tangential velocity contour of the 150 mm blade in 3 switches

The spanwise is Y-direction, the vertical is Z-direction, and the vortex is located on the negative parts of the Y-direction in the wind tunnel.

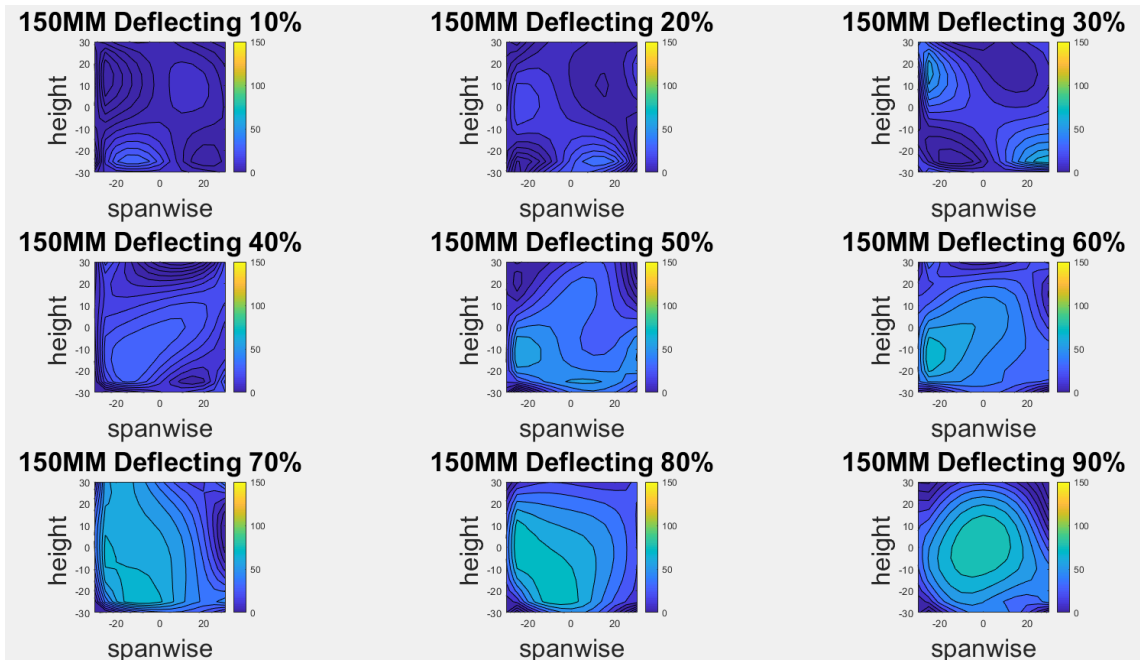


Figure 9.9 The vorticity contours of the 150 mm blade case in 3 switches

The bright color in the plot means a higher vorticity compared to the dark color.

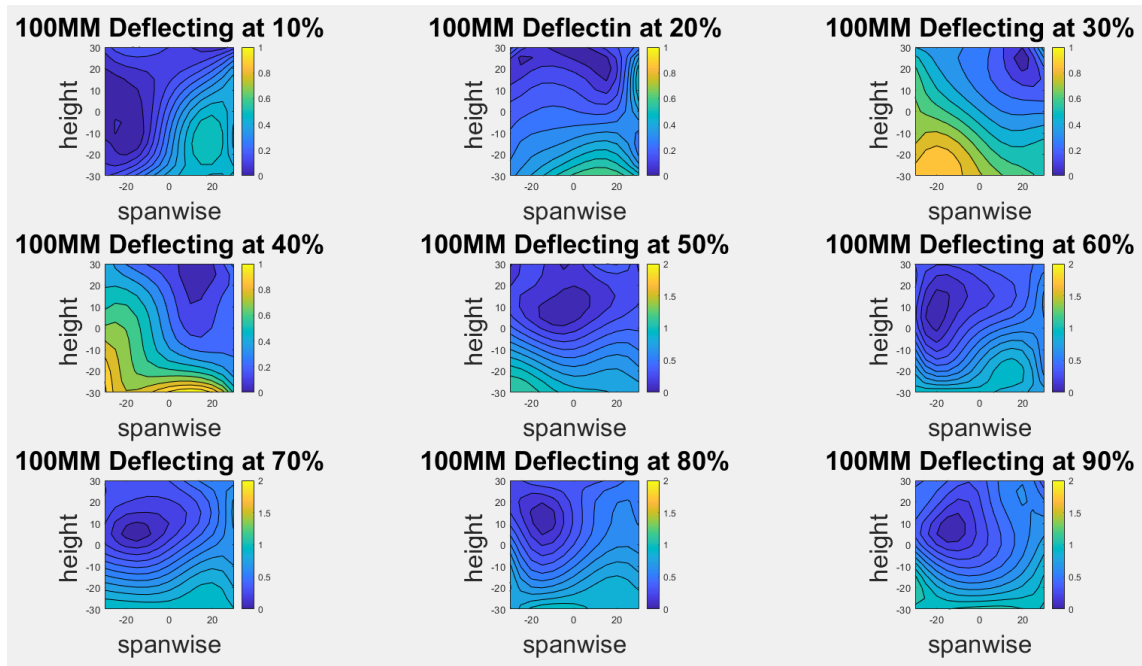


Figure 9.10 Tangential velocity contour of the 100 mm blade in 3 switches

The spanwise is Y-direction, vertical is Z-direction.

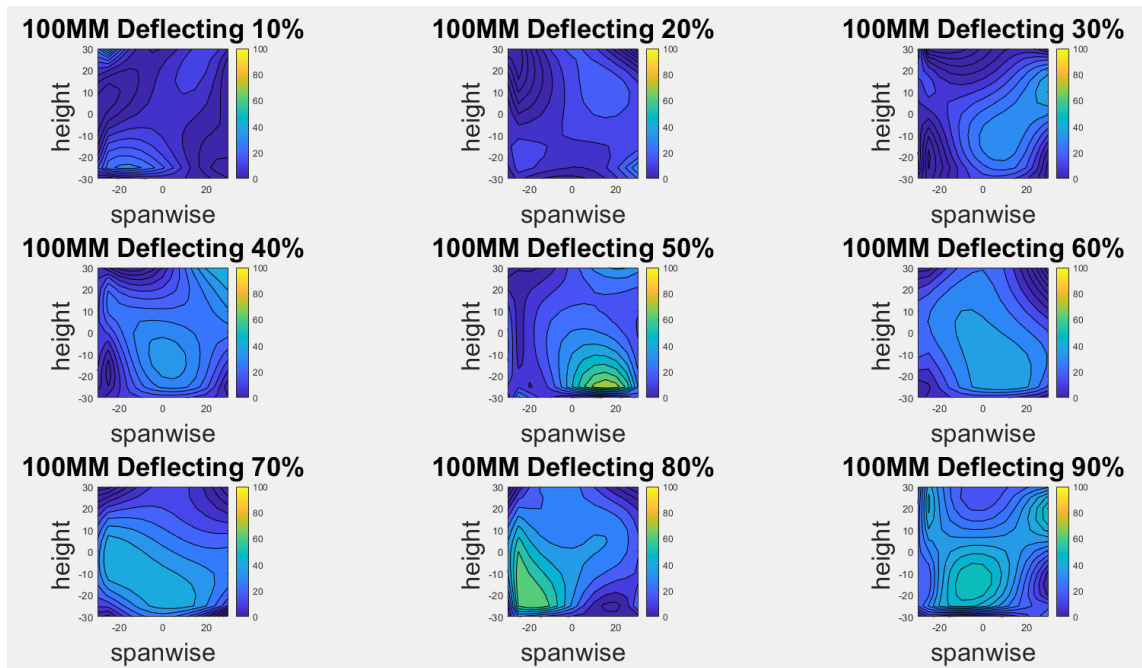


Figure 9.11 The vorticity contours of the 100 mm blade case in 3 switches

The spanwise is Y-direction, the vertical is Z-direction, and the vortex is located on the negative parts of the Y-direction in the wind tunnel.

The upper figures from Figure 9.6 to Figure 9.11 showed the active motion of the vortex in the 3-stages. The difference between the vorticity and tangential plots was clearer in 150 mm case than 200 mm and 100 mm case. The narrow velocity contours indicated the large velocity gradient, which generated the vorticity. The vorticity then led to a change in the shape of the vorticity circle and an error in the circulation integral.

In three cases, the vortex went to the center of the recording area from the middle and left bottom corner. The 3D tangential velocity plots were presented to show the relative direction. The result was as shown in Figure 9.12, Figure 9.13, and Figure 9.14.

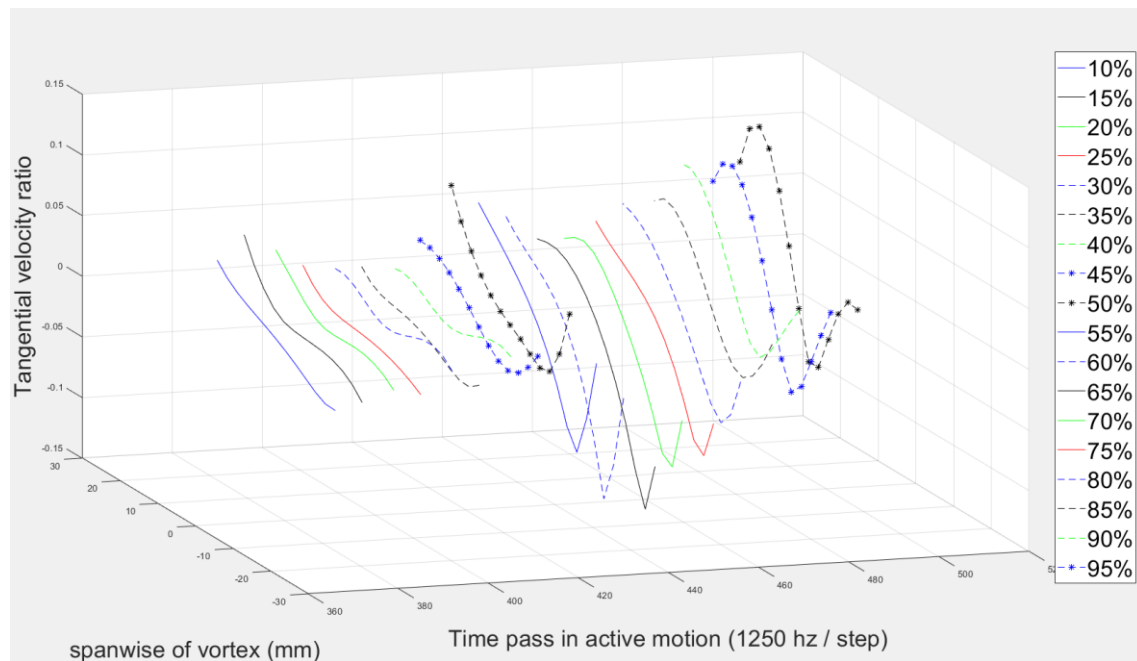


Figure 9.12 3D tangential velocity ratio against time at 200 mm blade.

The X-axis is the time pass, the Z-axis is the tangential velocity, and the Y-axis is the spanwise of the vortex. The legend refers to the motion of circulation from 0 to the steady state.

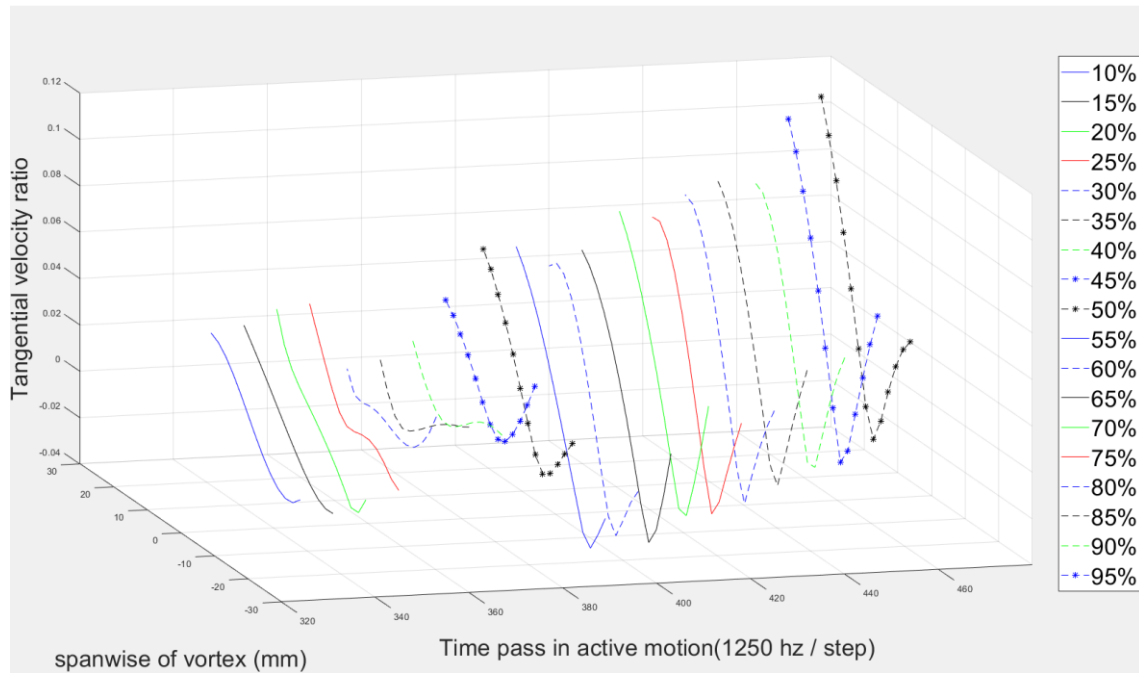


Figure 9.13 3D tangential velocity ratio against time at 150 mm blade

The X-axis is the time pass. The Z-axis is the tangential velocity, and the Y-axis is spanwise of the vortex. The legend refers to the motion of circulation from 0 to the steady state.

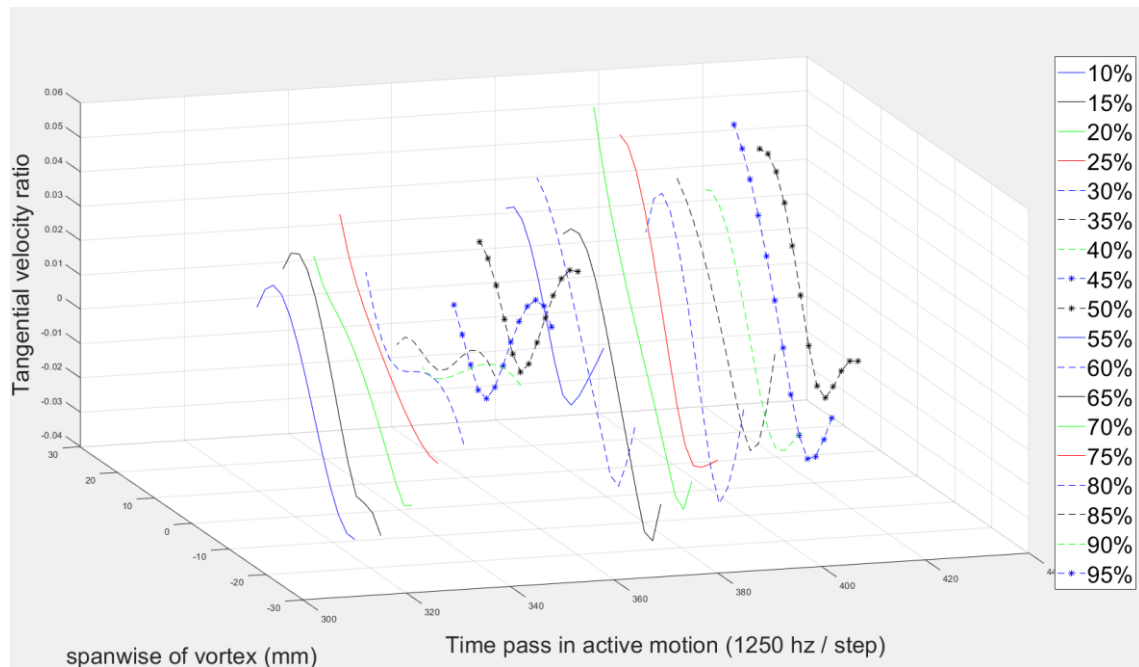


Figure 9.14 3D tangential velocity ratio against time at 100 mm blade.

Different line types represent the tangential velocity at different percentages of the circulation-increasing process. The X-axis is the time passed by the circulation's increasing process. The Z-axis is the tangential velocity ratio. The Y-axis is spanwise of the vortex.

The slopes of the tangential velocity ratio showed the flow structure changes from the wake of the vortex covering the area to the vortex moving into the area, and the vortex grew up in the area. In the 200 mm blade, the slopes had the same gradient in the beginning, followed by a small oscillation period, after which the static vortex formed. This behavior in the 150 mm and 100 mm case were clearer. In the 150 and 100 mm cases, the oscillation period became a clear opposite slope compared to the 200 mm case. After the slope direction changes back to the original direction, both ends of the slope go further.

Due to the interaction between the vortex and the bottom surface, the decay of the vortex accelerated in cases 150 mm and 100 mm. This causes the solid core to move into the area with larger velocity gradients than the recording area, leading to the clear change in spanwise tangential velocity slopes.

Two types of contour plots and plots of tangential velocity slope clearly showed the three stages of vortex formation in the blade detection process, as shown in Figure 9.15. The wake of the vortex causes the Stage 1. Stage 2 is the process of the vortex moving into the recording area or to the static vortex location. Stage 3 is the vortex growing at static locations; contour and velocity slope plots can confirm the growth. In the contour plots, the size of the vortex becomes larger, and the color becomes brighter. In the tangential velocity plots, the growth is shown by both ends of the velocities progressing.

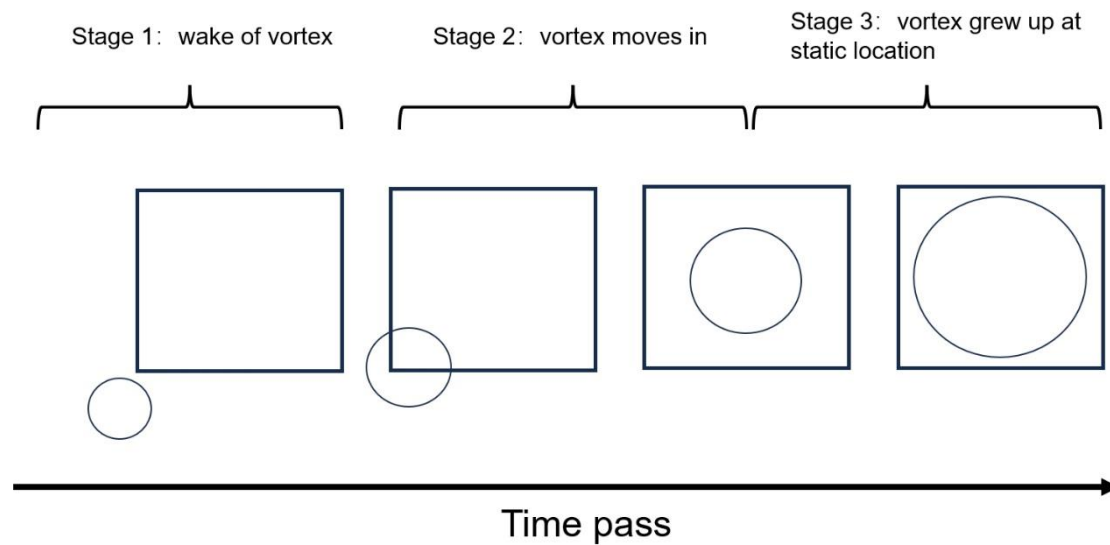


Figure 9.15 Three stages of the vortex formation

The vortex variation inside the recording area is clear; vortex movements lead to the three-stage circulation increase and growth. The reason why the vortex grew up at a static location is not clear.

9.2.2.2 The peak vorticity

The peak vorticity shows a similar response to circulation on the deflection motion. The two slopes of peak vorticity change were clear. The turning points of the slope change were at nearly 50%, and it was the time the vortex almost fully moved into the recording area. The wake and early-stage vortex moved into the area that caused the first part. The second part is the vortex that grew up in the area. Unlike in the blade restoration, the peak vorticity did not show an overshoot in deflection; even the vortex also exhibited movement.

9.2.3 Vortex movements

Vortex movement is one of the key parts of vortex formation in the current study. This movement results in circulation increases during half of the forming process. The Computational Fluid Dynamics (CFD) simulation the static condition to study the physical behind the vortex movements, and the simulated results show dynamic movements differ significantly from those created by static vortices.

The deflection is between the blade's tip moving from the bottom surface to the top position. The vortex continues to form during the entire deflection process. The streamwise velocity of the vortex is associated with the velocity surrounding the blade tip. Figure 9.16 to Figure 9.18 show the average streamwise velocity variations in the recording area with circulation increase.

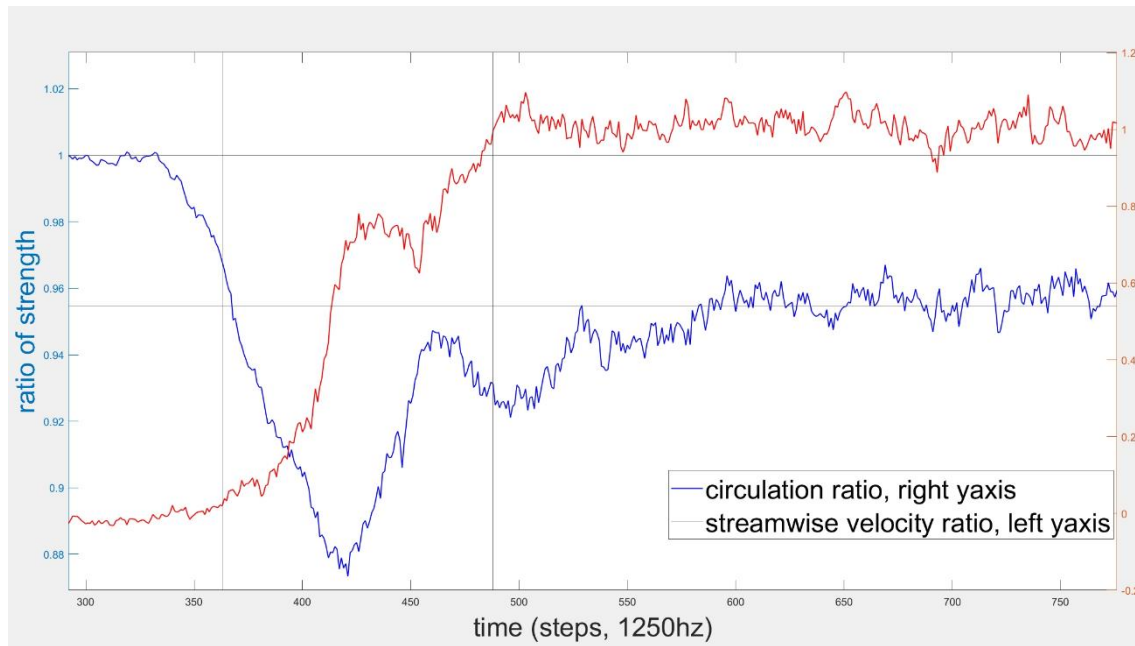


Figure 9.16 The Streamwise velocity with circulation increasing of 200 mm blade

The red solid line is the circulation ratio, with the right-hand side Y axis. The blue line is the average streamwise velocity ratio in the recording area, and the Y-axis is on the left-hand side. The two solid lines on the X-axis indicate the beginning and end of the circulation-increasing process. The two solid lines on the Y-axis are the static vortex's average circulation (upper line) and the vortex's average streamwise velocity (lower line).

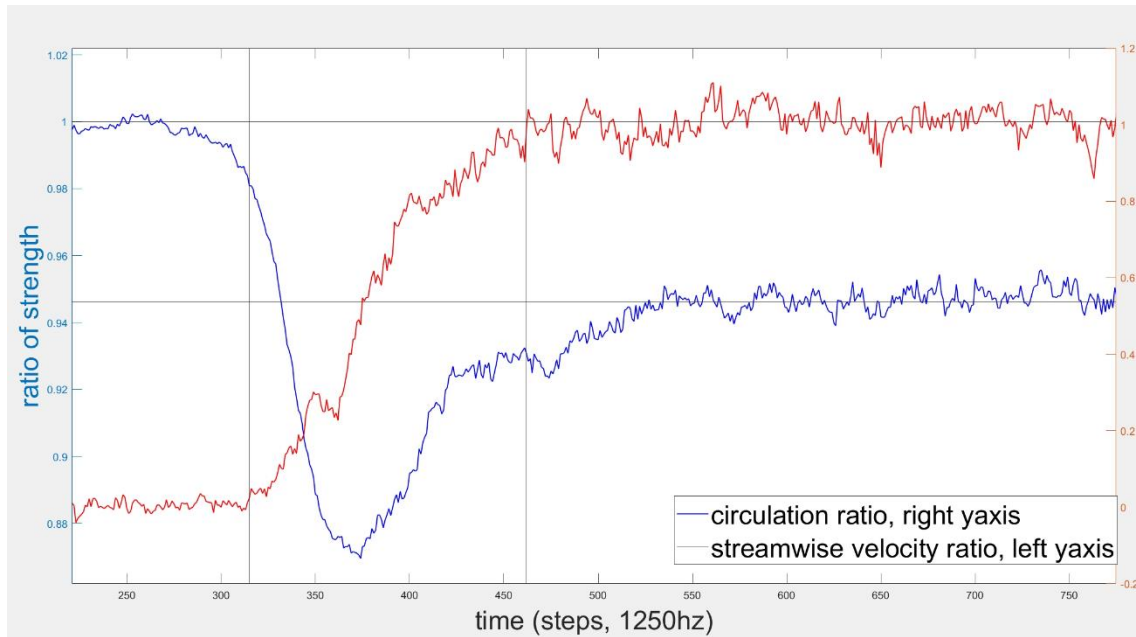


Figure 9.17 The Streamwise velocity with circulation increasing of 150 mm blade

The streamwise velocity at cases 150 mm and 100 mm shows a continued increase after the circulation reaches the static vortex level. The turning points of velocity and circulation are in the same time steps, but the continued increase indicates that the circulation is not directly related to streamwise velocity.

