CHARACTERIZATION AND TESTING OF PIV ILLUMINATION SYSTEM USING HIGH POWER LED ON NACA 0018 AIRFOIL AT LOW REYNOLDS NUMBER

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by

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c	Chord Length
CCD	Charged Couple Device
CFD	Computational Fluid Dynamics
CID	Charged Injection Device
CMOS	Complementary Metal Oxide Semiconductor
CW	Continuous Wave
DAQ	Data Acquisition
DC	Direct Current
DDPIV	Defocusing Digital Particle Image Velocimetry
DPIV	Digital Particle Image Velocimetry
DSV	Dynamic Stall Vortex
FFT	Fast Fourier Transform
FW-MAV	Flapping Wing Micro Air Vehicle
LEV	Leading Edge Vortex
LSV	Laser Speckle Velocimetry
MAV	Micro Air Vehicle
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
PIV	Particle Image Velocimetry

PTV	Particle Tracking Velocimetry
ROI	Region of Interest
TTL	Transistor-Transistor Logic
UAV	Unmanned Aerial Vehicle
UCA	Ultrasound Contrast Agent

PENCIRIAN DAN PENGUJIAN SISTEM PENCAHAYAAN PIV DENGAN MENGGUNAKAN LED BERKUASA TINGGI PADA KERAJANG NACA 0018 PADA NILAI REYNOLDS RENDAH

ABSTRAK

Tesis ini melaporkan kerja-kerja pencirian dan penilaian sistem pencahayaan partikel imej velocimetri (PIV) dengan menggunakan diod pemancar cahaya berkuasa tinggi (HPLED). Sistem pencahayaan dibina dengan menggunakan HPLED tersebut bersama dengan litar pemacu tersuai. Litar pemacu dan HPLED dicirikan. Sebagai hasilnya, isyarat input transistor-transistor logik (TTL) dan isyarat keluaran medan kesan semikonduktor oksida logam (MOSFET) untuk litar pemacu telah dibandingkan manakala panjang gelombang yang dipancarkan oleh HPLED pada tahap kuasa dan frekuensi denyutan yang berbeza telah diukur. HPLEDs memancarkan cahaya dengan panjang gelombang yang terletak pada puncak sensitiviti spektrum peranti pengimejan. Keterangan lampu yang dipancarkan oleh HPLED juga didapati meningkat secara linear bersama penigkatan kuasa yang dibekalkan. Sistem pencahayaan yang dibangunkan ini diuji melalui siasatan kajian kes bidang aliran melintasi kerajang NACA 0018 yang bermula secara dedenyut dalam tangki air. Airfoil tersebut ditetapkan pada pelbagai sudut serangan dari 0° hingga 45° dengan peningkatan sebanyak 5°, bagi kedua-dua aliran dengan nilai Reynolds 6740 dan 9235. Perbandingan kualitatif dan kuantitatif dibuat untuk kedua-dua sistem pencahayaan melalui imej-imej yang diperolehi. Daya angkat yang dihasilkan juga diukur pada masa yang sama untuk mewajarkan keputusan yang diperoleh daripada pengukuran aliran. Imej yang diperolehi dianalisis dengan menggunakan PIVLab, suatu perisian korelasi PIV berasaskan MATLAB. Kedua-

dua medan aliran untuk kes-kes yang mantap dan tidak mantap berjaya disiasat. Melalui kes yang dikaji, kelebihan dan kekurangan sistem pencahayaan yang dibina dapat ditentukan. Kajian menunjukkan bahawa HPLED menjanjikan beberapa kelebihan dari segi kos, keselamatan dan prestasi. Presetasi yang serupa dengan sistem pencahayaan yang menggunakan laser boleh diperolehi tetapi kos yang diperlukan tidak melebihi 10% dari kosnya dengan menggunakan HPLED sebagai sistem pencahayaan. HPLED mempunyai potensi tinggi untuk dibangunkan sebagai alternatif yang sanggup menggantikan sistem pencahayaan berasaskan laser untuk PIV pada masa hadapan.

CHARACTERIZATION AND TESTING OF PIV ILLUMINATION SYSTEM USING HIGH POWER LED ON NACA 0018 AIRFOIL AT LOW REYNOLDS NUMBER

ABSTRACT

This thesis reports the work on characterization and evaluation of the particle image velocimetry (PIV) illumination system using high power light emitting diode (HPLED). An illumination system using these HPLEDs was developed with the custom-built driver circuit. The driver circuit and the HPLEDs were characterized. As a result, input transistor-transistor logic (TTL) signal and the metal oxide semiconductor field effect transistor (MOSFET) output signal for the driver circuit were compared while emitted wavelength by the HPLEDs at different power levels and pulsing frequencies were measured. The HPLEDs emitted light with wavelength that is located at the peak of the spectral sensitivity of the imaging device. The light intensity emitted by the HPLED is also found to be increasing linearly together with the power supplied. The evaluation of the developed illumination system was performed by investigating the case study of flow field across the impulsively started NACA 0018 airfoil in a water tank. The airfoil was set at various angles of attack ranging from 0° to 45° with intervals of 5°, with both flow Reynolds numbers of 6740 and 9235. Qualitative and quantitative comparisons were made on images acquired by both illumination systems. Lift force generated were also measured at the same time to justify the results obtained from the flow measurement. Images acquired were analyzed using PIVLab, a MATLAB based PIV correlation software. Both flow fields for steady and unsteady cases were successfully investigated. Through the case studied, the advantages and limitations of the developed illumination system could be determined. It showed that HPLEDs promises several advantages in terms of cost, safety and performance. Similar performance to the laser illumination system can be achieved but only requires 10% of its cost by using the HPLEDs illumination system. It has a high potential to be developed into an alternative to replace the laser-based illumination system for PIV in the near future.

CHAPTER ONE

INTRODUCTION

1.1 Particle Image Velocimetry

Particle Image Velocimetry (PIV) is one of the widely used technologies in the field of fluid flow measurement. It was developed decades ago and first appeared in the literature in 1984 (Adrian, 2005). It has been employed to measure and provide instantaneous velocity field over global domain and since then it has become an essential technique in the field of flow measurement. It is an optical method to visualize the flow field which yields the instantaneous measurement and related properties in fluid as results. As the name suggests, PIV extracts the local fluid velocity by recording the position over time of tiny tracer particles that are introduced into the fluid flow. As the interval between two captured images is very short, PIV is able to provide an instantaneous velocity with high accuracy.

Based on a classification method suggested by Hinsch (1995), measurement systems can be classified into categories and labelled as *(k, l, m),* represented by respective numbers. *k* refers to the number of velocity components measured by the measuring system, ranging from 1 to 3; *l* indicates the number of spatial dimensions of the measurement domain, ranging from 0 to 3, while *m* indicates where the measurement system performs instantaneous or continuous time recording, represented by either 0 or 1 respectively. Based on this classification, it can be observed that there are a few categories of PIV with different capabilities.

Accordingly, the best point-wise techniques attain only a (3, 0, 1) status (Prasad, 2000a). The simplest form of PIV falls in the category of (2, 2, 0) as it is possible to provide a 2-Dimensional velocity data on a planar domain instantaneously, where the majority of the PIV falls in this category. A holographic PIV system conforming to the category (3, 3, 0) had been pursued by a mere handful of groups owing to its high cost and complex implementation (Barnhart, Adrian and Papen 1994; Meng and Hussain, 1995). In contrast, a stereo-PIV system which is able to provide 3-Dimensional velocity data on planar domain and falls in the category of (3, 2, 1) are becoming increasingly popular (Prasad and Adrian, 1993; Prasad and Jensen, 1995).

A complete properly functioning PIV system consists of a few basic subsystems, which are an optically transparent test section, illumination system, recording system, a synchronizer and a computer with relevant software to process the acquired images. The entire PIV system is sold with all the items mentioned except the optically transparent test section. As PIV is becoming a common equipment equipped by many fluid dynamic laboratories; there are many vendors of PIV available, developing and providing both sales and technical support for PIV systems. Examples of PIV vendors include Dantec, ILA GmbH, La Vision GmbH and TSI Incorporated. They also provide several PIV systems that have different capabilities and designed for different purposes.

For example, the basic PIV system can be slightly modified to become a stereo-PIV system by adding an extra camera into the setup and arranging them in different viewing axes. This will provide access to the otherwise unknown third component of the velocity vector, which is capable to analyze a 3-Dimensional flow (Brossard et. al., 2009; Wieneke, 2005). Instead of adding an extra camera, replacing the original camera with a camera with high magnification to acquire a magnified image, forming a micro-PIV (Poelma and Jerry, 2010). It is applied when the flow field is very small and requires a very high magnification to acquire the images, such as turbulence in high Reynolds number pipe flow of 50mm diameter and in vivo measurement.