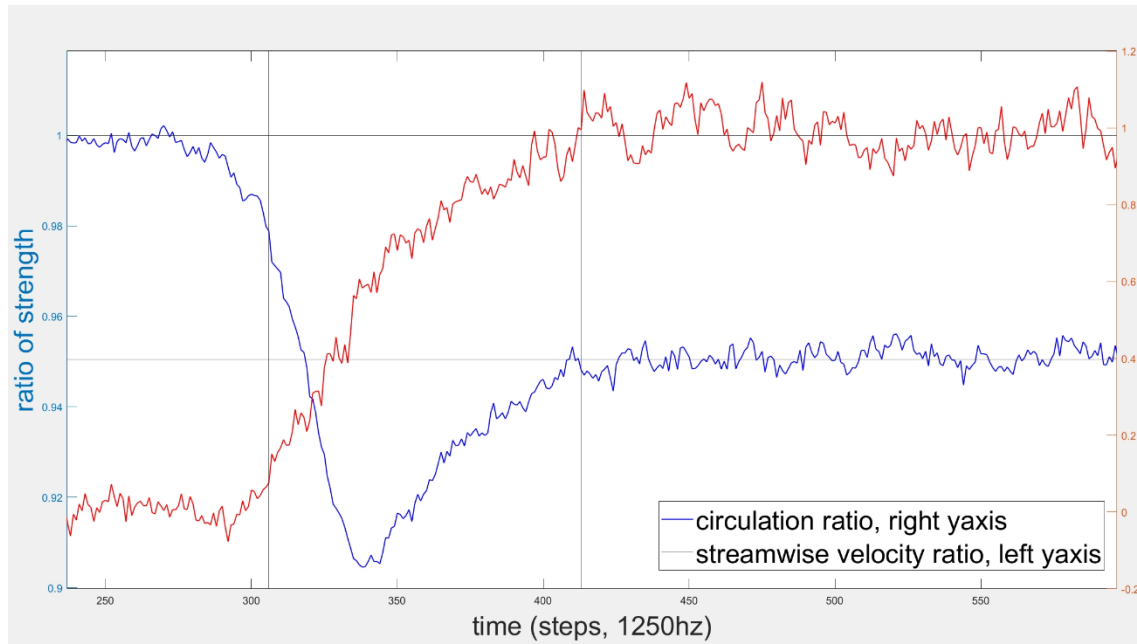


Figure 9.18 The Streamwise velocity with circulation increasing of 100 mm blade

Figure 9.16, Figure 9.17, and Figure 9.18 shows the average streamwise velocities initially decreasing from the undisturbed boundary layer and then increasing to static vortex level. The rapid circulation increase overlaps with the velocity decrease. After the streamwise velocity decreases, the velocity increases with a slow circulation increase. The rapid circulation increase corresponds with the vortex moving into the recording area, and this movement leads the streamwise velocity in the recording area to decrease from the local boundary layer velocity to the vortex streamwise velocity. And the vortex growing up leads to a slower circulation-increasing process and a velocity increase.

The minimal streamwise speed in each case is the streamwise velocity at where the vortex formed and lifted. The speed u at cases 200mm, 150 mm, and 100 mm corresponds to the velocity at heights around 85 mm, 63mm, and 52 mm. The upward motion of the blade has also lifted the vortex upward or given the vortex a force to move upwards, as shown in Figure 9.19.

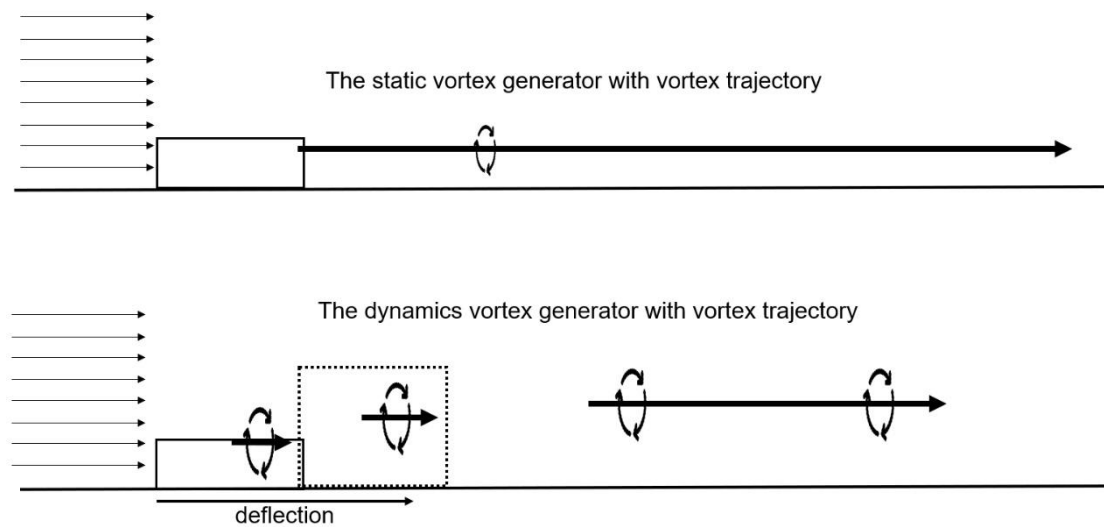


Figure 9.19 The vortex generator with vortex trajectory

Figure 9.19 indicates the variation in vortex trajectory with the blade deflection. The upper plot is the static vortex generator with the static vortex, which moves downstream straight forward. The bottom plot is the dynamic vortex generator; the initial vortex moves upwards with the blade deflection.

The blade deflection does not simply lift the vortex linearly in the current project. The linear vortex lifts more like shifting up the longitudinal vortex. The vortex formation at the final stage of the vortex forming is the vortex growing up at the static vortex location; only part of the vortex has been lifted. Streamwise velocity variations and circulation variations indicate the smooth connection between the lifted vortex and the static vortex.

The blade has a flat top in the Phase II study, and the shape is square or rectangular. In the last deflection period of the flat-top blade, some of the vortex was lifted but has not yet been shed, but newly formed vortices have not been lifted. So, the shedding vortices did not receive equal lift-up movement during deflection, as shown in Figure 9.20. The non-equally lifted-up motion well explains the non-linearly vortex movements, such as the vortex growing up in the same position in the final stage.

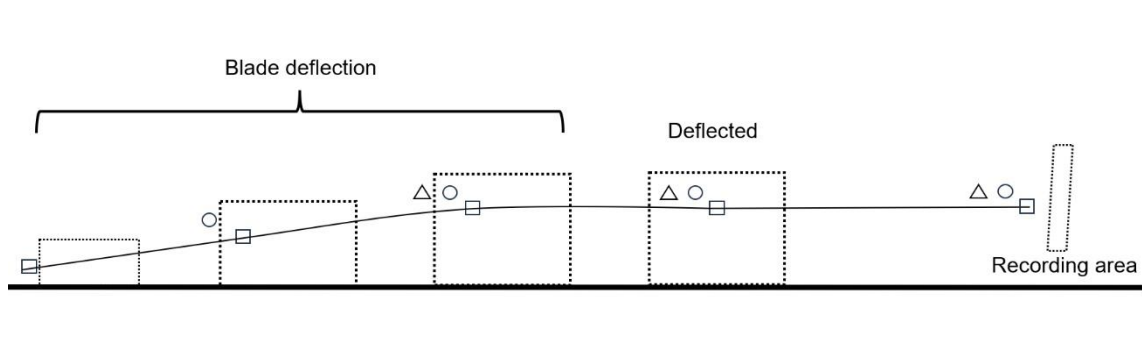


Figure 9.20 Blade deflection with vortex lift-up

Figure 9.20 shows the formation of vortices and their trajectory with blade deflection. The $\square$ is the vortex or air particle at the lower position. The $\circ$ is the vortex at the middle position. The $\triangle$ vortex is in the upper position. The air particle $\square$ reaches the blade at a lower position and forms the vortex, the vortex is also named $\square$. The vortex $\square$ has been lifted with blade deflection. The new vortex formed above the vortex $\square$ has also been lifted up, which is the vortex $\circ$. After the vortex $\circ$ has been lifted, the blade reaches the top, and the static vortex is formed, which is the vortex $\triangle$. The vortex combination includes the lower, middle, and upper vortices. The combination in the current study drives the vortex formation process, such as the two phases of three stages, which are shown in Figure 9.21.

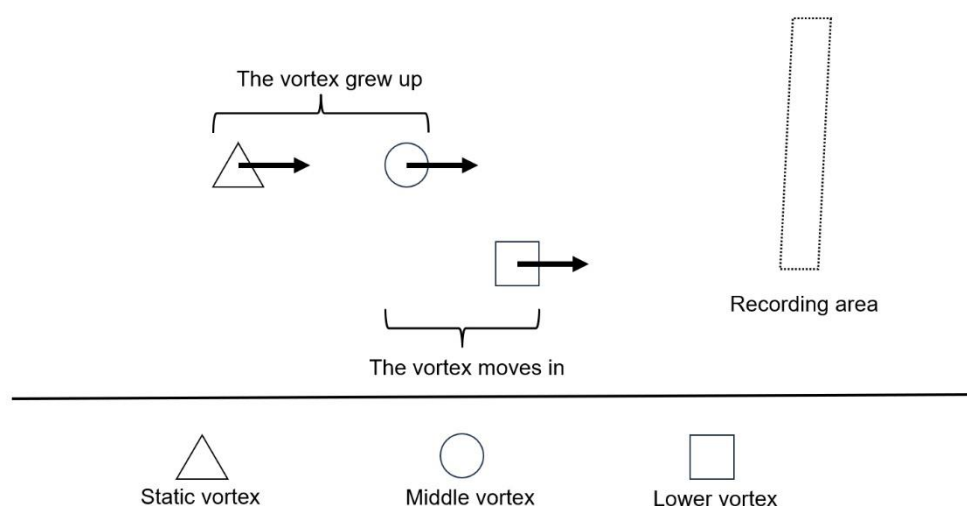


Figure 9.21 The vortex combination with vortex formation

Figure 9.21 clearly shows the vortex of the formation process in the recording area. The wake of part of the lower vortex into the recording area leads to the first increase in circulation. The lower vortex to the middle vortex is the vortex movement part, leading to a rapid increase in circulation. The continuity from the middle vortex to the static vortex is the grown part. The linear circulation increase caused by the lower position vortex is similar to the local Reynolds number increase.

The vortices shedding from the blade continue to form the longitudinal vortex. The three vortices, lower, middle, and static vortex, only represented the relative forming locations. There are vortices formed lower than the Lower vortex □, but they were not recorded in the area.

The vortex movement is crucial to the flow control. The vortex movements are relative to several factors in the current study, such as the speed ratio of airspeed and blade deflecting speed, the shape of the blade, etc. The airspeed and chord length are relative to the time the air particle crosses the blade, which is when the blade lifts the vortex, named as $Time_{blade\ effect}$. The deflecting speed of the blade is connected to the distance of the vortex being lifted up during the $Time_{blade\ effect}$. Both the high-speed ratio and the flat top blade can trigger the same vortex lifted motion, which is the non-equal lift-up; the previous vortex had been lifted up, but the following one did not.

Barth [65] also found a higher vortex vertical displacement on the starting vortex, and the maximum vertical displacement is around 1.7 times higher than the static vortex at 10 h downstream. The difference in the vortex movement is that the starting vortex reached a higher location than the static vortex and then went down. The starting vortex also reaches its highest strength when it is at the highest vertical location. In the current study, the dynamic vortex only has movements and is not higher than the vertical location of the static vortex. One of the possible explanations for the higher location is the common flow-up configuration of the VG pairs. The common flow-up configuration pushes the two vortices close to each other, and the interaction lifts the vortices. The stronger the

vortices, the higher the location of the vortex pair, so the strong starting vortices led to a strong interaction and lifted the vortex pair higher.

The response time is the blade deflection time plus the vortex traveling time. For the 200 mm case, the deflection time is from 0mm to 85mm, and the vortex traveling speed is the minimal speed of the experimental recording. The initial circulation response time and the computing times are shown in Figure 9.22.

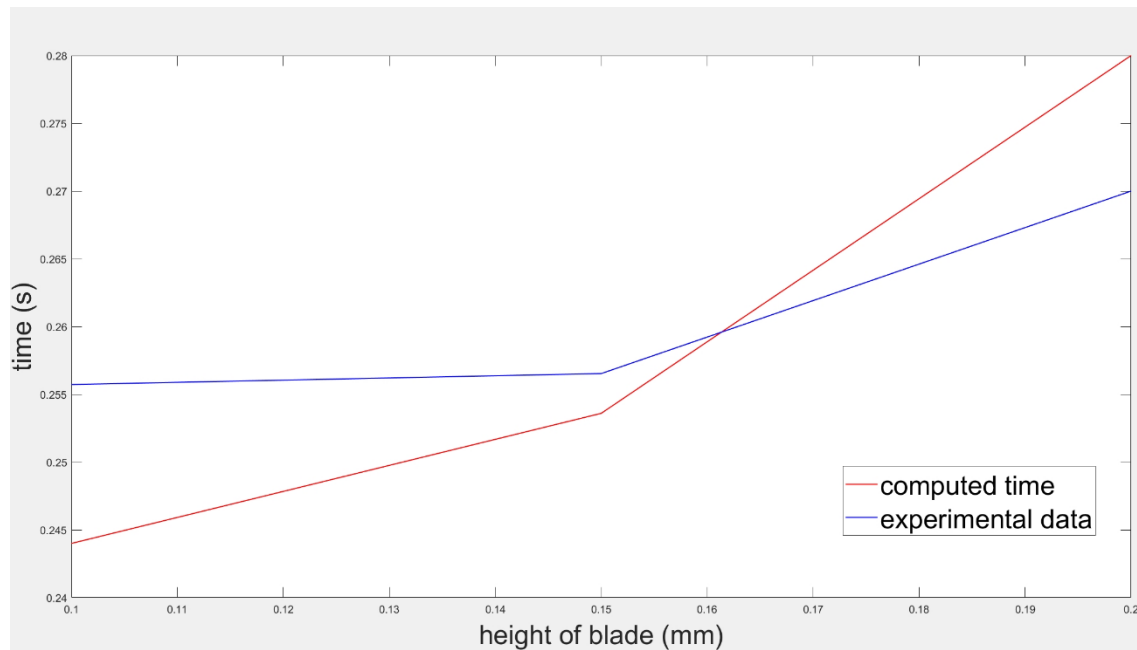


Figure 9.22 Computed time with initial response time

The initial response time is the time of circulation initial to increase. The blue line is the experimental data, while the red is the computed time. The result demonstrates a rough match between the two lines, and the match indicates the vortex section that first appeared in the recording area is forming at a lower position.

9.3 Blade restoration

The vortex movement at blade restoration was clearly studied. The study reveals there are two stages in the restoration: the vortex moves out, and the wake of the vortex remains in the area. The vortex moves out with blade descent, causing a fast decrease in circulation. The clear result will provide a guide of the active flow control device design.

9.3.1 Peak vorticity

The peak vorticities increase at the initial blade restoration stage in both 200 mm and 150 mm cases. The amplitude of the peak vorticity also increases with the height of the blade. The amplitude shows a maximum at the 200 mm condition and then is 150 mm but can not be identified at the 100 mm case, as shown in Figure 9.23.

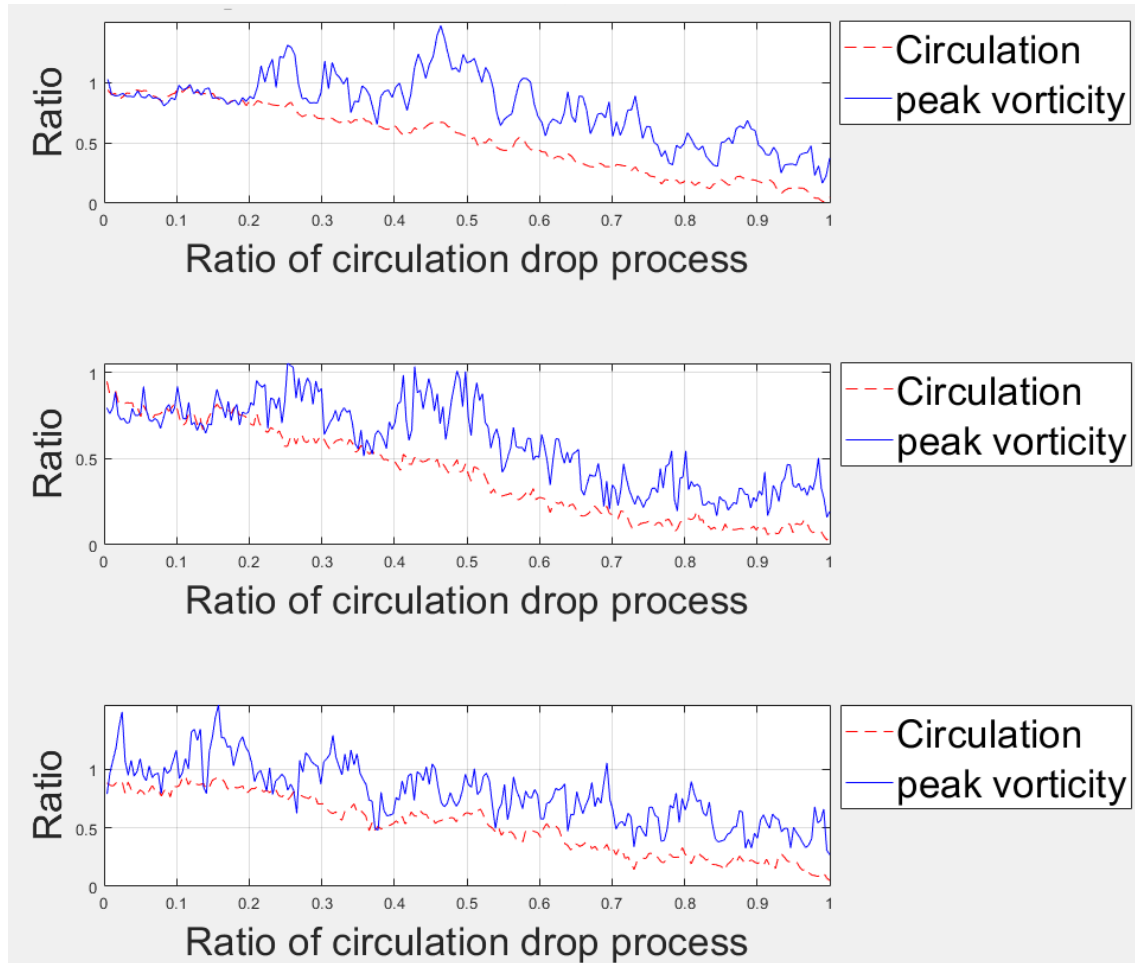


Figure 9.23 The peak vorticity in restorations

Solid line: peak vorticity ratio. — —: circulation ratio. The X-axis is the ratio of the parameter variation process without considering the blade restoration time. The top plot is 200mm, the middle plot is 150mm, and the bottom plot is 100mm.

Figure 9.23 shows peak vorticity late response and also the peak at the restoration. The blade restoration speeds of the three blades are similar, 100mm: 1.5 m/s, 150mm: 1.56 m/s, and 200mm: 1.43m/s. The peak vorticity response is

only related to the height of the blade, which affects the relative downstream distance. The flow control effects increase as the vortex moves toward the bottom surface.

The peak vorticity was a late response in the restoration, at 200 mm case. The peak vorticity shows a strong oscillation and is maintained after the circulation begins to drop; others have also recorded this behaviour [78]. A similar condition is also in the 150 mm case. The oscillation did not found in the case of 100 mm. The vortex movements cause the peak vorticity to have a late response. The vortex moving out of the area causes the circulation to drop, but the peak vorticity location is at the center of the vortex core, so the vorticity can be recorded even after half of the vortex was moved out, as shown in Figure 9.24.

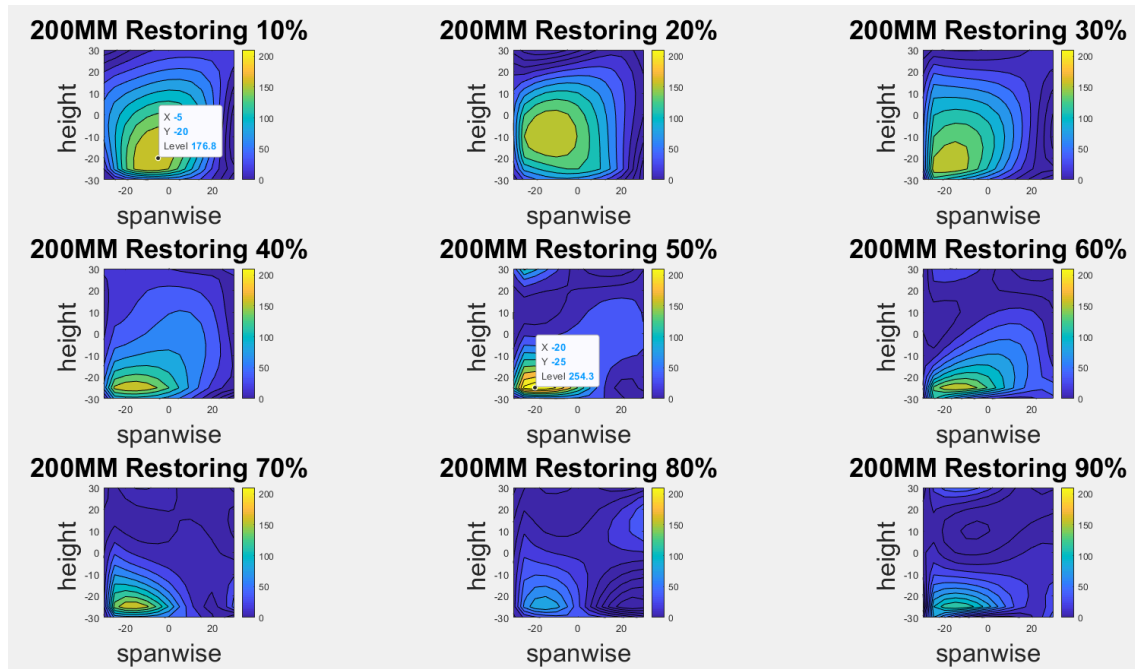


Figure 9.24 Vorticity contour in blade circulation decreasing motion

The increase of vorticity at the beginning of the blade restoration causes a later response or even an increase in the peak vorticity. The blade restoration causes the vortex to move downward, and the movements stretch the vortex core, causing this vorticity to increase. The stretch concentrates the vortex core due to the conservation of momentum. Theoretically, the conservation of momentum increasing the peak vorticity happens due to the radius of the vortex decrease,

but in SHIZAWA's work [69], the streamwise velocity contour of the vortex did not show a clear change in the early stage of blade descent, but the vortex in his work are close to the surface, the ground effects may lead the concentrates to the vortex.

9.4 Simulation of the vortex

The simple predictions were applied to the phase two experiment's static vortex and active motion. The CFD simulations and analytical studies were static and were made up to predict moving motion using static simulation results. The active movement was separated into several static stages for the static simulation. The comparison showed the predictions did not apply to the active motion, and the static prediction was fitted.

9.4.1 Analytical methods

The boundary layer and height of the blade were both involved in the equation for the sub-merged vortex generator. The equation shows the accuracy of static vortex prediction.

9.4.1.1 Active motion

The analytical method simulated the active motion of the vortex forming (circulation increasing in the recording area) and blade restoration (circulation decreasing in the recording area). Results showed the active motions were not predictable by the simple circulation equation.

The reason for the uncertainty was the vortex movements, which are caused by the non-equal vortex lift and size of the recording area. The empirical equation formed the analytical method and only simulated the vortex strength variations, regardless of where the vortex is. The vortex movements cause the circulation variations to differ from the static vortex strength change, such as the vortex going in or out of the recording area. The vorticity and tangential velocity contours showed the motions in the previous chapter.

The shape of the recording area affects the circulation increase slope, which is not a crucial aspect of fluid mechanics. The critical aspect of vortex formation in

Phase II is that the blade deflection has lifted the vortex. However, the previous study on the vortex movements indicates the vortices were not equally lifted. The vortices lifted before the static vortex are poorly understood, such as which vortex goes into the recording area first. Therefore, even vortex movements have an analytical method for simulation. The missing detail of the first vortex still leads to the analytical method combination not being able to simulate the vortex-forming process.

9.4.2 Computational fluid dynamics

The CFD simulation was applied to study the static vortex. The results showed the reasonable accuracy of the vortex location and tangential velocity.

The stages of the circulation increase were discussed. The vortex's movements cause the stages: the vortex's wake, the vortex's moved-in, and the vortex's growth. From the previous result from Chapter 8, the slow motion made up of static stages cannot simulate the vortex forming. The circulation's gradients show the two processes are different. The vortex forming in the Phase II is different from static vortex movements, as shown in Figure 9.25 and Figure 9.26.

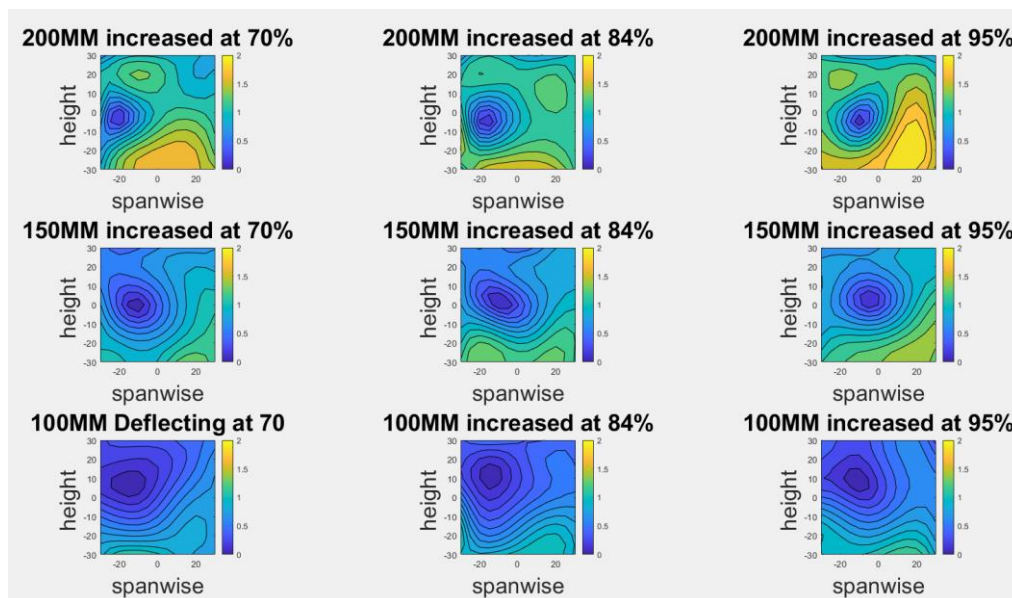


Figure 9.25 The tangential velocity contours of three cases at the final stage

The spanwise is Y-direction, vertical is Z-direction.

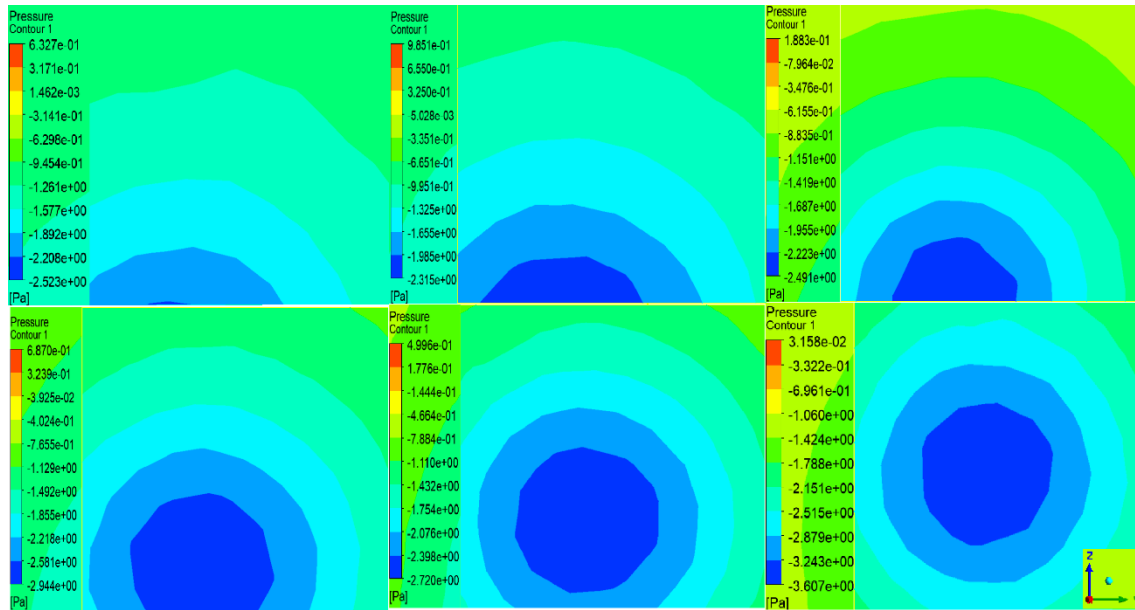


Figure 9.26 The vortex contour of the CFD simulation result

(The current figure is the same as Figure 8.81.)