Similarly, by changing the recording system, the other type of PIV system that is available in the market is the digital PIV (DPIV). It is the digital counterpart of conventional laser speckle velocimetry (LSV) and PIV techniques. Images are digitally recorded and computationally analyzed, where the photographic and opto-mechanical processing steps in PIV are removed (Willert and Gharib, 1991). It is actively used by the NASA Glenn Research Center to study the stable and unstable operating condition in high speed centrifugal compressor (Wernet, 1999). DPIV can be further developed into defocusing digital PIV (DDPIV), which is offered by TSI, Inc. as 'V3V' system. DDPIV modifies the typical 2-Dimensional imaging system by using a mask with two or more apertures shafted away from the optical axis to obtain multiple images from each scattering source. It is the natural extension of planar PIV to the third spatial dimension (Pereira and Gharib, 2002).

In short, many researches and modification attempts based on PIV have been conducted in order to increase the capabilities and improve the performance of PIV as it plays an important role in the flow measurement field.

1.2 Components of PIV

As mentioned in Section 1.1, a basic PIV setup is made up of an illumination system, recording hardware and a computer, working together with an optically transparent test section with seeded flow. Each of these components are integrated for the entire PIV system to function as desired. The most basic PIV setup is illustrated in Figure 1.1 (Pullek, 2009). A light sheet is shone into the test section where the flow is seeded with particles, reflecting the light and captured by the camera located at the side. The acquired images are then further analyzed by the computer to generate desired results.

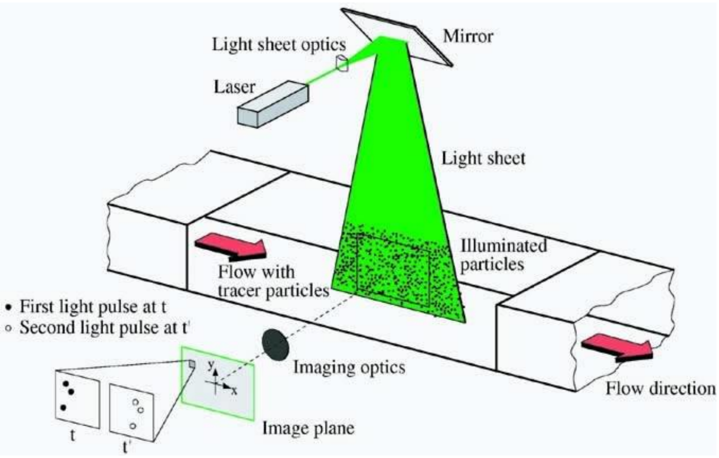

Figure 1.1: A simple PIV setup (Pullek, 2009)

1.2.1 Illumination System

One of the most basic and crucial components of a PIV system is the illumination system. The illumination system functions as light sheet generator, which makes the particles visible and possible to be acquired by the recording system. In traditional PIV system, lasers are commonly used as illumination system. This is because laser provides a monochrome light with high energy concentration. It also allows light to be bundled into thin light sheet for illuminating and recording of the tracing particles without chromatic aberrations.

The illumination system of the PIV consists of laser and a series of optics. The laser employed for PIV illumination system consists of three main components, which are the laser material, the pump source and mirror arrangement. The laser material can be in the form of atomic or molecular gas, semiconductor or solid-state, excited by the pump source through introducing electromagnetic or chemical energy. The mirror arrangement refers to the resonator that allows the oscillation between the laser materials (Raffel et. al., 2007) to build up the light energy in the beam. The colour of the light emitted by the laser differs is based on the laser material used.

Light generated by the laser is usually well focused, hence making it not suitable to be directly used for PIV application. The light from the laser must be converted into a thin light sheet in order to suit the PIV application. A series of optics are employed to perform the conversion of light from a beam to a thin sheet. The types and number of lenses used also depend on the type of lasers. Before the light beam arrived at the series of lenses from the laser head, a mirror system is employed to head the transmission. In some cases where the mirror system is not feasible, it is substituted by optical fiber which is flexible. In contrast, the light beam emitted experience loss in intensity, leading to a degrade PIV image (Grant, 1997).

The essential component to create a light sheet is a cylindrical lens, which is capable to diverge a light beam with small diameter to a light sheet. A cylindrical lens has the characteristic which causes the laser beam to expand in only one direction, i.e. the laser light beam is 'fanned' out. If the laser used generate light beam with small diameter, in this case Ar^+ laser, using one cylindrical lens is good enough to generate suitable light sheet for PIV application (Raffel et. al., 2007). For other types of lasers, for example the Nd:YAG laser, combination of different lenses is usually required to generate the light sheet with desired thickness at high intensity. At least one additional lens needs to be used to focus the light sheet into appropriate thickness. A simple light beam conversion module is presented in Figure 1.2.

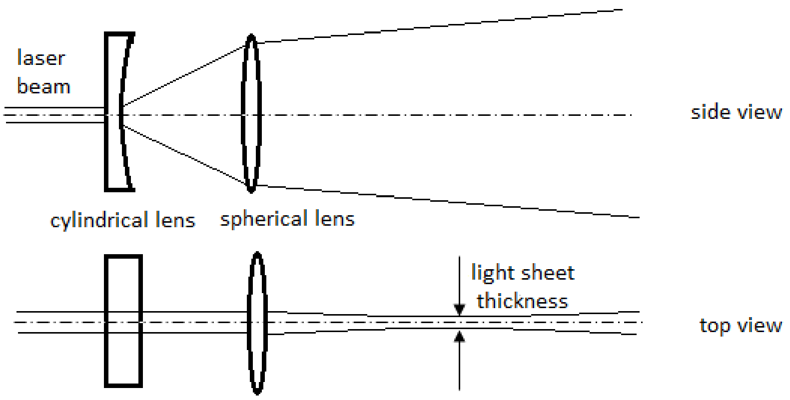

Figure 1.2: Series of lenses to generate light sheet from the laser beam

Adding a spherical lens into the light beam conversion module makes it become more versatile. The spherical lens focuses the expanding beam along the perpendicular direction. The light sheet will achieve the minimum thickness at the focal length downstream. The spherical lens is used as it is simpler to manufacture especially for those with short focal length. Generally, the use of spherical lens does not allow the height and thickness of the light sheet to change independently, ensuring the thickness of the light sheet produced. With the configuration as shown in Figure 1.2, the energy per unit area of the light sheet is higher. Adding or replacing other lenses can be done to change the light sheet characteristics based on the user preference. However, the optical lenses arrangement in the PIV illumination system is usually fixed and cannot be modified by the user.

1.2.2 Recording Hardware

Another essential component that will directly affect the performance of the entire PIV system is the recording system, which is also known as the imaging system. This system basically refers to the camera or the video recorder that is used to record or captured the images of particle movement. The fast development of electronic imaging hardware has replaced the traditional photography method. Electronic imaging is able to produce immediate image and avoid the photochemical process (Jahanmiri, 2011). Note that PIV has special demands on its recording system, especially if the flow is at high velocity, small imaging area or the size of the particle is small.

For PIV application, monochrome high speed camera is commonly used compared to a normal camera. The camera is connected to the computer so that all the images acquired can be directly transferred and saved in the computer to perform the analysis. High speed camera is more favourable than normal camera because it can achieve a higher frame rate and higher shutter speed. The latest high speed camera has a frame rate higher than 1000 frame per second, i.e. it is capable to capture more than 1000 images in one second. The use of monochrome high speed camera is possible to ensure the images with particles captured can be clearly seen for high speed flow application.

A high speed camera is possible to achieve a high frame rate because of its short exposure when capturing each image. The exposure time could be as short as 1/10000 s. The exposure time will affect the amount of light that will be sensed by the camera. The longer the exposure time, the more light will be collected by the sensor of the camera. A comparison of image with different exposure time is shown in Figure 1.3. It is obvious that image captured under high exposure time is brighter than image captured under short exposure time. This explains why a high power laser is required as the illumination system of the PIV system, in order to ensure more light is collected by the camera within the short period of exposure.

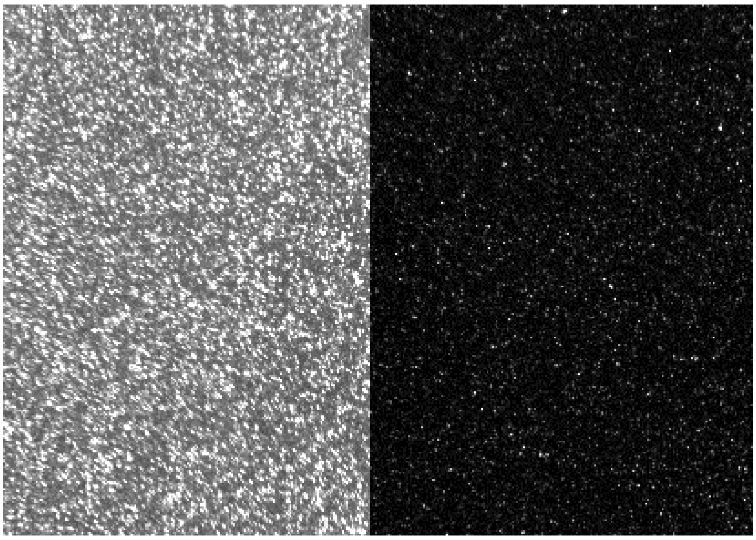

Figure 1.3: Images acquired under different exposure time. Exposure times are 1/5 seconds (left) and 1/40 seconds (right).