The heights of the vortexes remained constant in the recording area as shown by the contours plots, but the vortex's strength continued to growing to a steady condition. The vortex becomes stronger as the blade's height increases in the simulation, as shown in Figure 9.26. It also results in an increase in the height of the vortex. So, the active motion cannot be simulated by quasi-steady simulation.

The CFD static simulation accurately captures the vortex's location and simulates the tangential vorticity. The vortex's wake is captured in the simulation, which represents the first stage of the vortex forming in the experimental data.

Vortex movement is a key part of vortex formation. The lower static vortex is lifted up by the blade deflection is a complex and fully dynamic process. This motion caused the vortex to move into the recording area during the second stage, and the following vortices contributed to circulation growth. The static vortex simulation represents the vortex movement into the recording area, not the lower vortex. The vortices shed before the static vortex led to the grew-up motion. The result shows that the static vortex cannot simulate this part. Dynamics simulation may help provide more information than static simulation.

9.4.3 Downstream response time

The response time of the active flow control is important to the control systems design. Chapter 6 represents the circulation variation of the blade deflection and descent. This section discusses straightforward blade deflection and descent predictions based on blade movements and vortex responses.

The critical time points for the circulation response to blade deflection are the moments of the initial response and the formation of static vortices. The time points of the initial response and static vortex formed by all three blades are in Table 5. The local velocity u_h is the velocity in streamwise direction at the tip of the blade; it is measured in the experiments.

	100mm blade	150mm blade	200 mm blade
Local velocity u_h	9.64 m/s	10.16 m/s	10.44 m/s
Deflection time	83 steps,0.066 s	120 steps,0.096 s	175 steps,0.14s
Initial response time	305 steps,0.24 s	317 steps,0.25 s	360 steps 0.29 s
Static vortex formed	413 steps,0.33 s	462 steps,0.37 s	489 steps,0.39 s

Table 5 The key parameters of the flow response

The streamwise distance between the blade and the measuring location is 2 m. A simple model is made for the prediction of the initial response time. As shown in Equation 9.1, the model is the blade deflection time plus the local flow traveling time at the downstream distance. The compare of model and experimental data is shown in Figure 9.27.

$$T_i = T_{Deflection} + T_{traveling} \quad (9.1)$$

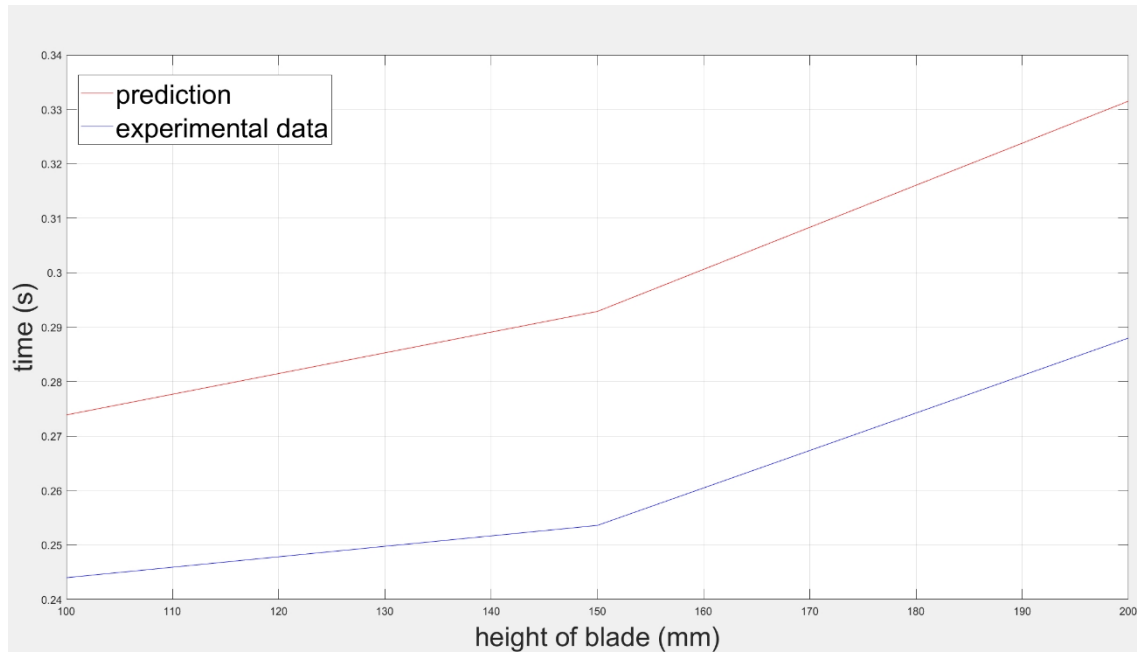


Figure 9.27. Prediction time with initial response time

Figure 9.27 indicates the model has a similar trend with experimental data. The ratio between the prediction data and experimental data is around 0.875. the new prediction with the correction ratio is shown in Figure 9.28.

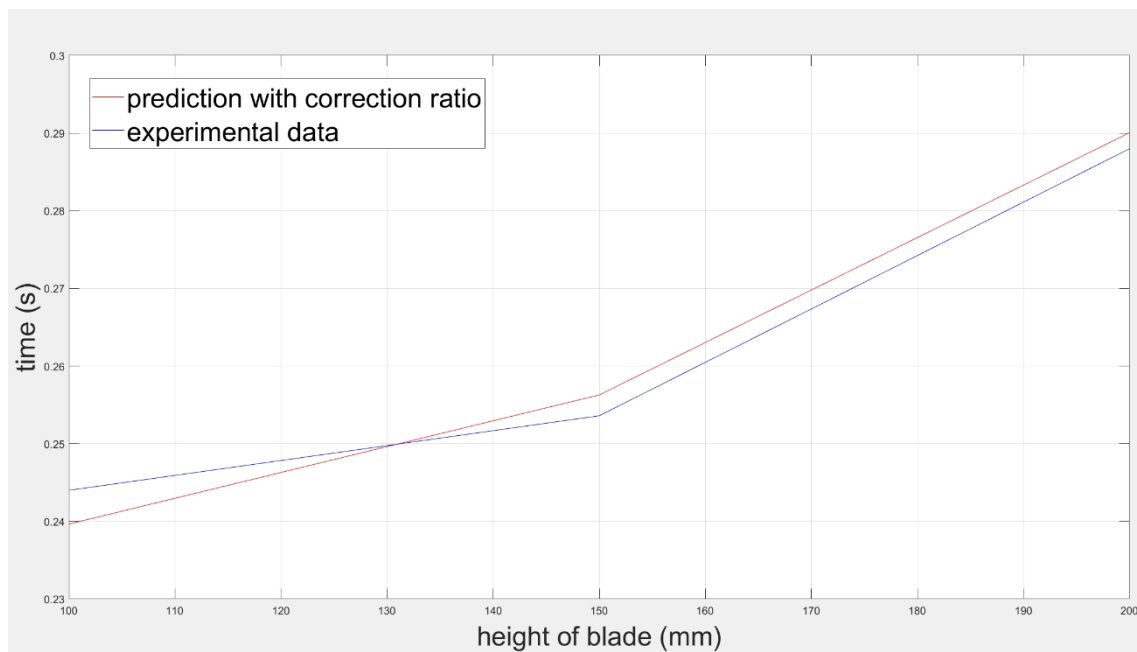


Figure 9.28 The prediction time with initial response time with correction ratio

The prediction result with the correction ratios shows a good consistency with the experimental data. The vortex begins forming when the blade is above the bottom surface and rapidly moves into the static location with blade deflection. However, the empirical model only considered the vortex forming after the blade fully deflects. The prediction result and experimental data show a similar trend; thus, the empirical model requires a correction ratio to match the experimental results. The exact correction ratio is undetermined due to a lack of thorough examination; therefore, the model is suitable solely for qualitative studies.

The flow response to the blade restoration is simple. The vortex moves downward as the blade height decreases. The key time points of the blade restoration process are shown in Table 6. The table includes the first response of circulation decrease and the circulation vanishing time points.

	200 mm	150 mm	100 mm
Total restoration time	0.67 s	0.4984 s	0.3247 s
First response	0.2624 s	0.206s s	0.2176 s
Total response time	0.416 s	0.4104 s	0.4088 s

Table 6 The time points of the blade restoration response

The total restoration time is the duration taken by the blade to complete the restoration process. The first response time point is between the blade beginning to restoration and the first circulation decreasing. The total response time spans from the moment when circulation starts decreasing until it reaches zero. The time points are shown in Figure 9.29.

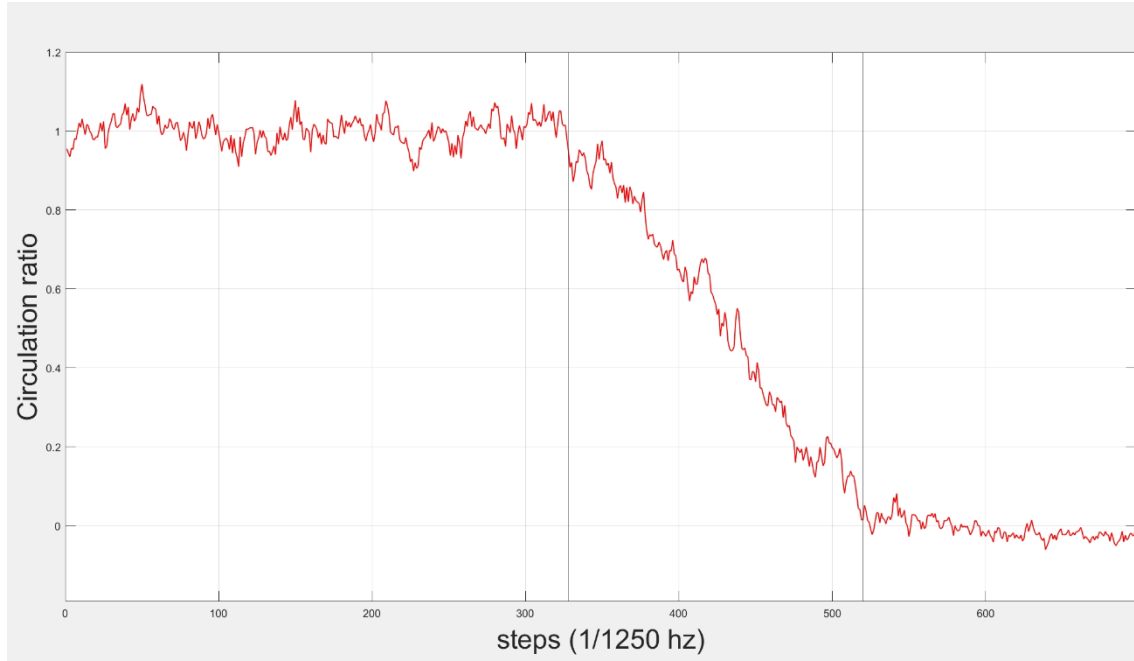


Figure 9.29 The time points of the blade restoration process

The two solid lines on X axis are the first response and the final point of circulation dropping. The period between the two lines is the time of circulation decrease.

The flow physics of blade restoration involves the downward movement of the vortex caused by the blade's decrease. The first time of circulation response is when the first circulation drop appears(from 0 to the left-hand sideline), and the physical meaning is the time of the first moving downward vortex that travels from the blade to the recording area, as shown in Equation 9.2.

$$T_{initial} = \frac{\text{downstream distance}}{\text{vortex traveling speed}} \quad (9.2)$$

The total response time is the time circulation drops to zero since the blade begins to restore (from 0 to the right-hand side line). The circulation-dropping process in the recording area is a result of the vortex moving out. This total time is linked to both the blade covering the same distance as the vortex and the time it takes for the vortex to travel, as shown in Equation 9.3.

$$T_{total} = T_{initial} + \frac{\text{vetical distance of recording area}}{\text{blade downward speed}} \quad (9.3)$$

The time consumed is the total circulation decrease time (between two lines on X-axis), equal to the time the blade moves the same distance as the vertical length of the recording area, as shown in Equation 9.4. The prediction times and experimental data are shown in Figure 9.30.

$$T_{consumed} = \frac{\text{vertical distance of recording area}}{\text{blade downward speed}} \quad (9.4)$$

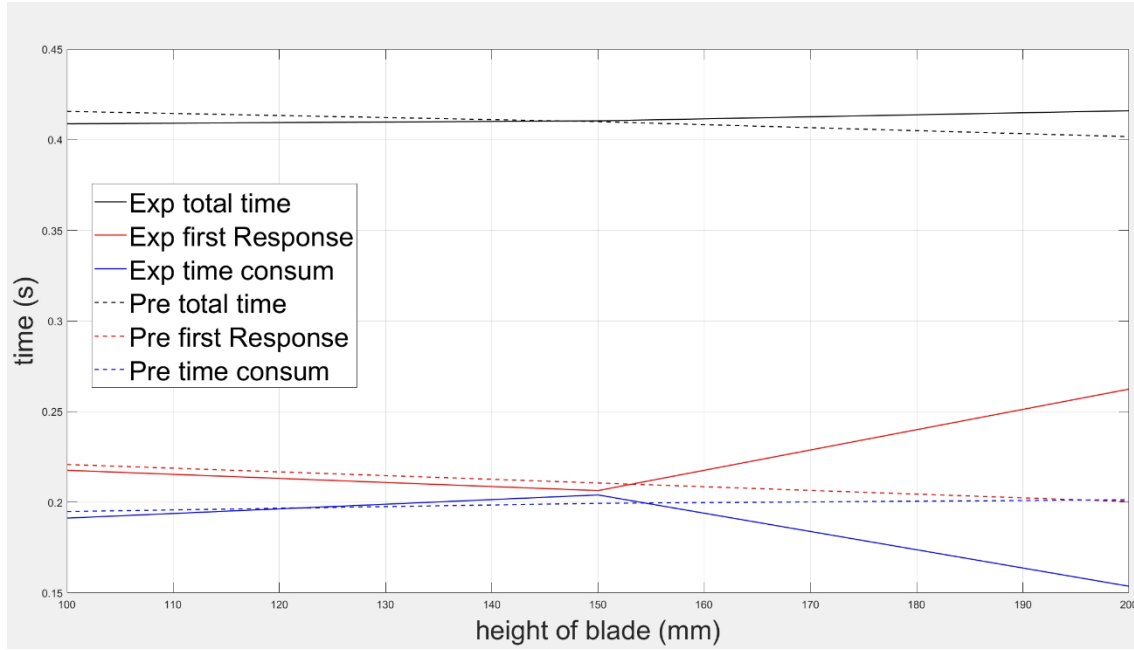


Figure 9.30 The prediction time with the initial response time of the blade restoration case

The comparison shows a close match. The error between prediction time and experiment data could result from the manual process of selecting key time points or measuring velocities, such as the vortex streamwise velocity or blade restoration velocity. The result indicates the possibility of predicting the downstream flow response of the restoration process from beginning to end.

10 Conclusion

This project studied the details of vortex response and guided the future design of active vane vortex generators. The result is contributed to the active flow control on blending wing body aircraft types.

10.1 Types of vortex forming

The current study contributed to the knowledge of vortex-forming types response to the blade deflections. The study highlights the benefits of various vortex formations generated by active vortex generators. The first type of flow response is about the strong starting vortex. The vortex forming with a strong starting vortex is preferred for short-range flow control, but vortex movements are complex, such as spanwise movements, vertical movements, and the combination of both directions.

The second type of flow response involves vortex formation without a starting vortex. According to theory, this type of vortex formation is usually linked to slower blade deflection. However, our comparison of deflection velocity ratios suggests that blade deflection alone is not the only factor contributing to the starting vortex formation. This second type of vortex formation is examined in Phase II in detail.

One of the key contributions of this study lies in the practical application of vortex-induced control mechanisms, in which the second type of vortex-forming has a smoother circulation variation compared to starting vortex. These characteristics in the vortex formation simplify the design approach for the control system.

10.2 Downstream Response with Blade Motion

In the current project, this work has demonstrated a significant contribution to the field of active flow control through the detailed study of the initial vortex movement. The study shows the vortex forming at a lower position, and the blade deflection lifted the weak vortex to the static vortex position. The blade deflection lifts up the vortex from the lower position and causes rapid vortex movements.

One of the key contributions of this study lies in the practical application of vortex-forming induced control mechanisms in the static vortex location. There are three parts in the forming process, with equal circulation increasing. They are the wake of the vortex; the static vortex goes to the static vortex area, and the vortex grows up. The vortex movements cause the wake of the vortex and the vortex to move into the recording area both with a rapid strength increase, but the vortex growing up has a slow-increasing slope. The stage circulation and vortex movement are well demonstrated and can be used as the device design guideline.

This study's relative size of the blade did not affect the staged slope of circulation increase. The blade size has increased from 100mm to 200m, leading to a distance decreasing from 20h to 10h, with less surface interaction. The circulation increase of the vortex forming in the recording area shows the three stages of the slope for all three cases.

10.3 Vortex simulation

The static/steady model cannot simulate the dynamic vortex forming process. The empirical model and CFD simulation used a steady approach that cannot predict the current vortex-forming because it is a dynamic process.

The vortex in the forming process is less affected by surface interaction. The path of the vortex movements from the CFD simulations is opposite to that of the experimental data. The vortex in simulations is affected by the surface interaction moving further spanwise, but actually the vortex in the process moves faster in the vertical direction, leading to less surface interaction.

The simple empirical model is made according to the vortex movements. The model involves the blade deflection time and the vortex traveling speed at the top of the blade. The model ignores the vortex movement during the blade deflection and is only possible for qualitative prediction.

The flow physics of the blade restoration is clear and predictable. As the blade moves downward, the vortex also moves out of the recording area, decreasing circulation. The simple prediction is based on the blade moving speed and vortex traveling speed, which matches the experimental result well.

Based on the current study, the separation controls in front of the engine on BWB aircraft employing an active vane vortex generator is possible. Once the vortex's strength is clear to prevent separation, the study can help illustrate the circulation variation before the static vortex at aim locations and show the effects of blade movements. The illustration can lead to a better control strategy design and the flow control device design.

11 Future works

The vortex forming at a static vortex location was studied, but the forming process was highly three-dimensional, with some information loss. The mechanical part of the active vortex generator was affected by wear and tear. The vortex's movement outside the recording area is still unknown, so a bigger recording area is needed. The probe in the experiment was in the flow, which led to distortion at testing points.

11.1 Future experimental works

The PIV (Particle Image Velocimetry) method can increase the recording area and eliminate the probe intrusion affecting the measurements. However, the blade movement was rapid, and the way the dye was injected into the moving vortex needed to be solved. The starting vortex may be shed in the early stage of the blade deflection process, and the small recording area used in the current study cannot catch the vortex, leading to missing details. The bigger recording area could examine the presence of the starting vortex and provide a detailed picture of the downstream response to the blade deflection.

The current study revealed the vortex has been lifted from the lower to upper position. So, the easiest way to examine this vortex movement is to inject the dye into the lower position and record the movement of the dyed vortex in a micro view by camera.

The blade deflecting speed has a significant impact on the formation of the vortex. The deflection speed of the blade is uncontrollable in the study, which leads to the deflection speed effects being remains unknown. So, the controllable blade is important for future studies.

The vane blade was bent due to the repeated tests in the experiments. The bent caused the deflection speed to drop in the following test. The geometry is also directly linked to the vortex. More blades are needed in future experiments.

11.2 Future simulation works

The current study focuses on the steady simulation and tries to sum up the steady vortices to predict the dynamic vortex formation, but the prediction did not fit with the experimental results. Unsteady CFD simulation could better address the vortex-forming process, which gives a bigger and more internal view of vortex formation.

The CFD model in the current study has a bigger domain than the experiment for an easier numerical stability. In future work, the model should be the same size as the wind tunnel to improve simulation results. The boundary layer thickness in the current experiment was important. Therefore, a better resolution of the CFD mesh in the boundary layer should be carefully addressed.

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APPENDICES

In the appendix, the context includes the additional literature review, experimental data processing details, data from the experiments, and analysis that were plotted and shown.

Appendix A

Appendix A introduces the additional literature review, which is not directly connected with the study.

A.1 Additional literature review of air jet

The air jet was the option for active flow control, and the vortex formatted downstream is similar to the passive vortex generator, but the flow physics of formations is different. Therefore, the study of air jets references the deflectable vane blade vortex generator.

A.1.1 Steady air-jet vortex generator

The steady air blowing has been studied and applied to the prototype for a long time, and the idea was given by Wallace [79]. Due to the flow mechanics, the orifices embedded in the boundary layer with a special skew pitch angle have better effects than the orifice normal to the wall.

The parameters involved in steady blowing were studied for recent decay. The skew and the pitch angles are important to the air-blowing vortex generator, as shown in Figure 11.1.

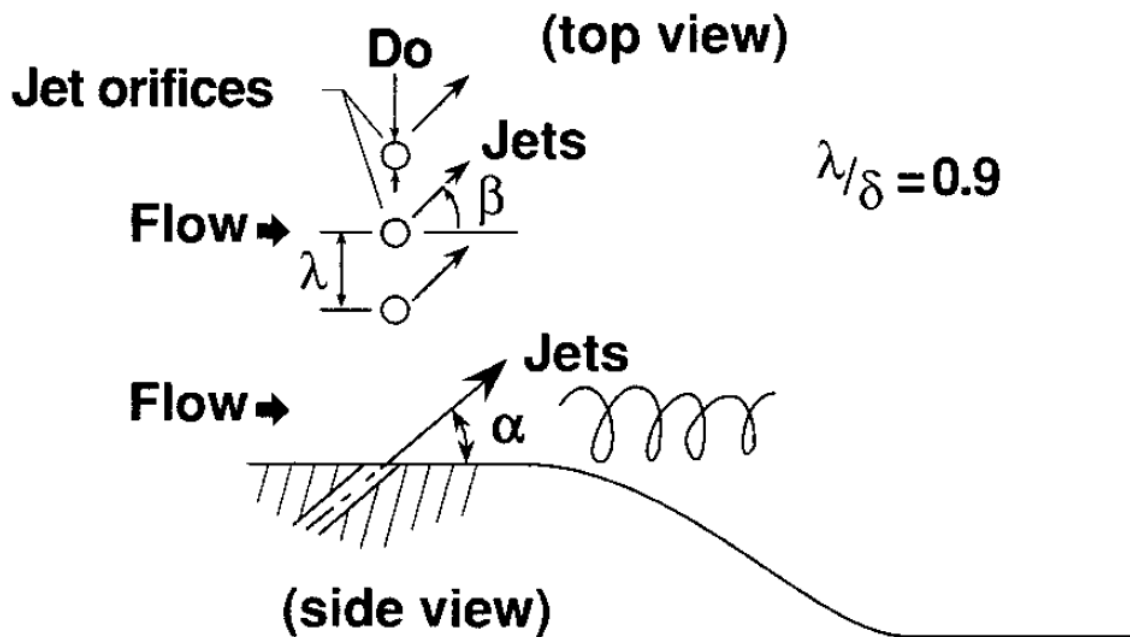


Figure 11.1 The key parameters of the steady air jets [80]

The typical geometry of the steady air-jet surface device is shown in Figure 11.1. The first part is the top view of the air jet. It shows the orifice diameter, D_o , and skew angle (β), the angle is between directions of coming air and air-jet in crosswise. The inclination angle (α) is shown in the bottom part of Figure 11.1, it is the angle between the directions of jet axis and the surface of the plane (horizontal plane).

Several research studies have investigated the skew and pitch angle range [56,64,81–84]. Selby carried out the parameters based on a row of air jets with controlled skew angles [79]. The air jet devices are the counter-rotating vortex downstream. The size of the orifice, the skew and pitch angles, and the VR ratios (the ratio of jet speed to free-stream flow speed) were examined. The result shows the optimum skew and pitch angles are highly related, as shown in Figure 11.2 and Figure 11.3; the optimum skew angle changes with pitch angle changes. The air jet effects were zero at some specific skew, pitch, and VR ratio combinations. Pearcy and Stuart studied the mechanism of the vortex when the skew angle increases [79]. When the angle increases, one of the vortices will become the dominant, and close to the surface, the weaker vortex goes up and

beyond the dominant vortex. The experiment result shows the optimum skew angle are between 60° to 90° . The pitch angle is related to the skew angle but less than 90° .

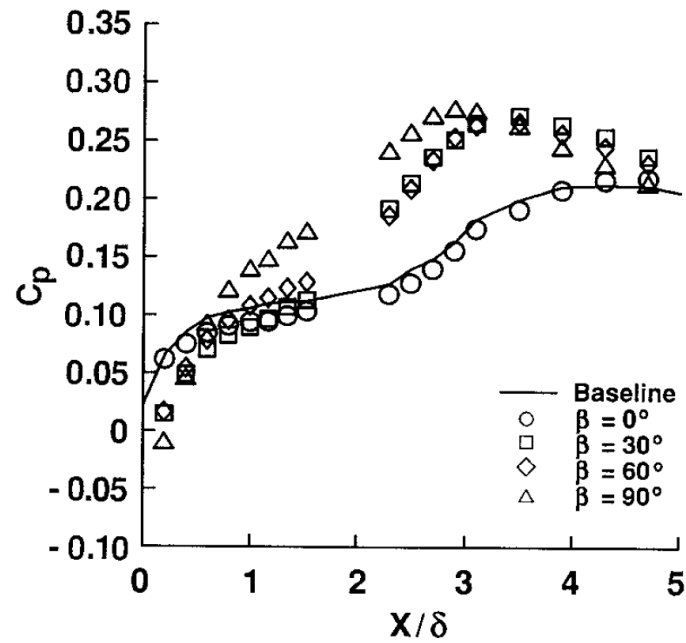


Figure 11.2 Pressure distribution for jet vortex generators with different skew angles [84].

For pitch angle is 45° $D_o/\theta = 0.24$, $C_Q = 0.034$, $VR = 6.8$. D_o is the diameter of the air jet ports. C_Q is total flow coefficient. θ is momentum thickness. VR is the ratio of jet speed to free-stream flow speed. The skew angle is β .

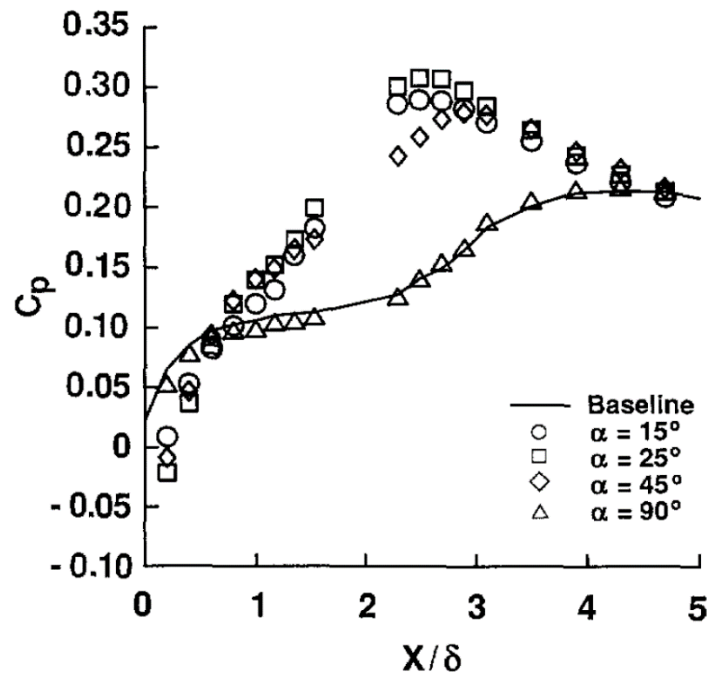


Figure 11.3 Pressure distribution for jet vortex generators with different pitch angle [84].

The skew angle is 90° , $D_o/\theta = 0.24$, $C_Q = 0.034$, $VR = 6.8$. D_o is the diameter of the air jet ports. C_Q is total flow coefficient. θ is momentum thickness. VR is the ratio of jet speed to free-stream flow speed. The pitch angle is represented by β .

The vortex in downstream of the single air jet was studied by Johnston [83]. The pitch angle was fixed at 45° , VR ratio controls at 1, only the skew angle changes from 45° to 135° . The results show the optimum skew angles are between 45° to 90° . The experiments with rectangular orifice air jets show the optimum range of the pitch and skew angles from 30° to 60° [85,86]. The optimum angle of the pitch and skew were summarised and suggested by Simon as skew at 60° and pitch at 30° [84].

The relative velocity of the air jet is important to the flow control. If the relative velocity (VR ratio) increased, the strength of the vortex increased, which led to an increase in effectiveness. Some of the air-jet parameters are related to the VR ratio, such as the diameter of the orifice and the total mass coefficient. The

improvement of those two parameters relates to increases of the VR ratio and vortex strength, shown as in Figure 11.4.

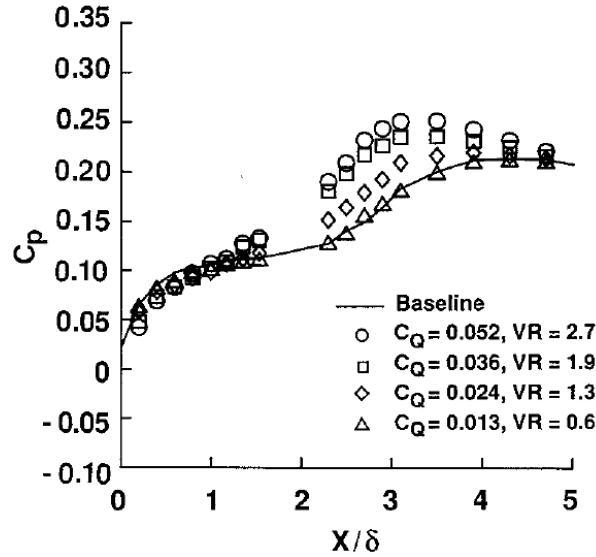


Figure 11.4 Pressure distribution for jet vortex generators with variable VR ratio [84]

For skew angle is 90° $D_o/\theta = 0.48$, pitch angle = 45° , skew angle = 90° . D_o is the diameter of the air jet ports. C_Q is total flow coefficient. θ is momentum thickness. VR is the ratio of jet speed to free-stream flow speed.

The vortex generated by the jet can achieve the 40δ downstream to control the local separation. The air jet energized the vortex core directly. This procedure led to the decay of the vortex on peak vorticity, and circulation is lower than the normal passive vortex generator. The classic orifice is a round hole, but the rectangular orifice has the higher vorticity shown in studies [11].

A.1.2 Periodic air-jet vortex generator

Pulsed air jets are better than steady air jets because of their lower mass flow requirements. These results are indicated by Mcmanus [87]. The experiments show that 50% of the frequency with the same orifice geometry and the same VR ratio have similar effects on separation suppression [88].

The starting vortex is one of the important features of the periodic air jet. It was studied by Johari [89] and Gharib [90]. The whole vortex's structure comprises a starting vortex and a steady vortex. The starting vortex separates from the jet port within the nondimensional distance four times the port's diameter. After the separation of the starting vortex, the steady vortex forms at the jet port. Compared to the steady jet, the main performance improvement of the periodic air-jet is pronounced. This is because of the starting vortex's flow control ability.

The pitch and skewing are important parameters of the pulsed air jet because the starting vortex has been affected directly. The starting vortex is a key factor that improves the ability of the pulsed air jet, which is similar to the steady blowing when the mass flow is less. Such an improvement is because the starting vortex has been amplified and re-directed by the boundary layer. Within the amplification and re-direction motion, the vortex ring formed based on the wall-normal vorticity of the boundary layer. The vorticity of wall-normal rolled up into the vortex, thus stretching and bending the vortex downstream. All of those procedures are given an incline between the vortex and boundary layer, which comes from the jet tube's pitch and skewing.

The diameter of orifices controls the size of the starting vortex structure, and the diameter is dicker than the boundary layer thickness. In that case, the circulation of the starting vortex increases. The starting vortex goes through the boundary layer. As a result, the degrees of the amplification and re-direction from the boundary layer are minimal.

A.1.3 Starting vortex

Additional information on the starting vortex is in this section. The starting vortex is one of the most important features of vortex formation. A large velocity gradient appears at the upper surface of the trailing with the movements of the airfoil. This situation leads to high vorticity and roll-up to format a vortex. The starting vortex is equal in magnitude, but the rotation direction is opposite. The starting vortex became stronger with the increase of circulation around the airfoil. Therefore, the starting vortex has equal strength to the circulation around the airfoil. This

situation exactly satisfied the Kutta condition. The picture of starting vortex is shown in Figure 11.5.

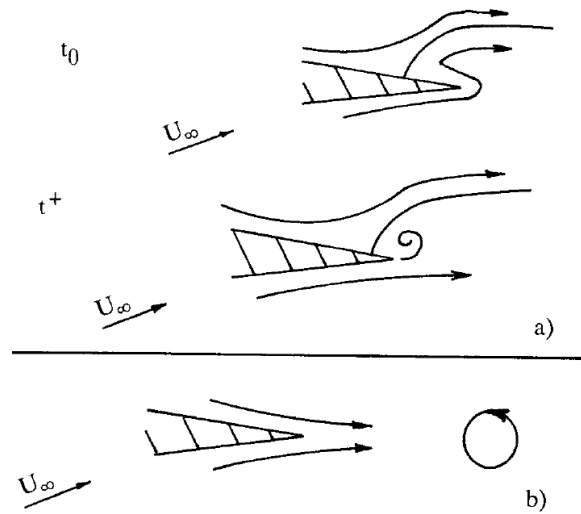


Figure 11.5 Starting vortex forming process [7]

a): Evolution of the starting vortex from the irrotational solution. b): The starting vortex after the Kutta condition was satisfied

According to the Kutta condition theory, the starting vortex circulation is equal and opposite to the circulation around the airfoil. However, the experiment shows a different result. The investigation which Faclo gives that it puts the Naca 0012 airfoil on a moving belt, and the vorticity was recorded by laser lines downstream after the airfoil moved forward suddenly [91].

The experiment showed only $2/3$ of the total circulation of the starting vortex, which was measured after 1.3 chord length of airfoil movement. The other $1/3$ circulation continued to shed from the airfoil. The strength of the starting vortex in the experiment was kept constant after the airfoil moved forward 0.3 chord length.

Lambourne studied the leading-edge vortex forming without the starting vortex [92]. The experiment focuses on the delta wing that put it in the low-speed water flow. The wing had a sudden change of incline if the flow with three inclines, 20° , 40° , and 60° . The Reynolds number on root chords was 2×10^4 . After the sudden incline change of the wing, the flow was separated at the leading edge

and thus rolled up to form the vortex. The vortex combined with the trailing edge vortex then moved downstream. The vortex was combined with different portions of vortex layers. The vorticities from different portions that are inside the vortex lead to distortion and diffusion. The distortion and diffusion show the initial vortex was an unstable condition. Then, the vortex turns to a steady condition.

A.1.4 Turbulent model of simulation

This chapter introduces the turbulence model used in the Phase II simulation. Turbulence flow is one of the most complicated flow phenomena. It was described as three-dimensional, rotational, disordered, diffusive, dissipative, and intermitted by Markators [93]. The smaller-scale fluctuations in the turbulence cause the momentum exchange and finally dissipate. Now, the turbulence is solved by a three-dimensional time-dependent Navier-stokes equation with different models.

A.1.5 Flow physics of turbulence boundary layer

The key point of the turbulence flow is energy transfer within the eddies. Simulating the variation of eddy size distribution and the fast variance is almost impossible due to the small mesh size and time step. The total mesh and time requirements become unacceptable to the model computer.

A conceptual shortcut of turbulence was applied to the turbulence flow to overcome the varying sizes of eddies. The eddies are contained in a control box with a unit volume and a unit time step. Differential equations are applied using the equations of conservation of mass, momentum conservation, and energy to the unit volume. The Navier-Stokes equation can be used to compute the average condition of this control box.

A.2 Turbulence model

The model of turbulence applied on the mesh box was based on Navier-Stoke equations, which were the partial differential equations describing conservations of flow.

In the unit volume, the volume fraction r_i of the phase i can be integrated with n phases, as shown in Equation A.2.1.

$$\sum_{i=1}^n r_i = 1 \quad (\text{A. 2.1})$$

The mass conservation of mass of phase i is shown in Equation A.2.2. The mass per unit volume flowing into all phases is zero by integrating all different phases, as shown in Equation A.2.3.

$$\frac{\partial}{\partial t}(\rho_i r_i) + \nabla(\rho_i r_i \vec{V}_i) = \dot{m}_i \quad (\text{A. 2.2})$$

$$\sum_{i=1}^n \left((\rho_i r_i) + \nabla(\rho_i r_i \vec{V}_i) \right) = \sum_{i=1}^n (\dot{m}_i) = 0 \quad (\text{A. 2.3})$$

The conservation of momentum in phase i is shown in Equation A.2.4. The momentum was generated by the velocity u_{ki} at the direction k of phase i . The momentum equals all internal and external forces, pressure, friction, interaction, unit vector, and body force. The unified pressures p are the same within all different phases. The body force per unit volume and the unit vector in direction k is B_{ik} and $\vec{k}$, respectively. Outside the united volume, friction and interaction forces in direction k is F_{ik} and l_{ik} .

$$\frac{\partial}{\partial t}(\rho_i r_i u_{ik}) + \nabla(\rho_i r_i \vec{V}_i u_{ik}) = r_i (-\vec{k} \cdot \text{grad } p + B_{ik}) + F_{ik} + l_{ik} \quad (\text{A. 2.4})$$

The conservation of energy is shown in Equation A.2.5. The energy in the united volume at the current phase was made up of three different parts, energy transfer in the volume, H_i , energy transfer to the volume from surroundings, Q_i , and the interactions with others, J_i . The total enthalpy in the volume at the current phase is h_i .

$$\frac{\partial}{\partial t}(\rho_i h_i - p) + \nabla(\rho_i r_i \vec{V}_i h_i) = r_i Q_i + H_i + J_i \quad (\text{A. 2.5})$$

The properties are described by conservation equations. The equation of total turbulent flow can be considered as a combination of the steady condition and fluctuations by Reynolds composition, shown in Equation A.2.6. The mean value of the steady condition is represented by $\bar{\phi}$. The random variation of flow is

represented by ϕ' . The time average of variation equals zero, $\overline{\phi'} = 0$. The total quantity of flow at the current time is ϕ .

$$\phi = \bar{\phi} + \phi' \quad (\text{A.2.6})$$

The mean value of turbulent flow $\bar{\phi}$ is the steady time average part of the instantaneous scalar quantity ϕ , as shown in Equation A.2.7. The time scale t_1 is for fluctuations, while t_2 , the slow motions, is the time scale for the time-dependent mean value.

$$\overline{\phi(x)} = \lim_{t \rightarrow \infty} \frac{1}{\Delta t} \int_{t_1}^{t_1 + \Delta t} \phi(x, t) dt \quad t_1 \ll \Delta t \ll t_2 \quad (\text{A.2.7})$$

The Reynolds compositing Equation A.2.6 are substituted into single-phase mass conservation Equations A.2.1 and then into Equation A.2.3 (Equation A.1.6.6: phase mass conservation, Equation A.2.1: all phase mass conservation, Equation A.2.3: phase united). Take the first derivatives, time average continuity NS equations from the resulting equations, shown in Equation A.2.8 and Equation A.2.9. Equation A.2.9 is the Reynolds Averaged Navier Stoke equation, RANS.

$$\frac{\partial \bar{u}_i}{\partial x} = 0 \quad (\text{A.2.8})$$

$$\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial}{\partial x_j} (\bar{u}_i \bar{u}_j) = -\frac{1}{\rho} \frac{\partial \bar{p}}{\partial x_i} + \nu \frac{\partial^2 \bar{u}_i}{\partial x_i \partial x_j} - \frac{\partial}{\partial x_j} (\overline{u'_i u'_j}) \quad (\text{A.2.9})$$

The velocity in phase i represented by u_i , the mean velocity represented by $\bar{u}_i$, the fluctuating velocity is u'_i . Kinetic viscosity is represented by ν . The mean value of velocity in two different directions is the Reynolds stress tensor, which is $\overline{u'_i u'_j}$ in Equation A.2.10. The tensor is symmetric within six components. The unknown pressure, tensor(stresses), and velocities make the modeling process harder. To model the Reynolds stresses, the model has been simplified to solve the "closure" problem by mean flow quantities.

$$\tau_{ij} = \overline{u'_i u'_j} \quad (\text{A.2.10})$$

The Boussinesg eddy-viscosity approximation is the most common model to resolve the problem of "closure". Both turbulent and molecular motions were

considered an analogy by the approximation to connect the Reynolds stresses with the mean motion's strain rate. The different scales of eddies in the turbulent flow were assumed as particles. The interactions and momentum exchange were similar with molecules, so the kinetic theory of gases can be applied to other particles. Therefore the Reynolds stresses can be analogized to the viscous stress of the molecule, as shown in Equation A.2.11.

$$\tau_{ij} = \overline{u'_i u'_j} = \frac{2}{3} k \delta_{ij} - \nu_t \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \quad (\text{A. 2.11})$$

The ν_t in the upper equation was the eddy viscosity or turbulence viscosity, which was not constant and had a large spectrum within the total flow. The δ_{ij} was the Kronecker delta. The k represents the kinetic energy of turbulence, shown in Eq A.2.12.

$$k = \frac{1}{2} \overline{u'_i u'_i} = \frac{1}{2} (\overline{u_1'^2} + \overline{u_2'^2} + \overline{u_3'^2}) \quad (\text{A. 2.12})$$

Substituting the Reynolds stresses tensor from Equation A.2.11 to the Reynolds Averaged Navier Stoke equation (RANS), Equation A.2.9. The result is shown in Equation A.2.13. The mean value of pressure $\bar{p}$ is absorbed by the isotropic part from the Reynolds stress tensor.

$$\frac{\partial u_i}{\partial t} + \frac{\partial}{\partial x_j} (\bar{u}_i \bar{u}_j) = - \frac{1}{\rho} \frac{\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial x_j} \left((\nu + \nu_t) \frac{\partial \bar{u}_i}{\partial x_j} \right) \quad (\text{A. 2.13})$$

The ν_t in the equation was relative to velocity V_t and characteristic length L_t . The most common models $k - \omega$ and $k - \varepsilon$ were two-equation models that involved solving the unknown ν_t as shown in Equation A.2.14 and A.2.15. The simplest model was considered the ν_t as the algebraic expressions.

$$\nu_t = C_\mu f_\mu \frac{k^2}{\varepsilon} \quad (k - \varepsilon \text{ model}) \quad (\text{A. 2.14})$$

$$\nu_t = \alpha^* \frac{k}{\omega} \quad (k - \omega \text{ model}) \quad (\text{A. 2.15})$$

In $k - \varepsilon$ model, f_μ was the damping function, ε was the rate of the turbulence energy dissipation. In $k - \omega$ model, the ω was the dissipation per unit turbulence kinetic energy. Both C_μ and α^* were constant.

In the one-equation model, the turbulence kinetic energy was applied to represent the velocity v_t . The length scale was settled algebraically, usually based on the experimental data as shown in Equation A.2.16. In the equation, C_{v1} is the nondimensional constant.

$$v_t = C_{v1} \sqrt{K} L \quad (\text{A.2.16})$$

The Spalart Allmaras (SA) model is the one-equation model. It is usually based on the turbulence kinetic energy k , shown in Equation A.2.16. Because the length scale is based on the experimental data, the data may not be possible for some applications, like elliptic flow (separated flow, recirculating). The current SA model is mainly used in aerospace studies, giving good results and easy to apply to any mesh. However, the diffusion in the flow is considered to simulate a complicated geometry (for example, the wing with high lift devices), due to the multiple transition processes. The model may fail to give an accurate result, even for the simplest integrated parameters, like drag, lift coefficients [94].

A.2.1 $k - \omega$ models

the $k - \omega$ model is a classical two-equation model for two turbulence properties. The first form was studied in 1942 [95]. The most common property is the turbulence kinetic energy k , and the second is the specific dissipation rate ω , or the length scale l . Wilcox's last version of the model is represented 2006 [96]. The $k - \omega$ only applied to the model check and vortex location prediction, not in the detailed study, so the model's detail is in Appendix A.

A.2.2 $k - \varepsilon$ models

The $k - \varepsilon$ model calculates the turbulence properties mainly by turbulence kinetic energy k and the dissipation rate of turbulence kinetic energy ε . Similar to the $k - \omega$ model, this is a widely used model in different areas.

A.2.3 $k - \varepsilon$ model

The equation of kinematic eddy viscosity is shown in Equation A.2.17. the constant ratio in the equation is $C_\mu = 0.09$.

$$v_t = C_\mu \frac{k^2}{\varepsilon} \quad (\text{A. 2.17})$$

The representation of Turbulence Kinetic energy k shown in equation A.2.18, The Prandtl number σ_k is equal to 1.

$$\frac{\partial k}{\partial t} + \bar{u}_j \frac{\partial k}{\partial x_j} = \frac{\partial}{\partial x_j} \left[\frac{(v + V_t)}{\sigma_k} \frac{\partial k}{\partial x_j} \right] - \varepsilon + \tau_{ij} \frac{\partial \bar{u}_i}{\partial x_j} \quad (\text{A. 2.18})$$

The representation of dissipation rate of turbulence kinetic energy ε is shown in Equation A.2.19.

$$\frac{\partial \varepsilon}{\partial t} + \bar{u}_j \frac{\partial \varepsilon}{\partial x_j} = \frac{\partial}{\partial x_j} \left[\frac{(v + V_t)}{\sigma_\varepsilon} \frac{\partial \varepsilon}{\partial x_j} \right] - C_{\varepsilon 1} \frac{\varepsilon}{k} \tau_{ij} \frac{\partial \bar{u}_i}{\partial x_j} - C_{\varepsilon 2} \frac{\varepsilon^2}{k} \quad (\text{A. 2.19})$$

The constant ratios in the equation are $C_{\varepsilon 1} = 1.44$, the $C_{\varepsilon 2} = 1.92$. Prandtl numbers is $\sigma_\varepsilon = 1.3$.

The standard $k - \varepsilon$ model is hard to predict separated flow conditions and worse in the viscous sublayer integrating because of the adverse pressure gradients and extra strains, i.e., rotation and skewing. The model is good at multiphase flow and flows with chemical reactions like combustion [93].

A.2.4 $k - \varepsilon - \text{Realistic}$ model

The realizable $k - \varepsilon$ model is one of the major improvements of K-Epsilon model [97]. Another one is the Renormalization Group $k - \varepsilon$ model [75].

The Realistic model is focused on turbulent shear stresses. It is by realizability constraints satisfaction within the Schwartz inequality and normal Reynolds stresses. The equation of kinematic eddy viscosity computed by a constant ratio C_μ in the standard model. In the new model, C_μ is calculated by an eddy viscosity equation. Two constants are changed in the new model, the $C_{\varepsilon 2} = 1.92$

and Prandtl numbers $\sigma_\varepsilon = 1.3$ were in the standard model, $C_{\varepsilon 2}=1.9$ and Prandtl numbers $\sigma_\varepsilon = 1.2$ are in the new model.

Those improvements lead to better performance than the standard model within the separated flow, boundary layer, jets, and mixing layers [75].

A.2.5 Boundary layer

The power-law is obtained from the nondimensional velocity gradients of the velocity profile. The velocity and boundary layer thickness were transferred to nondimensional parameters divided by the freestream velocity and the boundary layer thickness, respectively [98]. The processing and equation are shown in Figure 11.6.

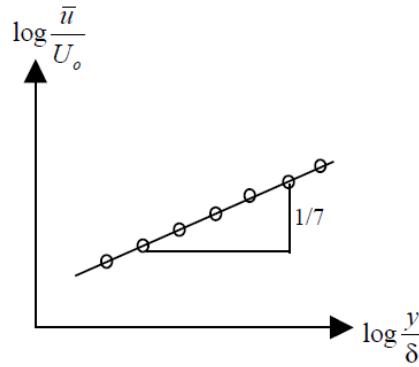


Figure 11.6 Power law of the turbulent boundary layer

$$\frac{u_{local}}{U_e} = \left(\frac{y}{\delta}\right)^{1/7} \quad (A. 2.20)$$

The CFD simulation employed the equation for the boundary layer setting (inlet velocity). Equation 6.4 is same with the Equation A.2.20.

Appendix B

Appendix B introduces additional information about the Phase I experiment.

B.1 Data analysis and experimental setting

There were three blades involved in the Phase I experiment, and the length and height of the blades were the same. The front views of the blades were as shown in Figure 11.7.

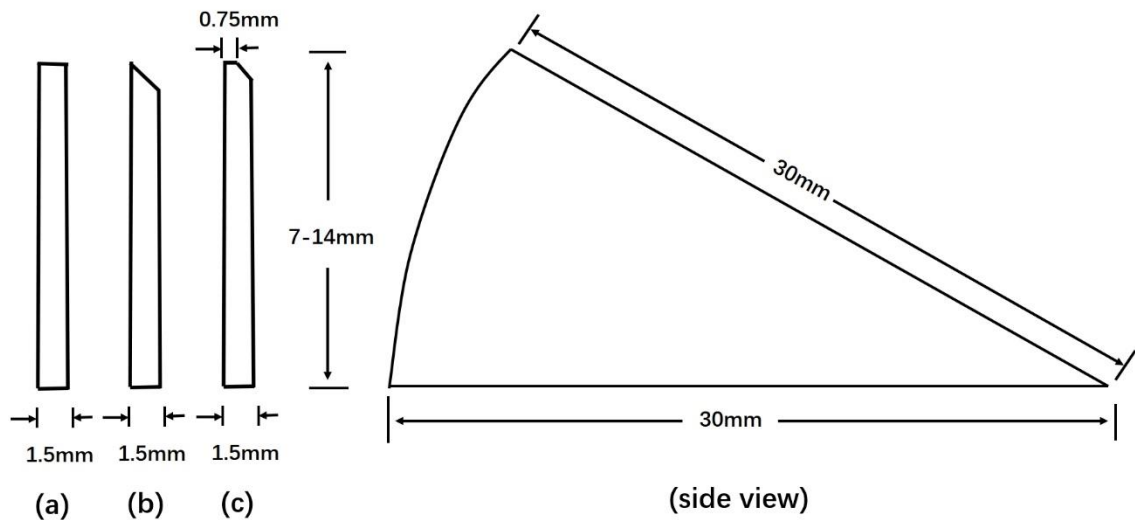


Figure 11.7. The geometry of the leading edge with three blades

(a): blunt leading blade, stage one. (b): sharp leading edge 45° , stage two, angle effect, height effects. (c): half-sharp leading edge 45° , stage two, nondimensional test.

The new half-sharpened blade showed a vortex-forming process similar to that of a fully sharpened blade. The experiments were conducted at the static port's first row, and the sizes of both blades are 7 mm and 14 mm.

Time synchronization from different runs. In all cases, the pressure behind the trailing edge decreases with blade deflection. The pressure is used as an indicator signal. In the lower angles of attack condition, the indicator signal increased first and then decreased; the peak point caused by increasing motion in every run was used as the common feature for statistical analysis. With the increase of angle, the peak became smaller and invisible. Therefore, the first negative gradient point was the new unified feature before the pressure decreased. However, the new features were not as obvious as the "peak point", so it may cause errors in unification. Results of indicators based on these two features were shown in Figure 11.8, and Figure 11.9.

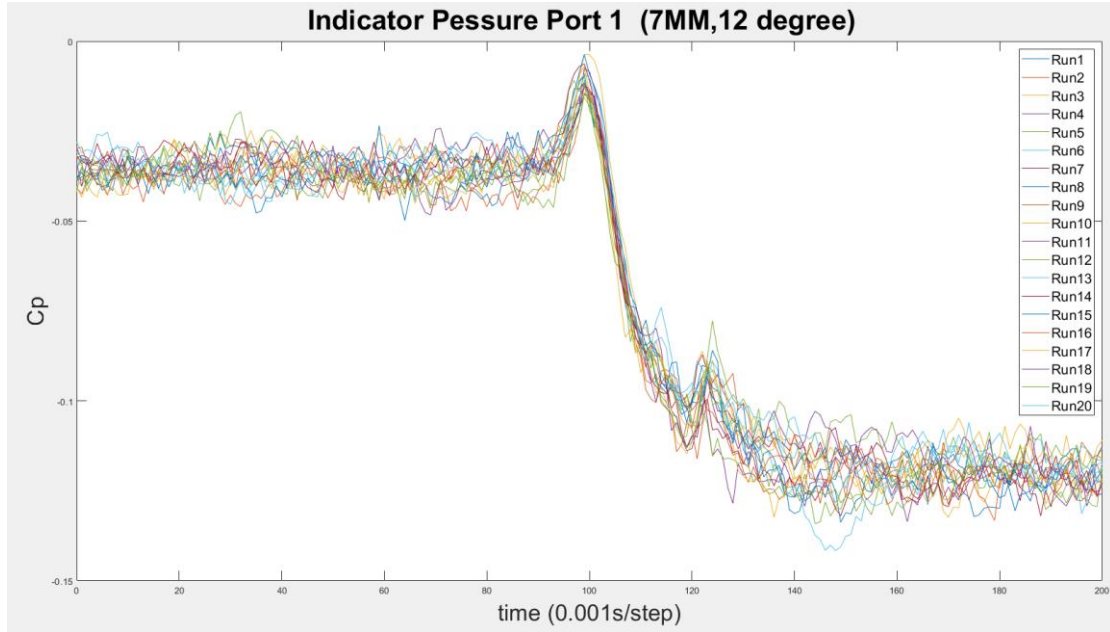


Figure 11.8. The pressures recorded at port 1.

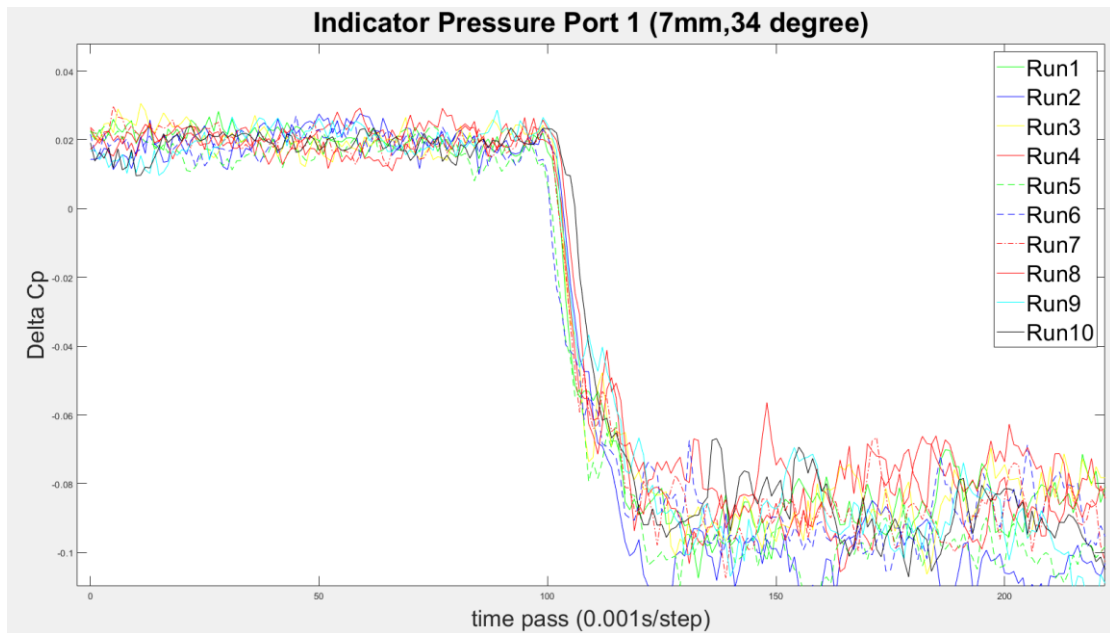


Figure 11.9. The first negative gradient unifies time steps in the time domain.

The impacts of tube length show no significant effects in previous studies. Several lengths of tubes and transducer locations were used to examine the impact of tube length on the experiment.

The tube length effects were examined in the experiment. The original tube was 90 CM, and the new tubes were $\frac{1}{2}$ and $\frac{1}{4}$ of the original length. With the length

reduced, the transducer box is closer to the flat plate and exposed to the air blowing. The wind shook the tubes; therefore, the tubes were tied with a bar. Studies show that the tied and curvature do not cause significant changes. The transducer with tubes is as shown in Figure 11.10.

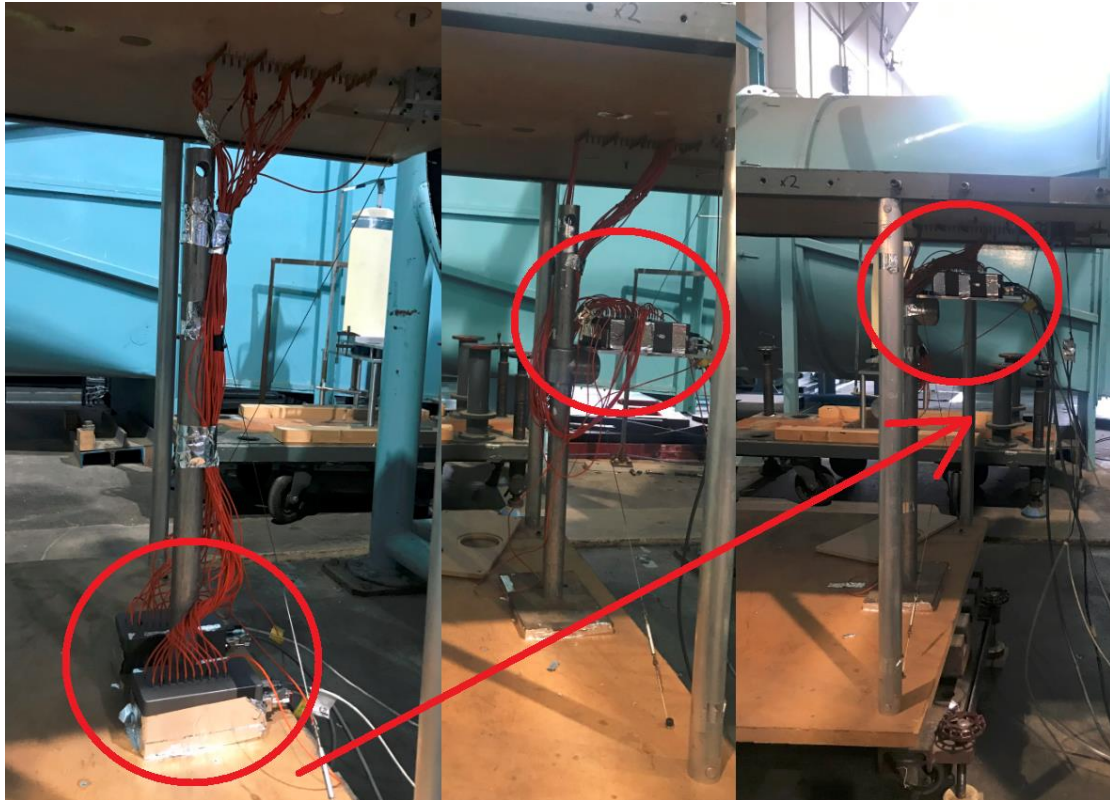


Figure 11.10. Different locations of transducer boxes with the same tube

The result shows that there was mainly a time delay, as shown in Figure 11.11.

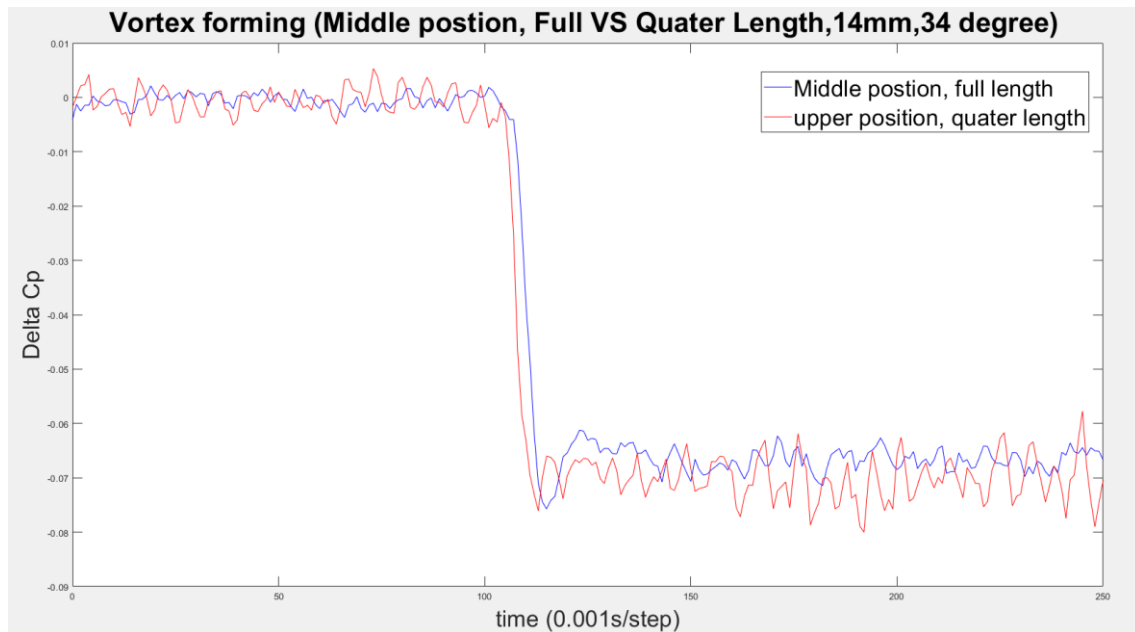


Figure 11.11 Vortex forming (tube length effects)

The blue line in the plot indicates the full-length tubes with the middle-position transducer, and the red line indicates the quarter-length tubes with the upper-position transducer. The Y-axis is the delta C_p , the X-axis is the time period in seconds.

B.2 Phase I, stage 2

The pressure recorded was the static surface pressure. Two key parameters that influenced the pressure were the vertical distance between the vortex core and the surface and the strength of the vortex (initial circulation, development, and decay).

The circulation of the vortex can be influenced by the angle of attack and the size of the blade. The blade's height decided the distance. The distance between the blade's trailing edge and the measuring location influences the vortex decay. The decay rate can be represented by the nondimensional distance (the distance divided by the height of the blade).

B.3 Angle effects

The changes of the angle of attack show an apparent effect on the vortex forming. With the angle increasing, the vortex becomes stronger and takes longer to form. The vortex forming rates were kept constant when the angle changed, and the gradient of pressure drops was kept constant, as shown in Figure 11.12. The angle changes caused the strength of the vortex to change, but the forming rate kept constant.

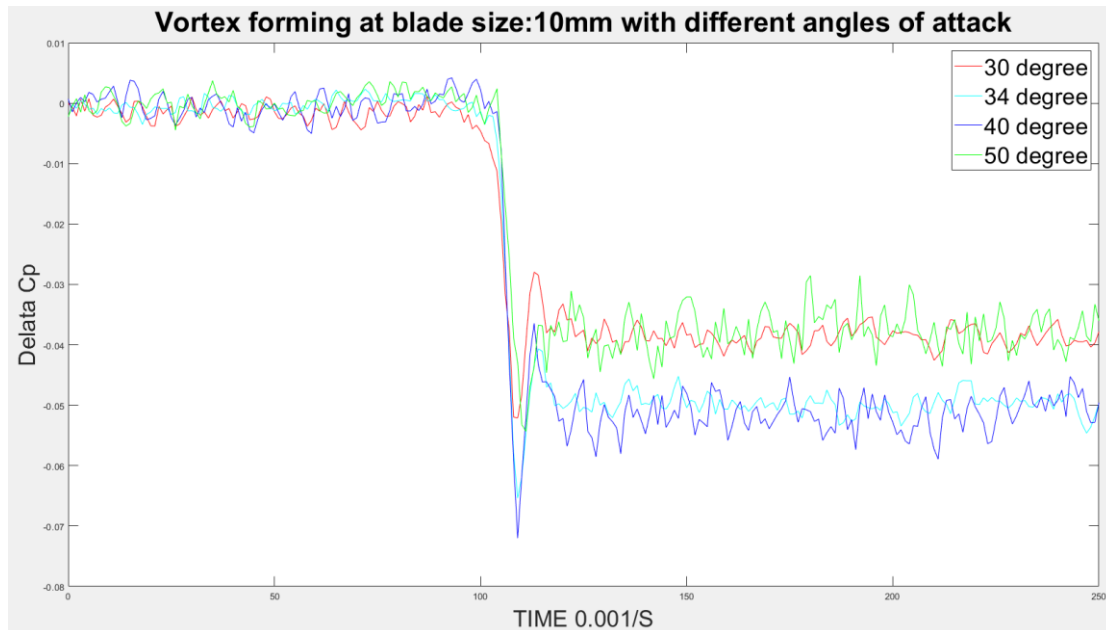


Figure 11.12 The vortex forming with angle changes with different angles

The overshoot in the vortex forming appeared with the angle increasing. When the angle range is lower (below 40°), the overshoots were weak. When the incline increases to 40° , the overshoot became the strongest. In 50° , the angle went too high to form a stable static vortex - but the starting one still had good strength as in 34° . Below 20° , no starting vortex appeared, as shown in Figure 11.13. The variation of the starting vortex showed that it was affected by the angle of attack.

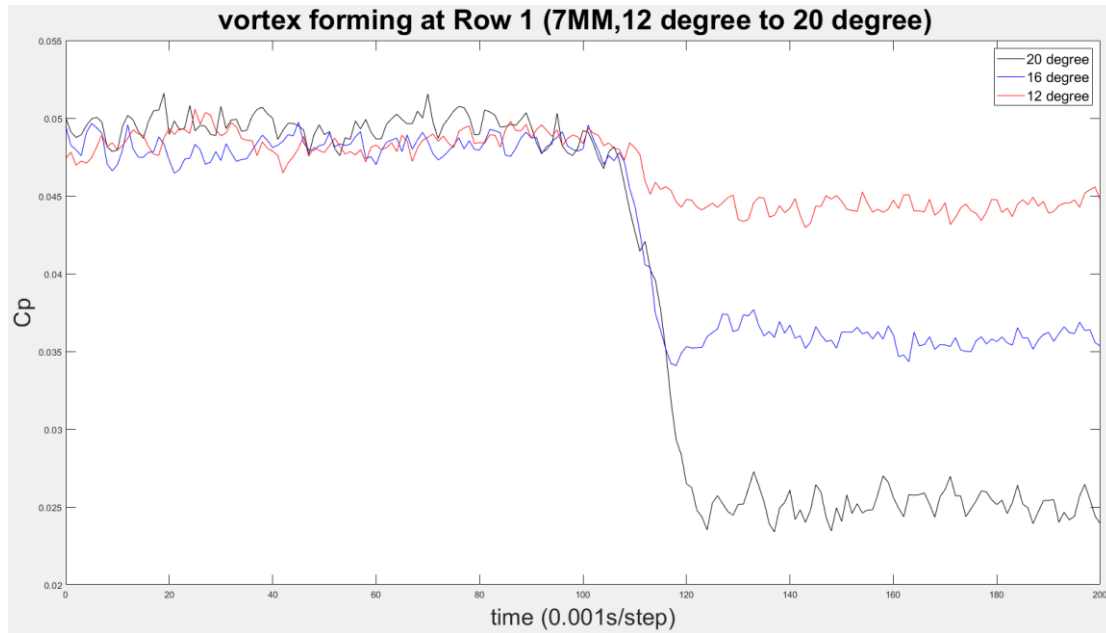


Figure 11.13 Vortex forming within lower degree condition with non-sharped leading edge blade.

Under 20° , the vortex forming rate is similar to that of other conditions, but the starting vortex was not identified in the experiment.

B.4 Height effects

In contrast to the angle of attack, the height of the blade influences the vortex-forming rate. From the angle test, a stronger vortex took longer to form. This principle applied in the height effects. From Figure 11.14, the pressure drop slope became sharper as the height increased.

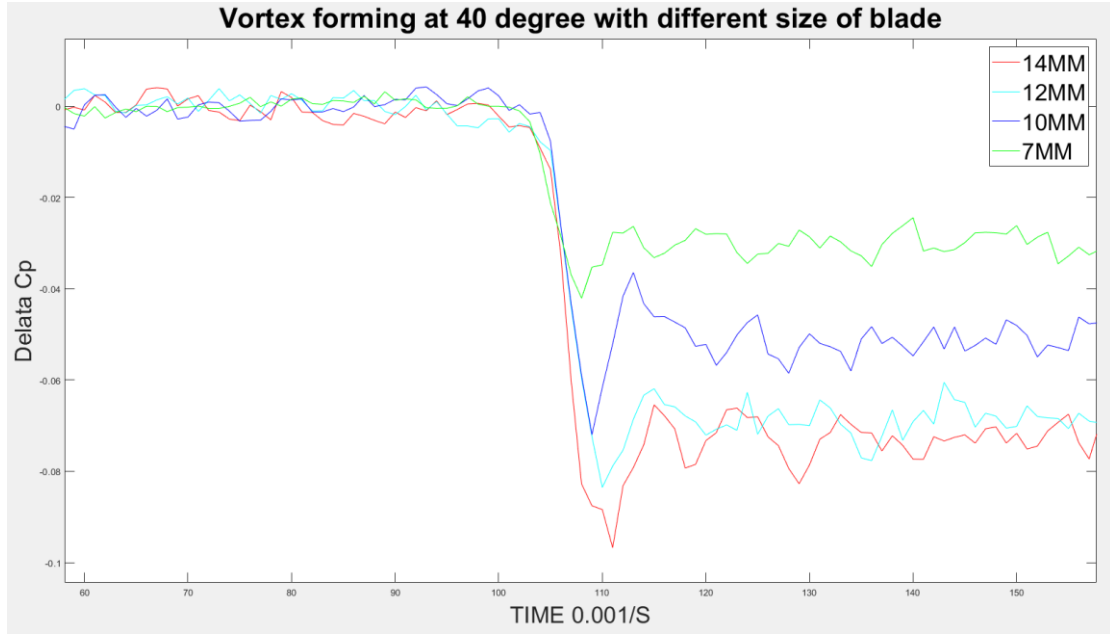


Figure 11.14 The vortex forming at 40° with different blade heights

The highest degree i.e. 50° was plotted in Figure 11.15, showing a similar result as in Figure 11.14. As the angle increased, the vortex formation became clearer to analyze. With the increasing height of the blade, the vortex-forming rate increases.

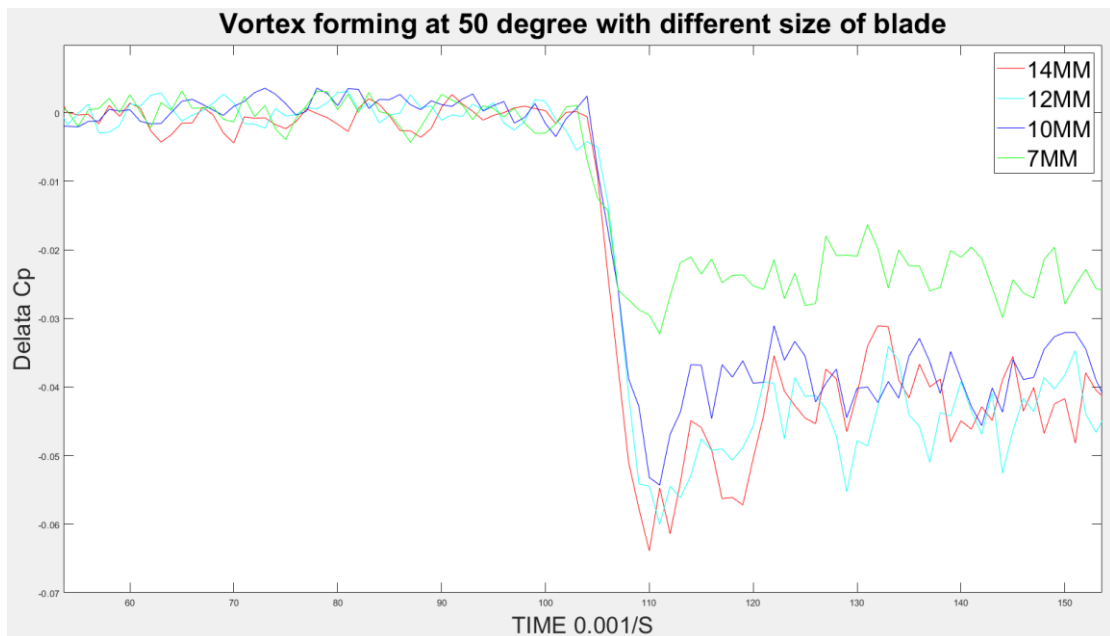


Figure 11.15 Vortex forming with the height of blade increase, 50° Condition

B.5 Nondimensional distance effects

The dimensionless distances between the trailing edge and every static port row were calculated by the downstream physical distance divided by the height of the blade. Those distances are shown in Table 7. The physical distances and dimensionless distances. Similar dimensionless distances are marked with the same color. Table 2 shows three groups of similar nondimensional distances, around 20h, 24h, and 13h.

	physical distance	7mm	10mm	12mm	14mm
Row1	136mm	19.4h	13.6h	11.3h	9.7h
Row2	186mm	26.6h	18.6h	15.5h	13.3h
Row3	236mm	33.7h	23.6h	19.7h	16.9h
Row4	286mm	40.9h	28.6h	23.8h	20.5h

Table 7 The physical distances and dimensionless distances

All three distances were tested. It should be noted that some of the data were missing at higher inclined conditions due to the limited recording area. As a result, only a few tests can be analysed: at the distance of 13h (non-13), all angles were recorded; 19h, degree 30° and 34° were recorded; 23h, only 30° was recorded.

The nondimensional effects on the vortex-forming slopes, which involved all four different blade heights, were plotted in Figure 9.16 and Figure 9.17. The angles were chosen to represent the maximum strength. Both results clearly show the vortex-forming rates were similar at the same "distance".

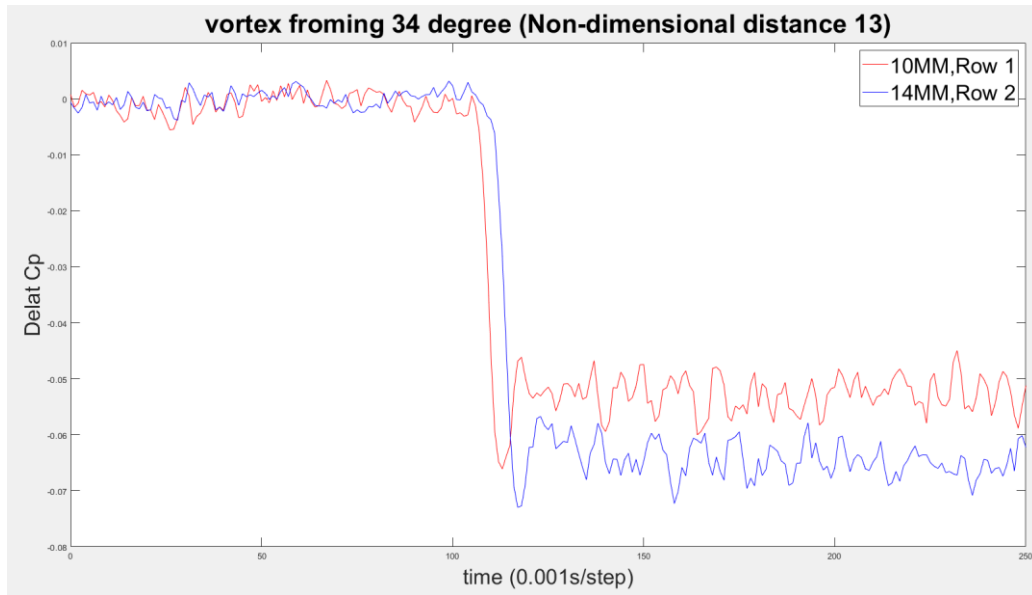


Figure 11.16 Vortex forming at 13h, 14MM&10MM

The angle of attack is 34° , wind speed is 35 m/s.

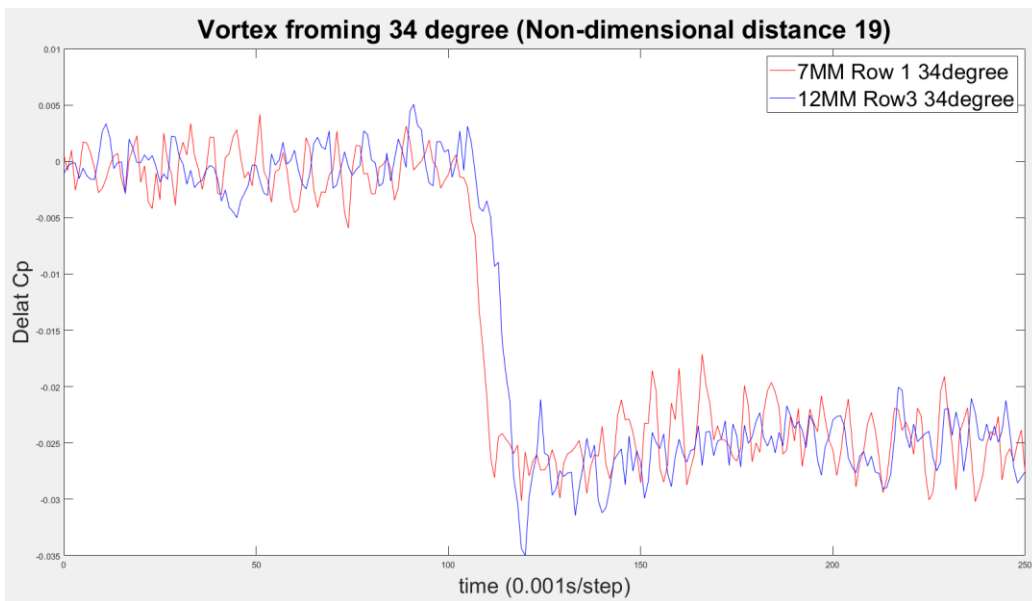


Figure 11.17 Vortex forming at 19h, 7MM&12MM

The angle of attack is 34° , wind speed is 35 m/s.

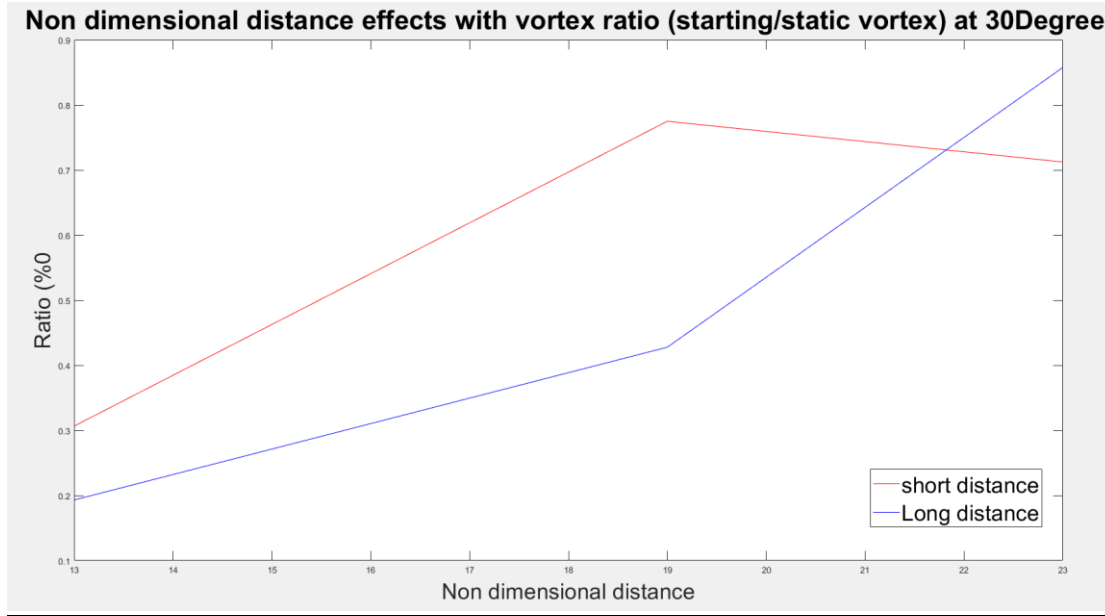


Figure 11.18 Starting vortex and static vortex ratios with nondimensional distances

The red line is a short distance with a smaller blade group; the blue line is a longer distance with bigger blade groups.

From the plot of the vortex ratio ($\frac{\text{starting vortex}}{\text{static vortex}}$) in Figure 11.18, both lines show a similar trend. As the distance increases, two ratios increase. After distance 19h, the two lines show the gradient changes but in different ways. The group of shorts distance with the smaller blade decreases, but the long-distance line with the bigger blade increases.

Appendix C

The Phase II experiment support data are in Appendix C. The repeated tests, data processing, and some of the results are in this chapter. The results mainly involve cases 150mm and 100mm. The turbulent kinetic energy contour plots were represented.

C.1 Data processing in Phase Two

The data processing of Phase II, such as the data extension, vorticity, and circulation calculation, is introduced in this chapter.

C.2 Experimental data extend

The polynomial function in Matlab extended the data from the experiment. The space between two blue neighbor experimental points was 15mm. The distance between the two points is reduced to 5 mm to increase the resolution. The number of points in every row and array were increased to 13. The data extension result as shown in Figure 11.19.

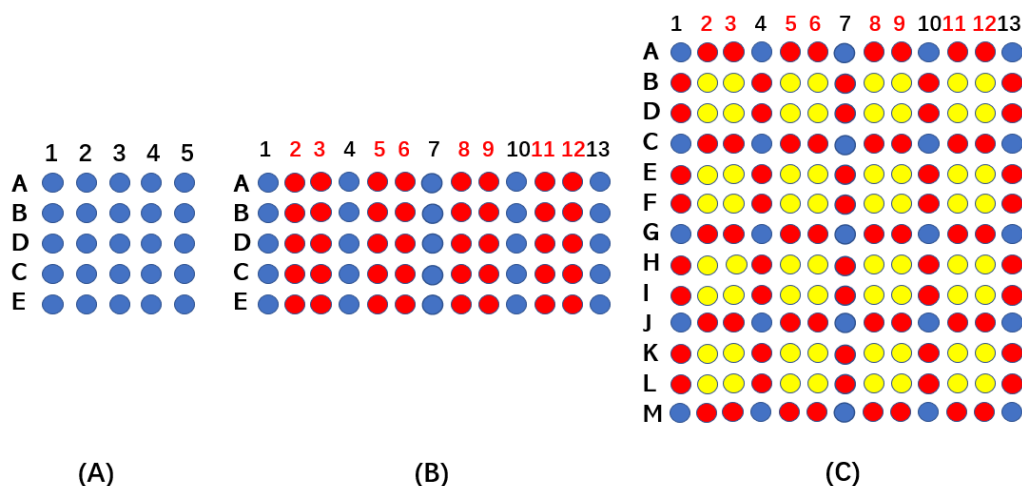


Figure 11.19 Experimental data in polynomial function processing

The blue color points represent the experimental data only. The red points refer to the predicated first-step data based on the experimental data. The yellow points are the predicted data of the second-step based on the first-step data and real experimental data. Figure (A) shows the experimental data only. Figure (B) indicates the first prediction of numerical data based on experimental data, and this first prediction processing can be vertical or horizontal. Figure (C) shows the experiment data's final extension; some data points are predicted according to the numerical data.

The polynomial fitting process was carried out using MATLAB software. The polynomial equation obtained by the software was shown in Equation C.1. The degree of the equations was chosen to be 4 at the beginning to examine the possibility of a 4th order. The fit checking of velocity "w" is shown in Figure 11.20.

$$p(x)=p_1x^n+p_2x^{n-1}+...+p_nx+p_{n+1}$$

C.1

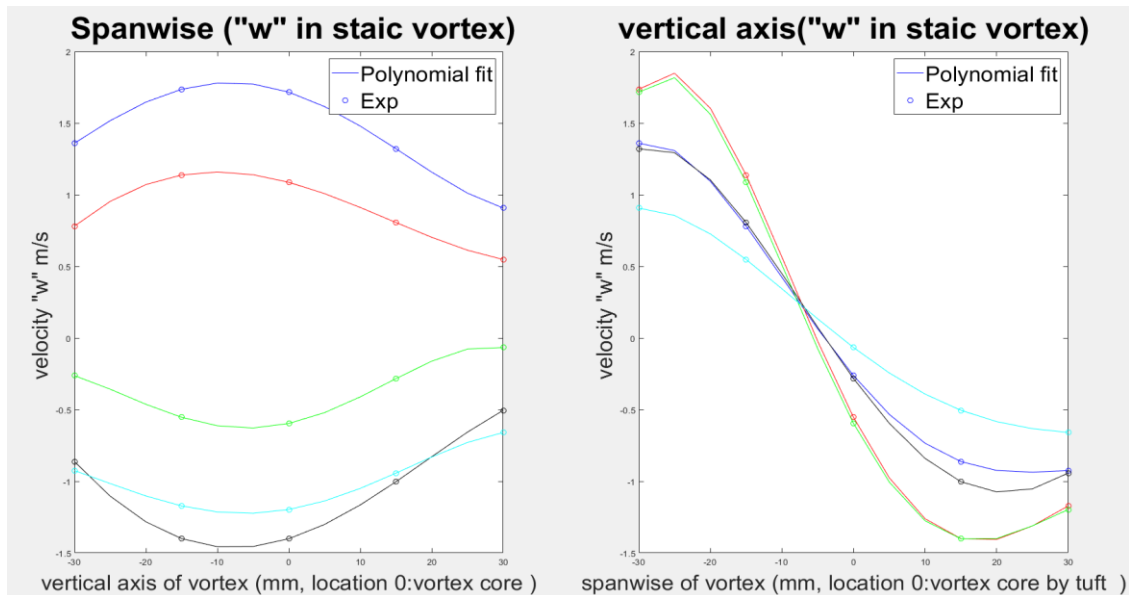


Figure 11.20 The polynomial curves with experimental data

The curves fit the data perfectly. Polynomial equations plot the solid lines, and the circles are experimental data. The polynomial function is 4th order.

Figure 11.20 shows the 4th-order polynomial function fitting the experimental data. The fit between the experimental data reveals the overestimation in the right plot, such as the red and green lines between -30 mm and -20 mm on the X-axis. So, the 4th order is too high to fit the data correctly.

Based on the two processing checks (spanwise fist, then vertical direction, or vertical direction fist, then spanwise), the results were the same, as shown in Figure 11.21. Based on Figure 11.21, the extension plots also show the differences in velocity contour. Compared with purely experimental data, the sharp changes become smooth in both extended ones, but velocity increases at the bottom of both polynomial velocity contours.

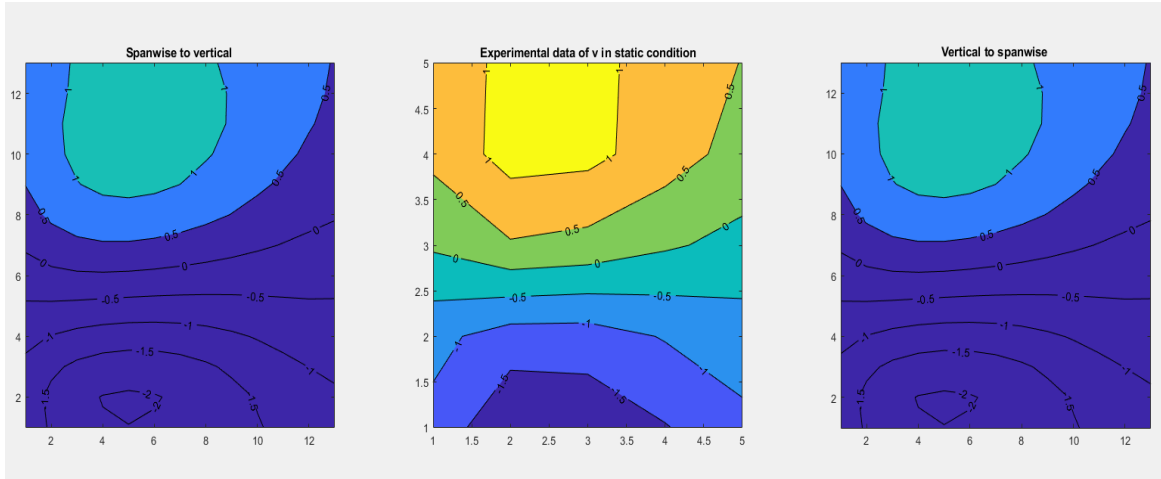


Figure 11.21 The comparison of polynomial extension velocity contour and experiment data

The middle plot is based only on the experimental data. The left and right plots come from two orders of processing.

The overestimated velocity contours were observed due to the higher degree function (4 order) in Figure 11.20. The degree of the polynomial equation was estimated as 3 to compensate for the overestimation. The results are as shown in Figure 11.22, and Figure 11.23.

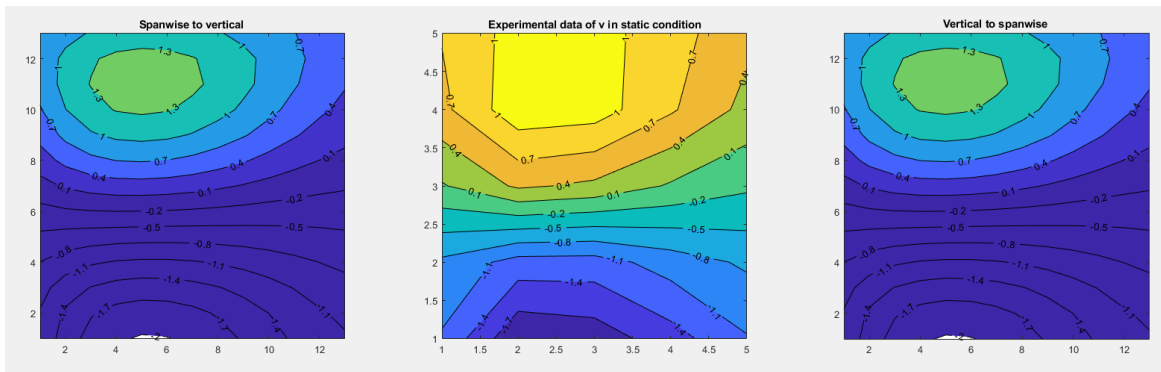


Figure 11.22 The 3 degrees polynomial result compared with experimental data, velocity ' v '

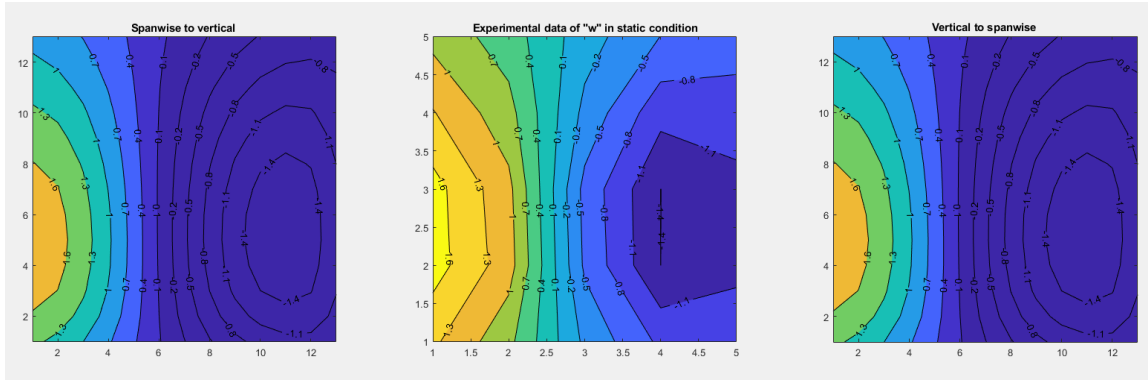


Figure 11.23 The 3 degrees polynomial result compared with experimental data, velocity "w"

Most overestimations were fixed, with some parts impossible to be eliminated, as shown in Figure 11.22 and Figure 11.23. The tangential velocity of the experimental and extension vortex were plotted in Figure 11.24.

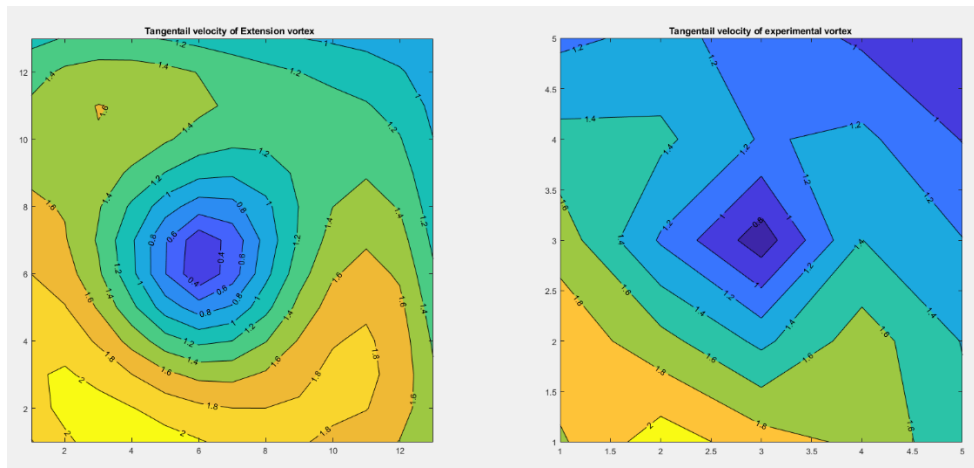


Figure 11.24 The Tangential velocity of the experimental and polynomial vortex

The left part of the plot is the extension vortex; 169 points total, 25 points come from the experiment. The right part of the plot is the experimental vortex, and all data comes from the experiment.

The data extension was the 3-order degrees polynomial function, which avoids the overestimation under the 4-order condition. The data extension only increases the resolution of the plot.

C.3 Vorticity computation

The detail of the vorticity computing is shown in this chapter. The vorticity and circulation computing processing were based on the original data locations shown in Figure 11.25.

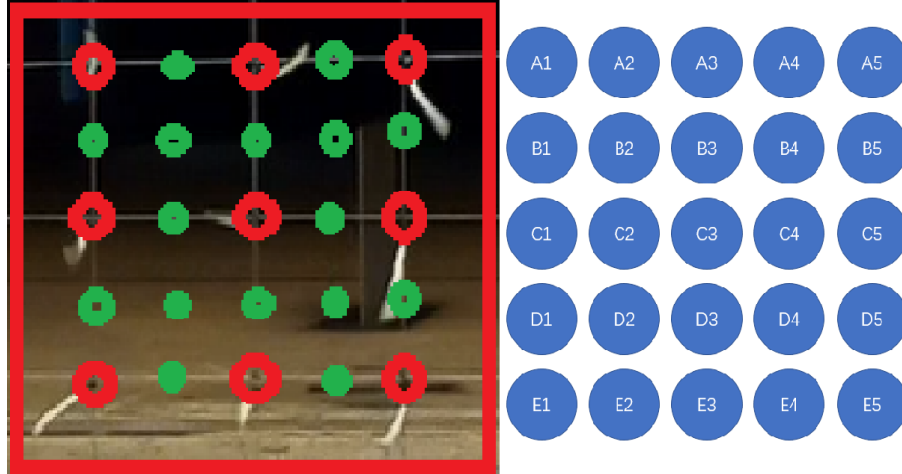


Figure 11.25 Testing points in the experiment (200 mm case)

v and w were obtained from the experimental data to compute the vorticity. The contour plots of v and w shown in Figure 11.26.

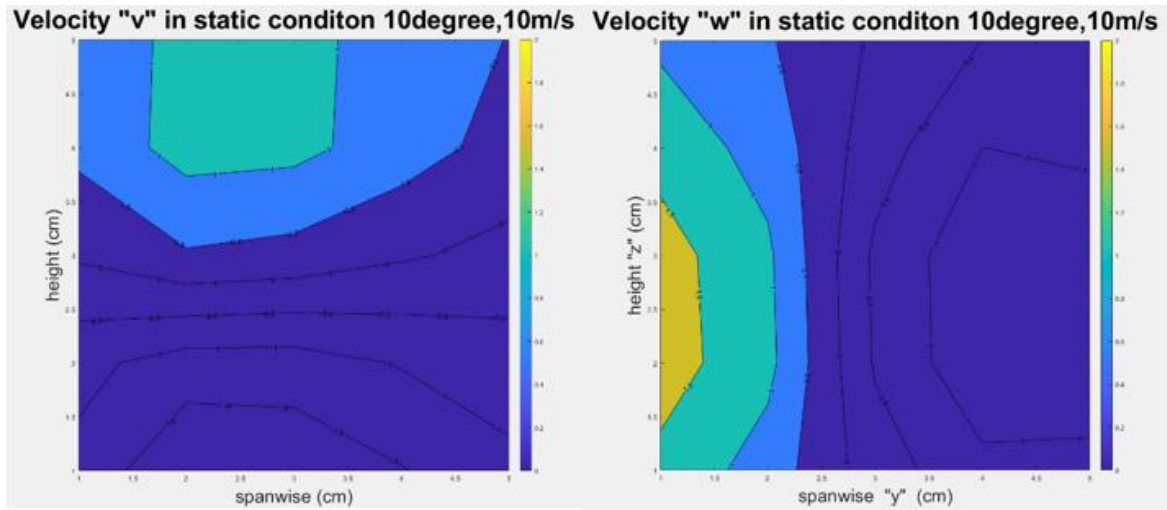


Figure 11.26 The velocity v, w in the static vortex from the experiment

According to Figure 11.26, velocity contours show clear velocity changes. Vorticity is the rotation of the point, which is caused by the velocity difference and distance between two axes. The equation is as shown in Equation C.2:

$$\omega_x = \frac{\partial v}{\partial z} - \frac{\partial w}{\partial y} \quad (\text{C.2})$$

The components $\frac{\partial v}{\partial z}$ and $\frac{\partial w}{\partial y}$ are the angular speeds of the point in two directions. The ∂v and ∂w are the velocities difference between nearest neighbor points. The velocity v varies with the increase of vertical distance from the middle line (X axis, Row C) shown in Figure 11.25. So, the ∂v at Row B was calculated from $v_{Row A} - v_{Row B}$ from the top row to the bottom row. The velocity w varies with the horizontal distance increase from the middle line (column 3). The ∂v was calculated from $w_{Row 1} - w_{Row 2}$, from the left-hand side column to the right-hand side column.

For example. The ∂v_{B2} of B2 was computed from $v_{A2} - v_{B2}$, $\partial z_{B2} = z_{A2} - z_{B2}$ the angular speeds of points B2 are $\frac{\partial v}{\partial z} = \frac{v_{A2} - v_{B2}}{z_{A2} - z_{B2}}$ and $\frac{\partial w}{\partial y} = \frac{w_{B1} - w_{B2}}{y_{B1} - y_{B2}}$, take into Equation C.2 is shown in Equation C.3.

$$\omega_{B2} = \frac{v_{A2} - v_{B2}}{z_{A2} - z_{B2}} - \frac{w_{B1} - w_{B2}}{y_{B1} - y_{B2}} \quad (C.3)$$

In the application of vorticity computation, the $\frac{\partial v}{\partial z}$ and $\frac{\partial w}{\partial y}$ were computed from the difference between neighbor rows and arrays. The vorticities at red points were calculated with only one parameter ∂w or ∂v . At point A1, vorticity remains 0 in the results. This is shown in Figure 11.27.

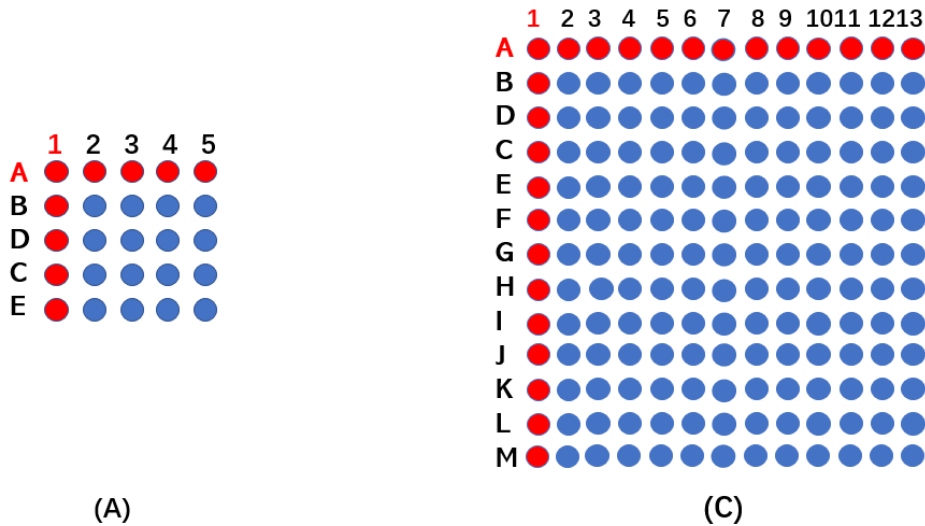


Figure 11.27 Vorticity matrix after calculation

The left part A is the vorticity matrix from the experimental-data-only condition. Polynomial functions compute the right-hand side part B from the extended matrix.

The ω_{max} from pure experimental data was 217, while the extended polynomial data gave 197.2, which underestimated the data.

C.4 Data of Phase II experiment

Due to the similarity of the vortex-forming process in the results, only part of the results are represented in this thesis's previous chapters. Therefore, this part represents all the results of this study.

C.5 Vorticity contours

Only 200 mm cases are represented in the previous chapter of the vorticity analysis, the vorticity contours of the case are 150mm in deflection as shown in Figure 11.28.

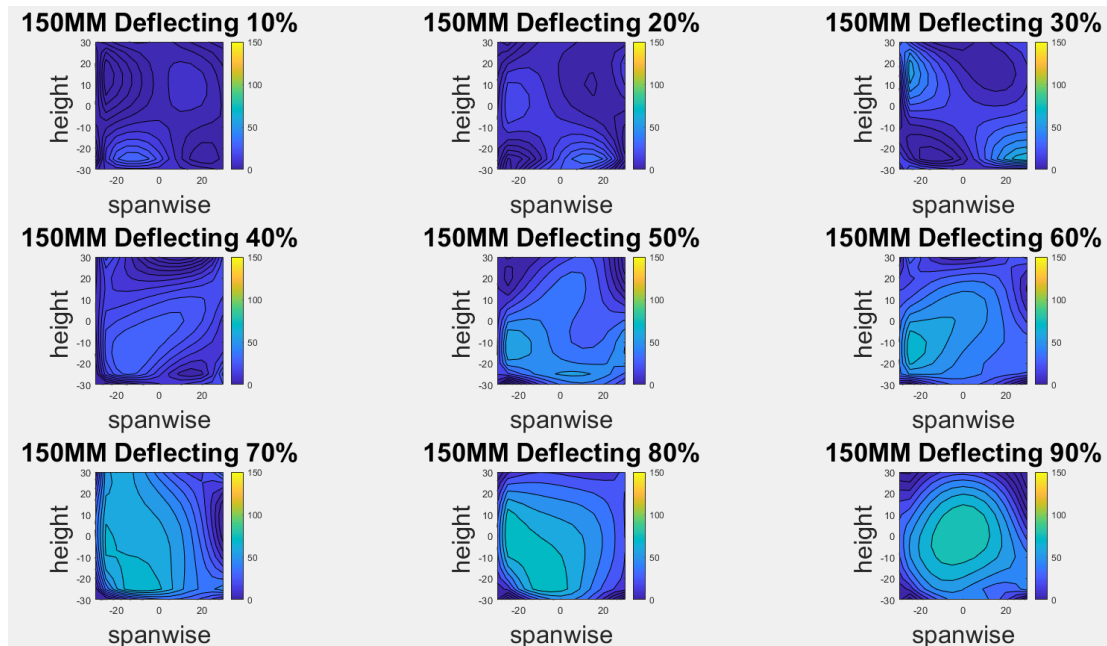


Figure 11.28 The vorticity of the deflecting 150mm blade

The range of the strength of the plot is from 150 to 0. The bright color shows the shape of the vortex. The vorticity matrix has been fitted by the polynomial function.

The vorticity plots showed the vortex-forming motion of the 150mm blade in Figure 11.28. At the beginning of the deflection, i.e. 10% to 20%, the high vorticity

area appeared at the bottom of the recording area. At 40% to 80% stage, the vorticity area became bigger. It kept its shape and grew until it covered the whole area. The vortex shows a clear and classic vortex shape at 90% of deflection. The 100mm case was as shown in Figure 11.29.

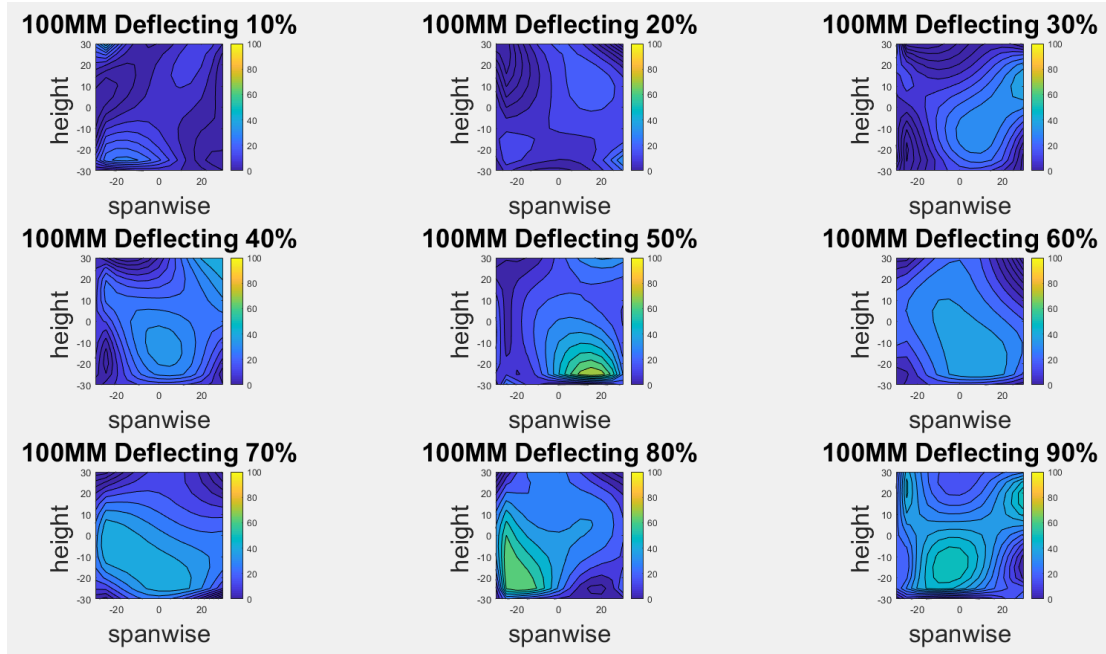


Figure 11.29 The vorticity of the deflecting 100mm blade

The range of the strength of the plot is from 100 to 0. The bright color shows the shape of the vortex. A polynomial function has fitted the vorticity matrix. Unit: s^{-1} .

Figure 11.29 plots the vorticity variation of 100mm blade deflection. At the 10% deflecting, the vorticity appeared at the bottom of the area but was not stable and disappeared at 20%. The bigger vorticity area covered half of the area when the deflection reached 30% and 40%. At 50%, the vorticity returned to the bottom with higher strength, and then the strength decreased, but the vorticity area went to the full area at 60%. From 70% to 90%, the shapes and strengths of vorticity varied. The vortex showed unsteady motion because the location of the vortex changes.

The vorticity contours of case 150mm in the restoration was as shown in Figure 11.30.

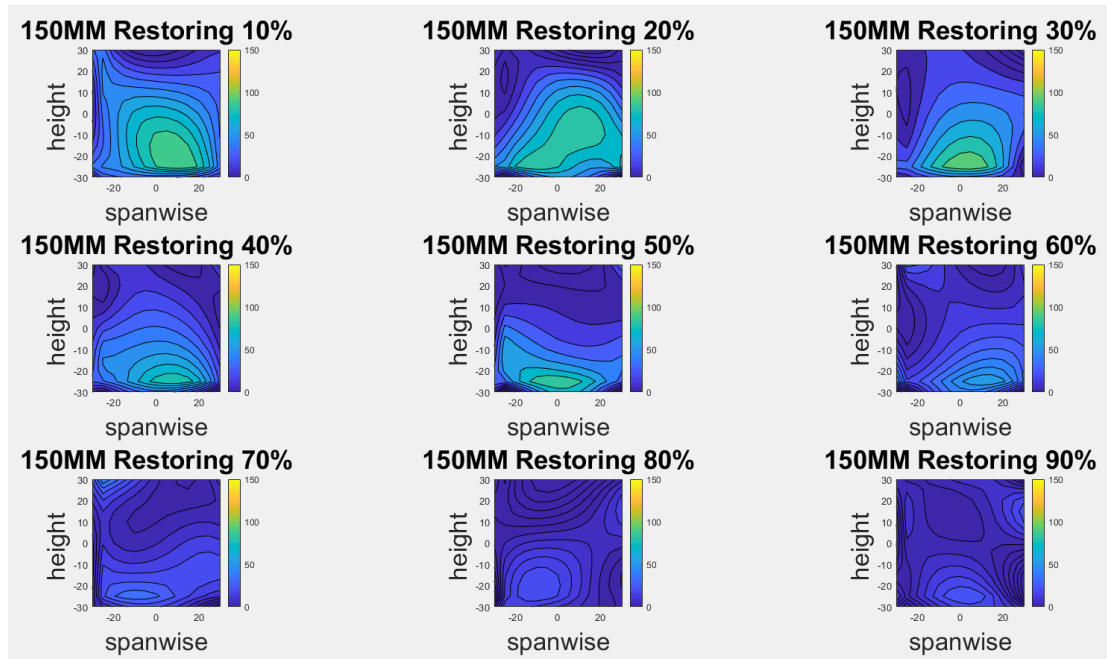


Figure 11.30 The vorticity variation of the 150mm blade restoring

The vorticity within the restoring motion has been separated to 9 stages, the space between each stage is 10% of circulation decreasing. The vorticity range of the figure is from 150 to 0, and the bright colour is the high vorticity area. Unit: s^{-1} .

Figure 11.30 shows the vorticity variation of the restoration motion in the 150mm blade case. The vorticity regions were unstable from 10% to 30%; the vorticity circle went to the bottom. The middle stage ranged from 40% to 60%, and the vorticity area remained constant in the middle of the bottom; the peak vorticity decreased. During the final stages, the peak vorticity continued to decline. The location of the vorticity area was kept at the bottom of the area but unstable in the spanwise direction. The shortest blade 100mm restoration motions were shown in Figure 11.31.

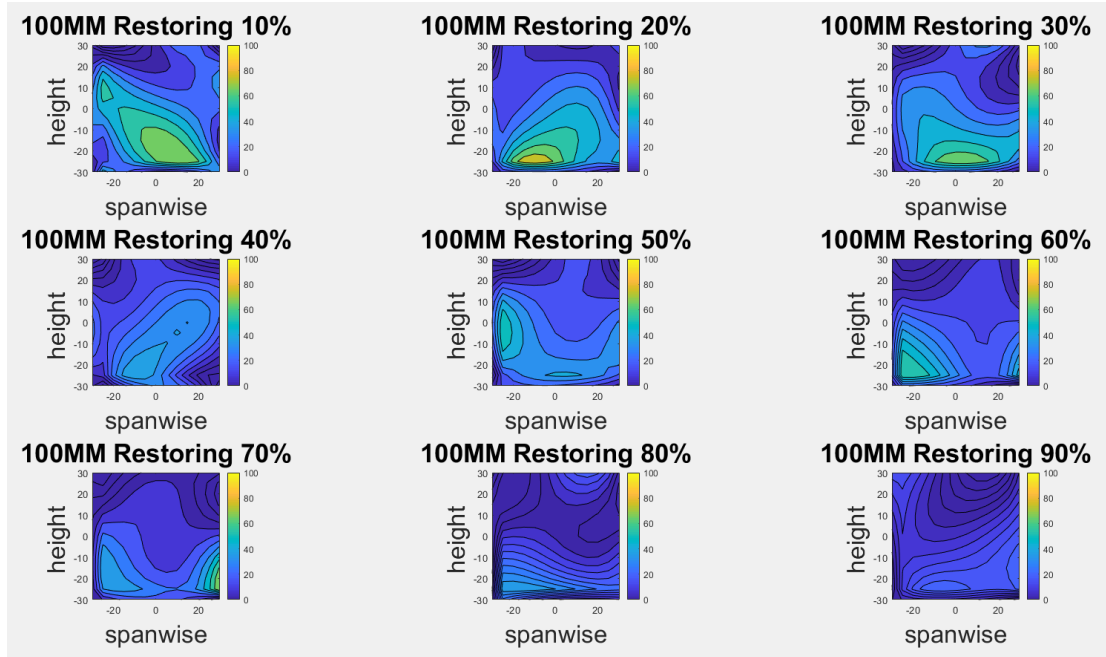


Figure 11.31 The vorticity variation of the 150mm blade restoring

The vorticity of the restoring motion has been separated into 9 stages. The space between each stage is 10% of circulation decreasing. The vorticity range is from 100 to 0, and the bright colour is the high vorticity area. Unit: s^{-1} .

The 100mm blade was associated with the weakest vortex. The shapes of the vorticity areas at the initial stages were unstable, and the high vorticity areas was near the bottom of the measuring area. In the middle stage, from 40% to 60%, the vorticity areas were even harder to keep unified in shape. At 50% and 60% stages, the high vorticity area seemed to be separated into two pieces and the peak vorticity also decreased. The vorticity area was divided at the final stages and could not maintain a clear shape.

C.6 Tangential velocity contours

The contour plots of streamwise and tangential velocities are compared in the previous chapter. The rest of the two cases are 150mm and 100mm, which are represented in Figure 11.32 and Figure 11.33.

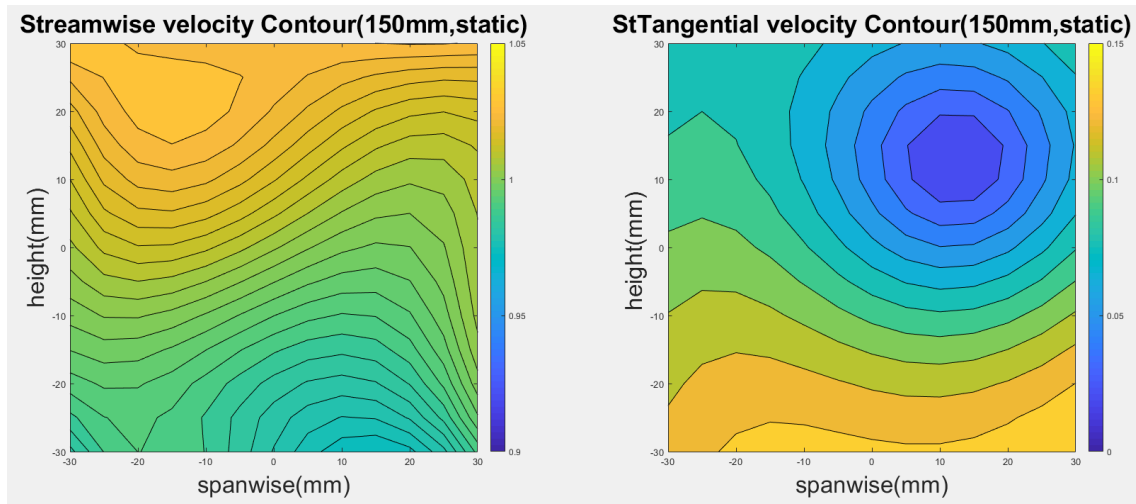


Figure 11.32 Velocity contours of the static vortex (150mm blade)

The left plot is the streamwise velocity ratio contour, and the right plot is the tangential velocity ratio contour. The ratio of the airspeed (10m/s) represents the velocities.

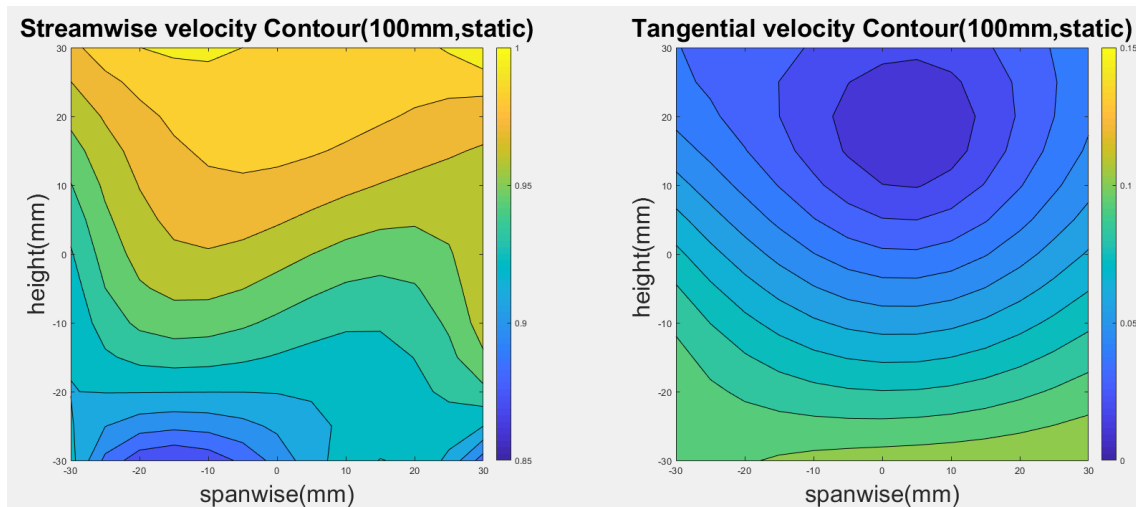


Figure 11.33 Velocity contours of the static vortex (100mm blade)

The left plot is the streamwise velocity ratio contour, and the right plot is the tangential velocity ratio contour. The ratio of the airspeed represents the velocities, the air speed is 10m/s.

The tangential velocity contours of the 150 mm and 100 mm deflection are shown in Figure 11.34 and Figure 11.35.

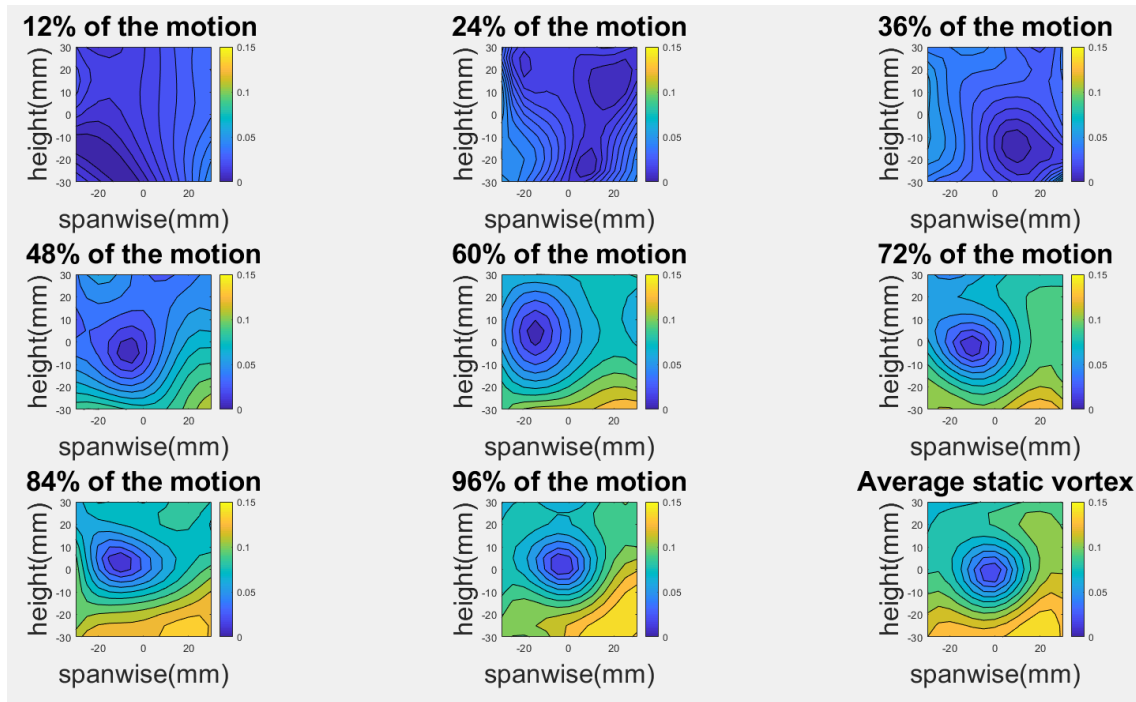


Figure 11.34 The variation of the tangential velocity contour of 150 mm blade in deflection

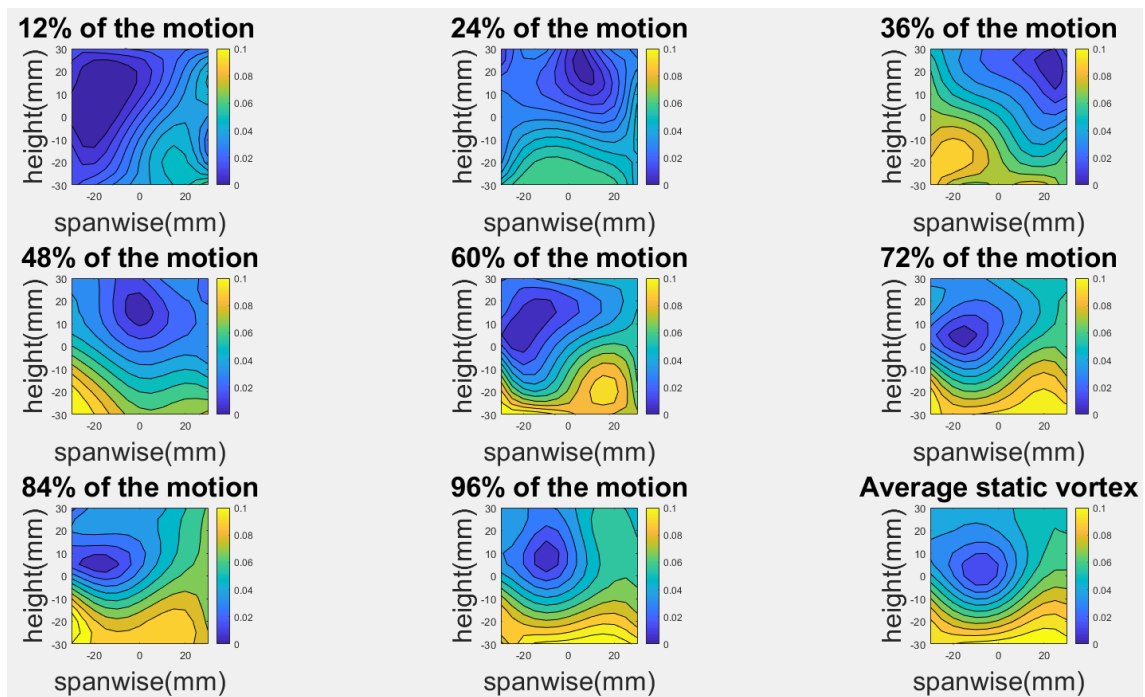


Figure 11.35 The variation of the tangential velocity contour of 100 mm blade in deflection

The vortex movements of the 150mm and 100mm blades are different from the 200mm blade condition. The vortex cores are obvious at 48% deflection in all three cases, but the vortex cores went to the recording area from different directions. The core first appeared at the bottom right-hand side in the 150mm case but on the top right-hand side of the 100mm case.

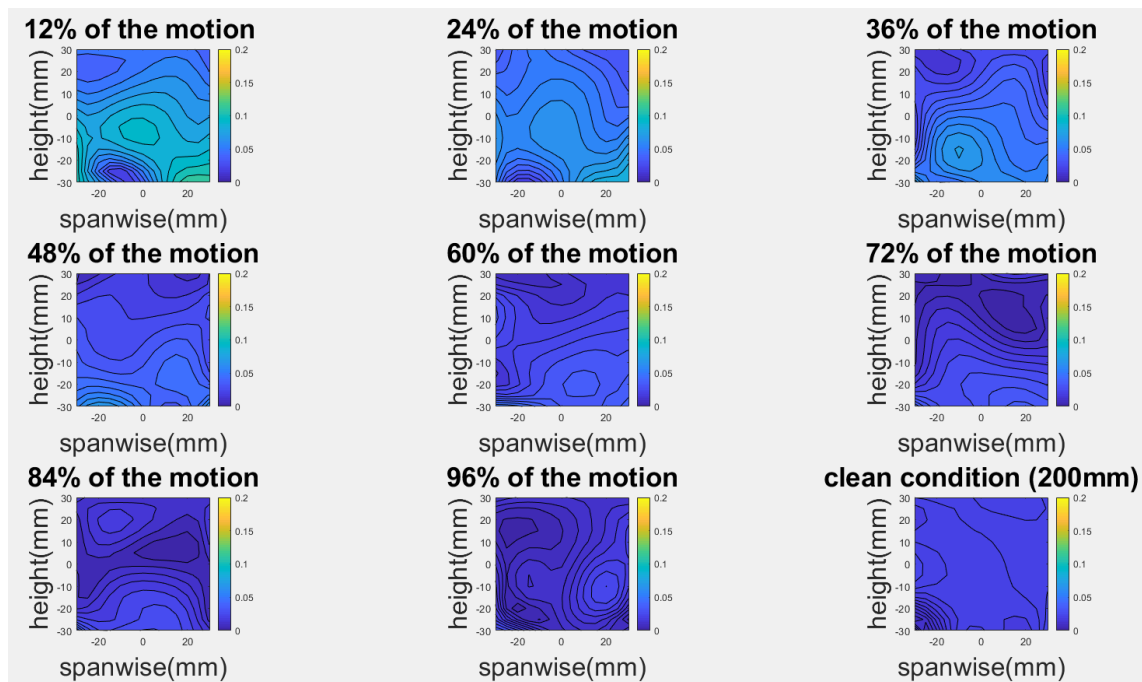


Figure 11.36 The tangential velocity contour of the 200 mm blade restoration

The structure of the vortex is considered as the circular shape of the tangential velocity. With the radius increase, the tangential velocity increases.

The contours of the 200 mm blade restoration show the vortex only in 12% and 24% of the area's bottom. In the other motion, the vortex structure is not present. The contours of the 100 mm case are shown in Figure 11.37. The case 150 mm is shown in chapter 6.7.6, and the Appendix only contains the support results, which are not shown in the main part of the thesis.

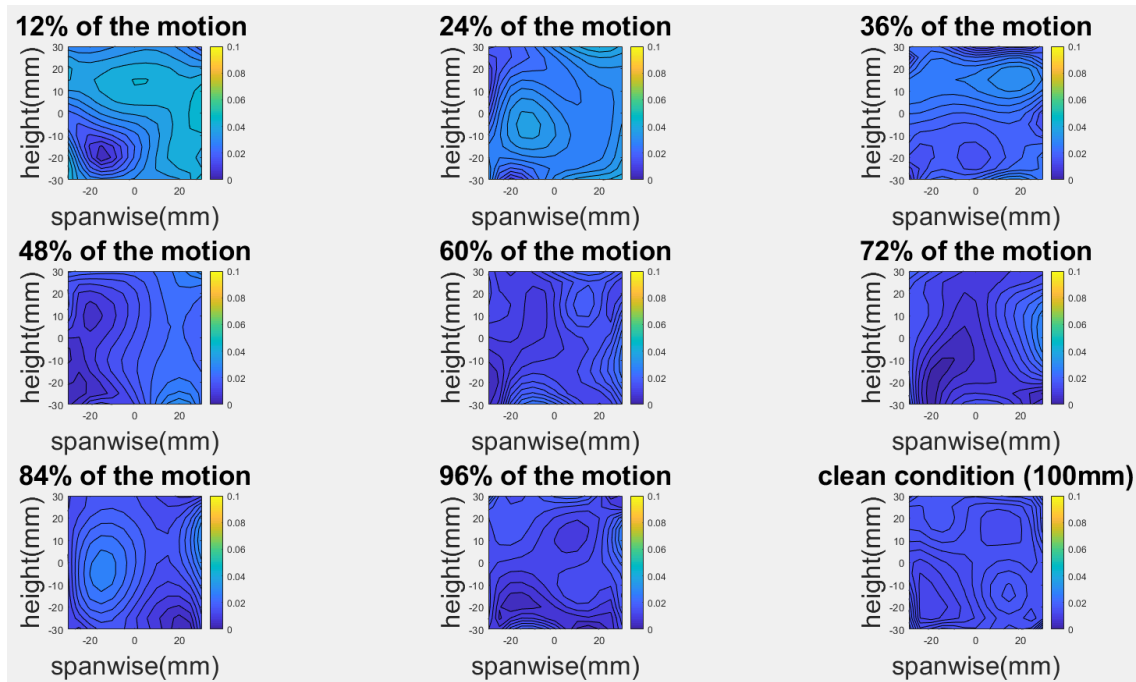


Figure 11.37 The tangential velocity contour of the 100 mm blade restoration

The contours of the 100 mm cases show the vortex at the bottom of the area in 12% of the restoration. The vortex left the recording area at 24% of the motion. The rest of the motion does not have any clear vortex structure.

C.7 Spanwise velocity at the central location

This subchapter represents the vortex motion by spanwise velocity. The changes of locations of the peak velocity show the different stages of the vortex-forming process.

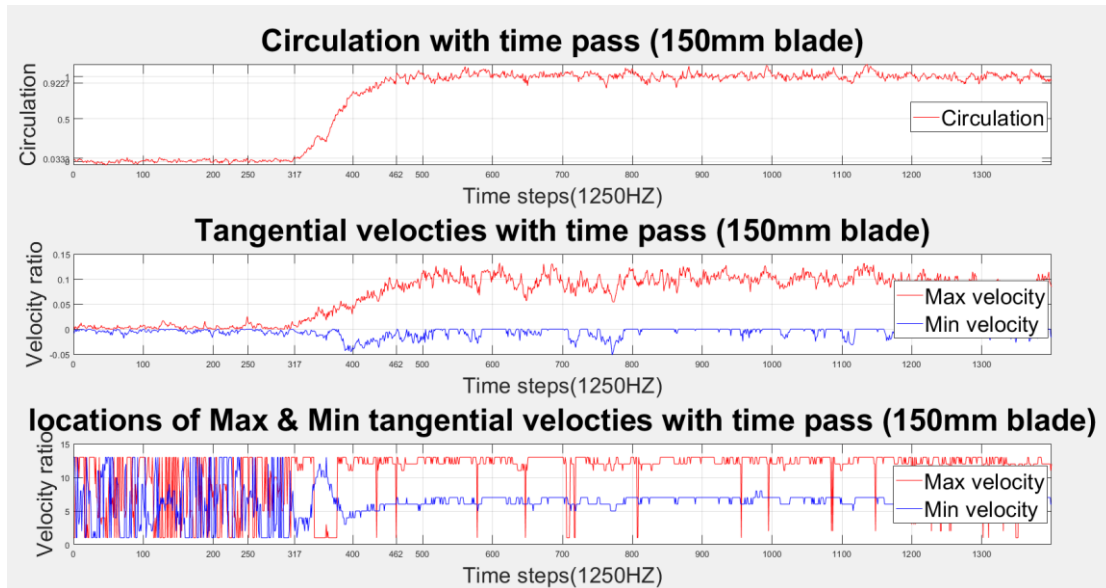


Figure 11.38 The Max & Min tangential velocities with corresponding locations with 150mm blade condition

The first plot is the circulation variations, and the middle one is the maximum and minimum points of the radius velocity with the period. The bottom one is the locations of the key points variations of the time period.

Figure 11.38 shows the circulation variations, two velocities, and locations against the time period. The circulation shows a smooth increase with small oscillations. At similar steps, the trend of two velocities show the difference between the minimum speed (blue line) and maximum speed (red line). The minimum speed of this case was zero, so the blue line maintained zeros at the static condition. Similar to the 100 mm blade case, the location of the two key points had a 3-times switch within 2 locations. The crossing points did not have the corresponding effect on the circulation or key velocities simultaneously.

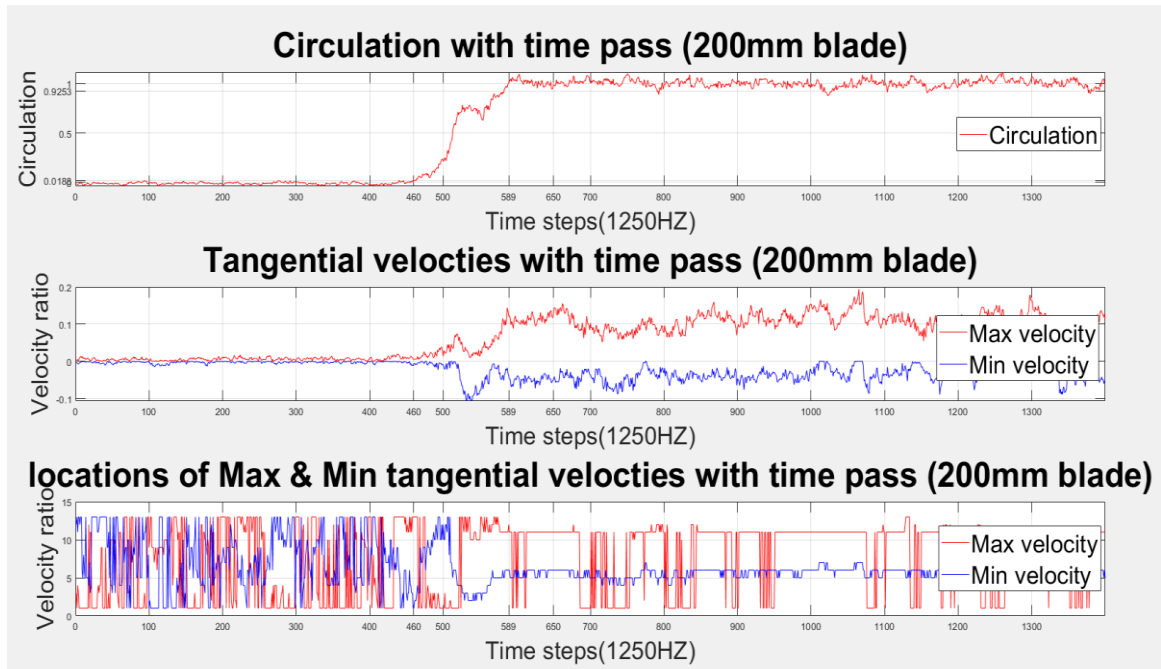


Figure 11.39 The Max & Min tangential velocities with corresponding locations with 200mm blade condition

The first plot is the circulation variations, and the second is the maximum and minimum radius velocity. The last plot is the location of two key points variations of the time period.

The 200mm blade condition was different from the previous two cases, and the circulation reached the static condition before the blade was fully deflected. The circulation variations and two critical velocities show a strong oscillation. The circulation increases at step 460, but on the radius velocity plot, the velocity increases before step 460. The two tangential velocities experienced a huge decrease at step 520. Even though the 200mm case had a shorter forming time, the key point's switch motion was similar to previous cases.

C.2.3.1 Spanwise velocity in restoration

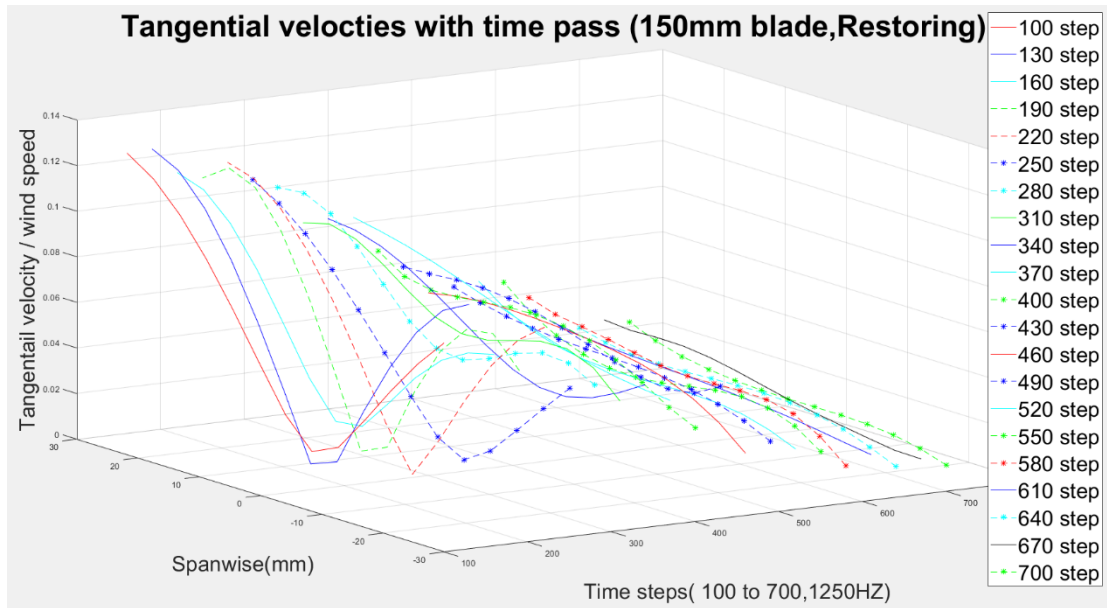


Figure 11.40 Tangential velocities with time pass at 150mm blade condition, restoring motion

The x-axis of the plot is the time steps from 100 steps of total recording to 700 steps, covering the whole restoring process. The Y-axis is the spanwise cross-section of the vortex, the middle location is 0, considered as the vortex core, also is the center of recording area, the Z-axis is the velocity ratio of the radius velocity.

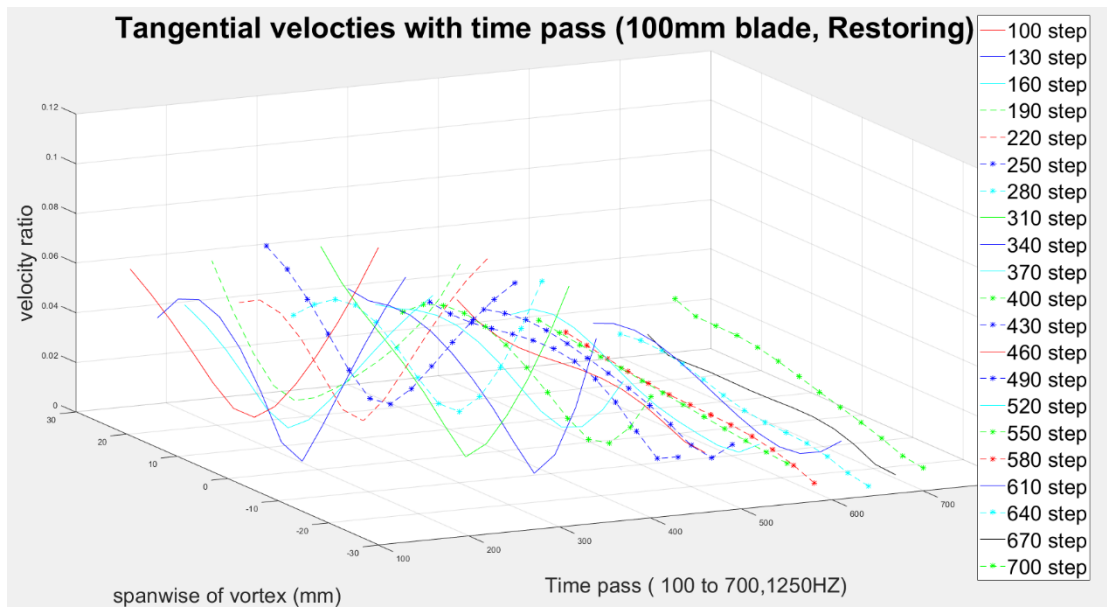


Figure 11.41 Tangential velocities with time period at 100mm blade condition, restoring motion

The plot's x-axis is the time steps, the Y-axis is the spanwise cross-section of the vortex, and the Z-axis is the velocity ratio of the radius velocity.

From Figure 11.40 and Figure 11.41, the curve shape of the tangential velocity decreases smoothly, and all speeds decline. Similar to the 200mm case, the bending of the blade did not cause the difference. The spanwise cross-section tangential velocity shows that the vortex broke down and vanished in the recording area. The slow-motion did not to affect the vortex's position; the vortex's shape was almost fixed within the restoring motion.

The radius velocity at the vertical section of case 150 mm and 100 mm are plotted in Figure 11.42 and Figure 11.43.

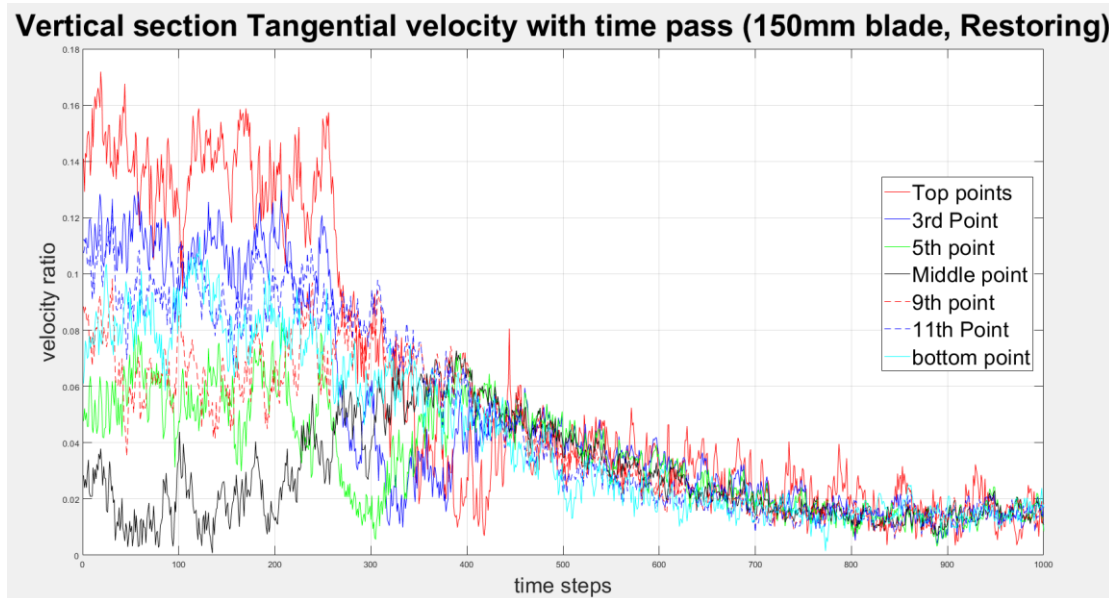


Figure 11.42 The vertical section tangential velocity with time passes

150mm blade restoring condition. 7 points are plotted in the figure, from top to bottom. The X-axis is the time steps, and the tangential velocity ratios vary with the time period. The circulation began to drop to 258.

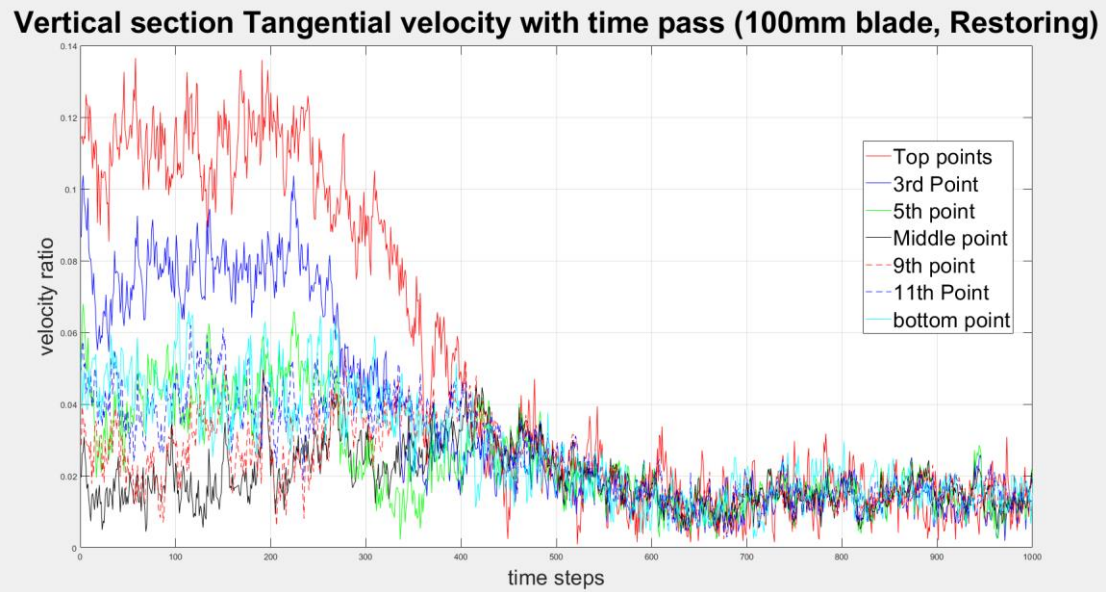


Figure 11.43 The vertical section tangential velocity with time pass 100mm blade restoring condition

Totally 7 points are plotted in the figure, from top to bottom. The X axis is the time steps, the tangential velocity ratios vary with the time period. The circulation began to drop to 272.

From Figure 11.42 and Figure 11.43, the results of 100 mm and 150 mm were similar to the case 200 mm blade. The tangential velocity at the upper parts decreased faster, and then all speeds decreased simultaneously. The decreasing process was smoother and faster than the blade motion, as shown by the tangential velocities.

C.8 Turbulence kinetic energy contours

The turbulence kinetic energy of the static vortex for three cases was computed; the data of case 200 mm, case 150 mm, and 100 mm are shown in Figure 11.44, Figure 11.45 and Figure 11.46, respectively.

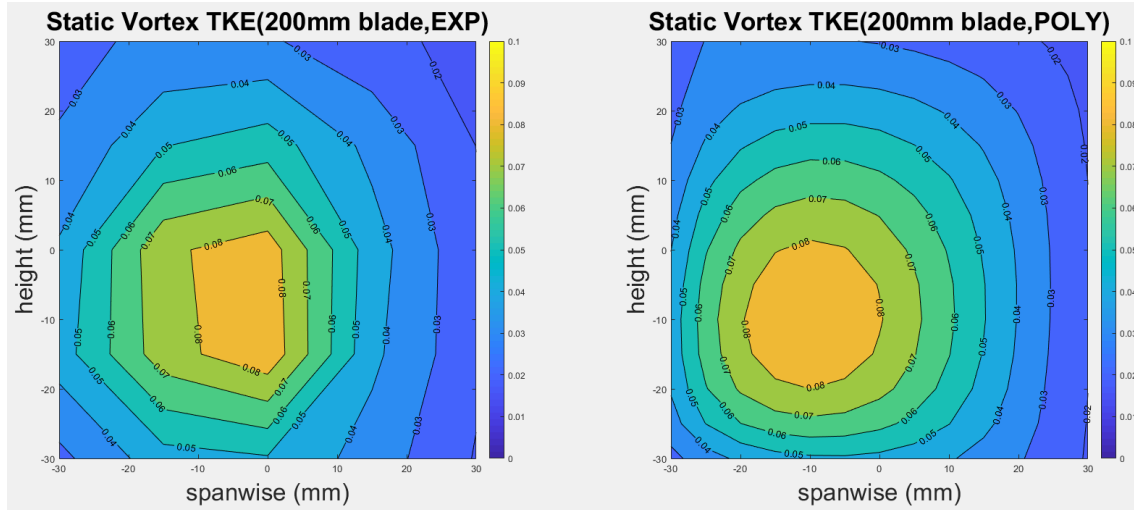


Figure 11.44 Turbulence kinetic energy of 200mm blade, static condition

The left-hand side contour is experimental data, totally 25 data points, and the right-hand side contour is three three-order polynomial function fitted, totally 169 data points. The bright colors indicate the higher energy area in the vortex. The unit of the turbulence kinetic energy is $m^2 \cdot s^{-2}$.

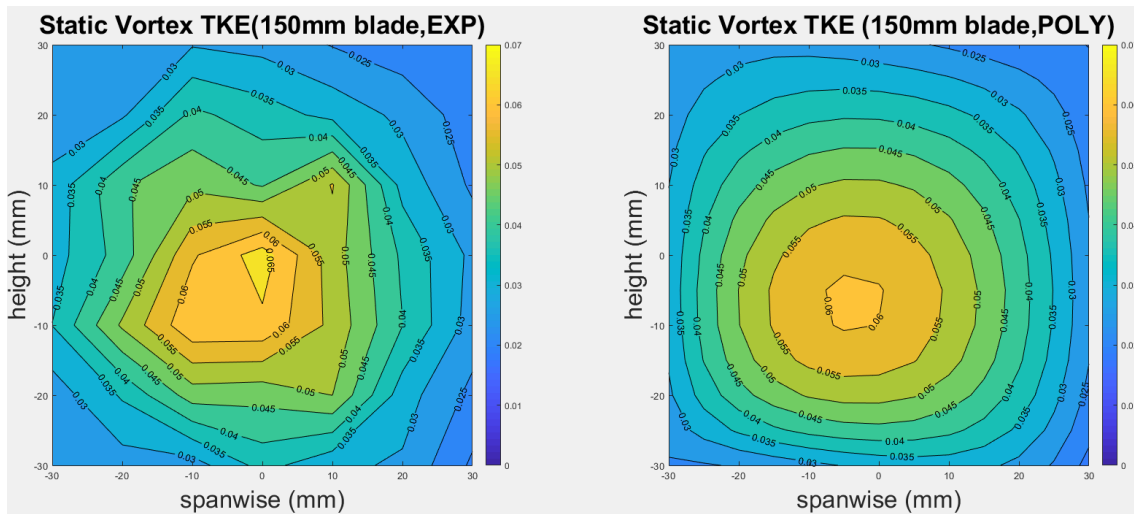


Figure 11.45 The turbulence kinetic energy of the 150 mm blade condition

The left-hand side contour is experimental data only, totally 25 data points. The right-hand side contour is the three-order polynomial function fitted, totally 169 data points. The bright colours indicate the higher energy area in the vortex. The unit of the turbulence kinetic energy is $m^2 \cdot s^{-2}$.

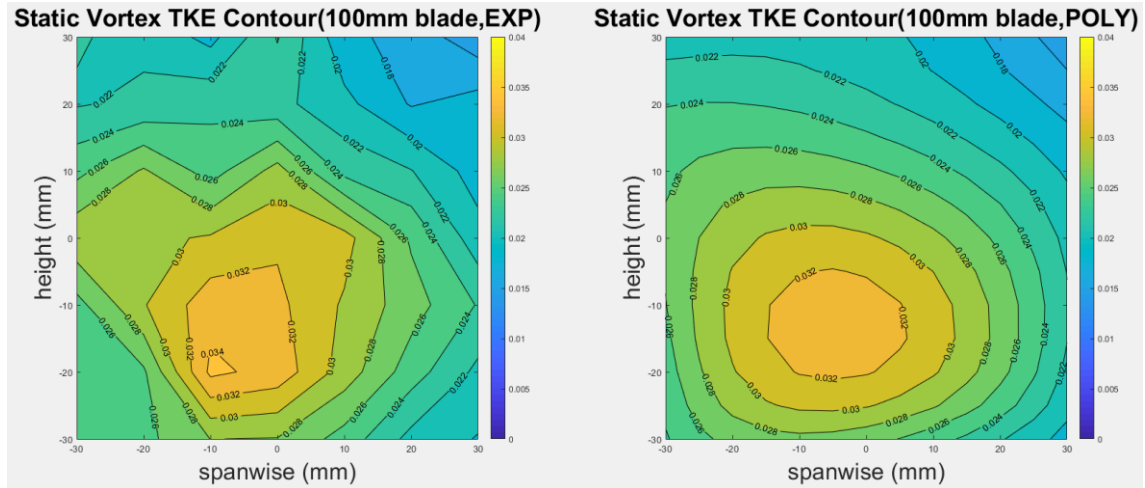


Figure 11.46 The turbulence kinetic energy of the 100 mm blade condition

The left-hand side contour is experimental data only, totally 25 data points. The right-hand side contour is three three-order polynomial function fitted, totally 169 data points. The bright colours indicate the higher energy area in the vortex. The unit of the turbulence kinetic energy is $m^2 \cdot s^{-2}$.

The turbulence kinetic energy plots show the higher energy areas are located at the centre of the static vortex. The higher energy indicates the greater fluctuations at the vortex core. The strength of the energy was associated with the vortex's strength, which was affected by the height of the blade. The stage contours are computed based on the combination of the average of high-frequency periods due to deflection and restoration energy variations. The stage contours of the 200 mm, 150mm, and 100 mm cases are shown in Figure 11.47, Figure 11.48, and Figure 11.49.

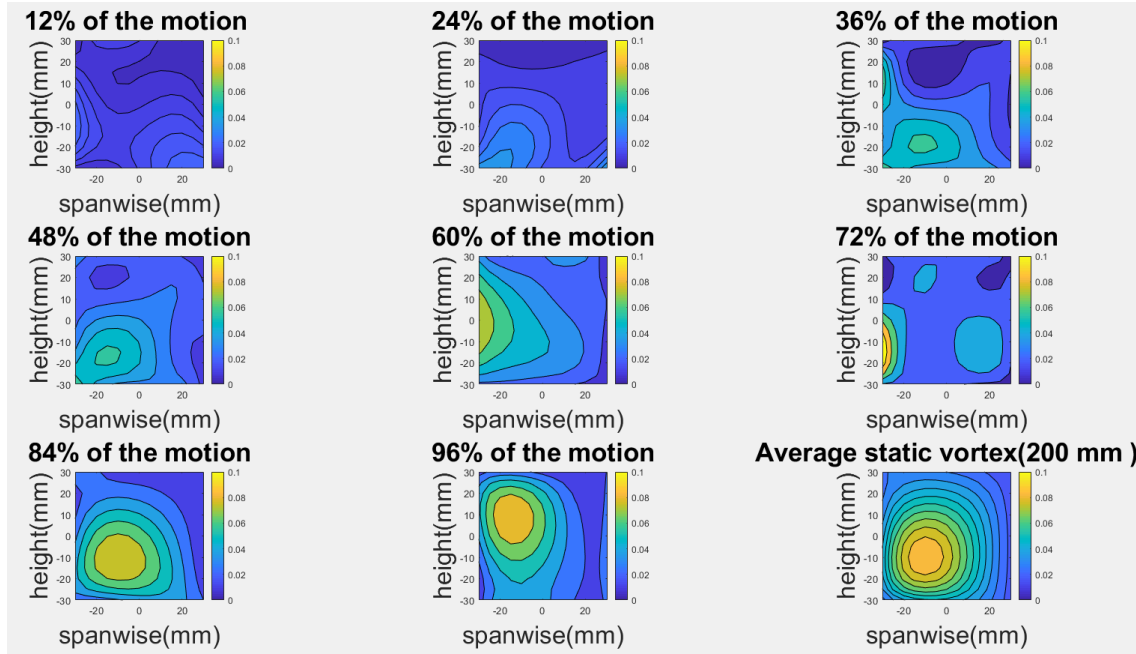


Figure 11.47 Turbulence kinetic energy variation with the deflection (200 mm).

The percentages in the subtitle are the ratio of the circulation increasing process. The bright colors indicate the high energy area (high fluctuations), and the dark colors show the low energy area. The unit of the turbulence kinetic energy is $m^2 \cdot s^{-2}$.

Figure 11.47 shows the shape of the vortex via the circular contours and the vortex's strength through the brightness of the colors. At the initial stage, the vortex was not present in the area, and only the wake was visible. The second stage involves the vortex moving into the area. In the final stage, the vortex is positioned statically, but its location within the area is not stable. Meanwhile, the height of the vortex is more stable than the spanwise location, and the energy of the vortex increases.

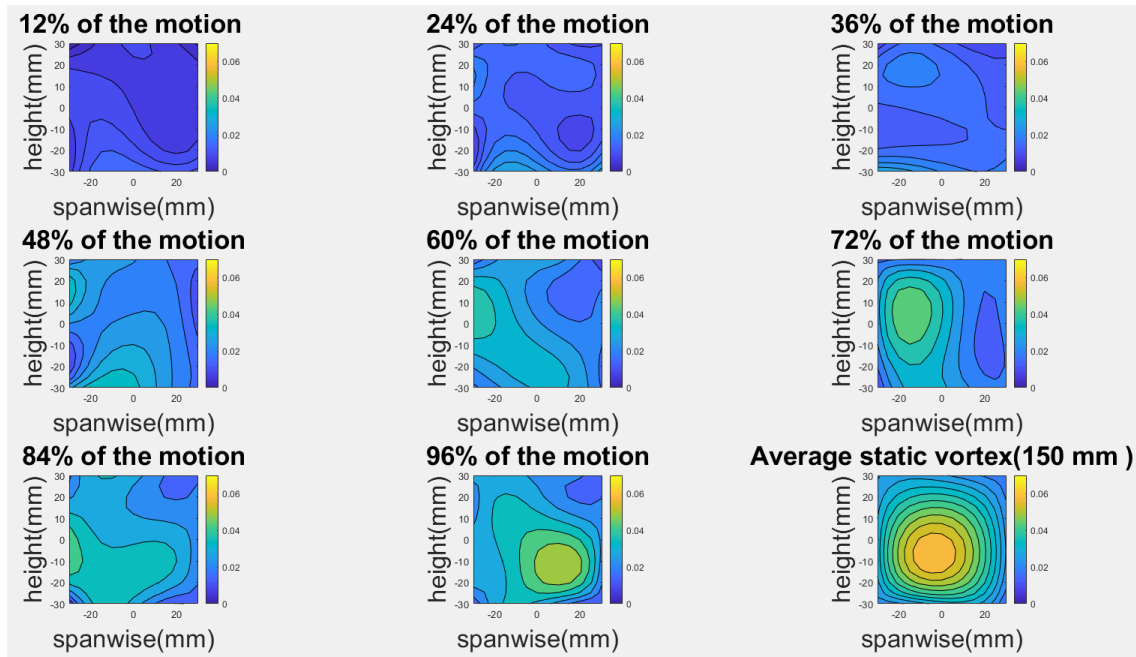


Figure 11.48. Turbulence kinetic energy variation with the deflection (150 mm)

The percentages in the subtitle are the ratios of time-pass in the process of increasing circulation. The brighter colours indicate the high energy area (high fluctuations), and the darker colors show the low energy area.

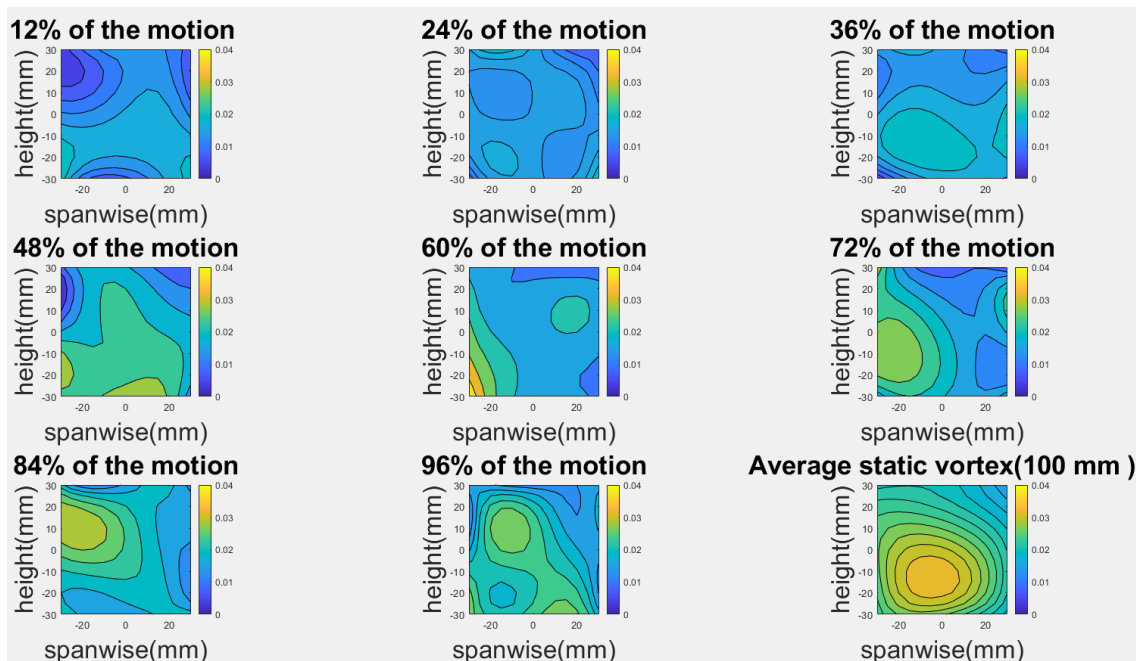


Figure 11.49. Turbulence kinetic energy variation with the deflection (100 mm)

The percentages in the subtitle are the ratios of time-pass in the process of circulation increasing. The brighter colors indicate the high-energy area (high fluctuations), and the darker colors show the low-energy area. unit: ($m^2 \cdot s^{-2}$)

The restoration of the cases also shows a similar way. The energy contour shows a similar two-stage structure to the vorticity and tangential velocity; the restoration has two parts: first, the vortex moves out in part one. Second, In part two, the wake of the vortex remains. The contour of the restoration of 200 mm is shown in Figure 11.50.

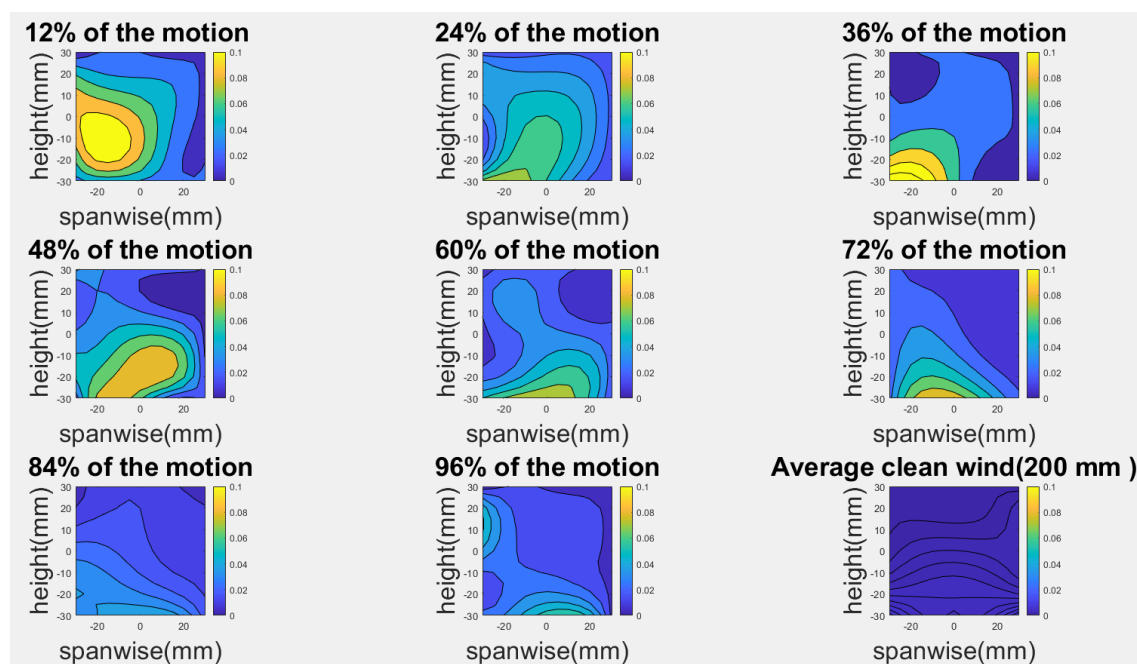


Figure 11.50 The Turbulence kinetic energy contour of the blade restoration (200 mm)

The bright colour indicates the higher energy area, and the percentage of the subtitles reflects the progress in the process of circulation dropping.

Figure 11.50 shows the contour of the turbulence kinetic energy of a 200 mm blade in recovery. The plots show that the energy in the area is always higher than the clean air condition even though the circulation drops nearly zero, which means the flow in the area is still affected by the vortex wake.