Besides high frame rate, another important feature of the PIV recording hardware is monochromatic. Monochromatic simply refers to drawing, design or photo which contains only one colour. This means that the camera will capture and produce black and white images which are also known as gray scale. The images shown in Figure 1.3 are in gray scale, and it is obvious that the images only present one colour. The presence of particles in the image can be recognized through the white dot shown in the images, which represents the light reflected by each particle.

The accuracy of the PIV measurement relies on resolving features at sub-pixel level. With the use of monochrome camera, accuracy is achieved when light intensity of each pixel is registered accurately. Colour cameras are possible to be used to perform correlation on the images acquired, provided that the images must first be converted into a monochrome signal while the method by which this is achieved can have a significant effect on the results (Forsey and Gungor, 2016).

The usage of monochrome high speed camera also promises several advantages. Firstly, the image resolution from a monochrome camera is higher than from a normal camera. A monochrome camera also has a lower noise compared to a normal camera under the same ISO speed. This helps the monochrome camera to increase its ISO speed. Monochrome camera also improves the appearance of noise under artificial lighting and colour temperature which differs a lot from daylight. This makes monochromatic one of the important aspects to be employed as PIV imaging system.

Besides, a monochrome camera is able to capture a more detailed image and has a higher sensitivity. This phenomenon can be explained with further understanding in sensor technology. Virtually, each sensor in the camera functions by collecting light through an array of photosites. Its concept is similar to how a grid of buckets would store falling rain. Thus, when the exposure begins, each photosite in the camera sensor is uncovered to collect incoming light. The amount of light collected by the photosites is read as an electrical signal, which is then quantified and stored as numerical value in an image file when exposure ended.

However, the photosites only measured the amount of light collected. Photosites must be able to differentiate the colour and record the value separately for each colour in order to achieve colour. Colour filters are used so that each photosite only detects light of one of the three primary colours. This indicates that only 1/3 of the light will be detected by the photosites, where the other two colours on the image are obtained through interpolation with neighbouring photosites. Different from a colour camera, colour filter is not required in the sensor of the camera. Thus, all incoming light is captured by the monochrome sensor regardless of the colour, i.e. each photosite received three times more light. This leads to increase in the camera sensitivity and ISO speed.

There are three types of off the shelf sensors for cameras, which are the charge coupled device (CCD), charge injection device (CID) and complementary metal oxide semiconductor (CMOS). CCD sensor is most widely used for the past three decades (Jahanmiri, 2011). However, with the development of chip manufacturing technologies in the early 1990s, CMOS sensors are able to be manufactured with improved noise to signal ratio and resolution, which increases the frequencies of CMOS sensors being applied in digital photography, machine vision and high speed PIV (Jahanmiri, 2011).

As mentioned before, electronic imaging has replaced the traditional photography method using film. Even though using film can achieve a better image resolution compared to CCD sensor in a monochrome high speed camera, the process of preparing the photo from the film and digitizing it consumes a lot of time. Using a CCD sensor with the same setup helps to save time (Prasad, 2000a). On the other hand, CCD sensor is more sensitive to light compared to a film. It gives a linear response towards light intensity while a film responses logarithmically (Jahanmiri, 2011). In short, the rapid development of electronic technologies contributes to a wide range of cameras available in the market to be used as PIV imaging system. Users should choose the imaging system based on respective research requirements to achieve maximum efficiency in terms of cost, time and accuracy of the measurement.

1.2.3 Computer

Extraction of particle displacement from the acquired image requires some sort of interrogation scheme (Jahanmiri, 2011). The invention of computers has eased and fastened the PIV experiments. Before computers became popular, interrogation processes are performed manually at each image where regions with low particle counts are selected so that movement of each individual particle can be traced (Agüi and Jiménez, 1987). In this modern era where computers are popular and widely used, automated interrogation process of particle tracking has become possible (Grant, 1997). The high performance of the computer processors allow the PIV results of the flow to be obtained in just a split second.

In a PIV system, a computer plays an important role and has a few functions. It can be used to edit the images acquired during the experiment, analyze the flow field by performing correlation and control the pulsing of the illumination system and imaging system. Specific software is required to perform each of these functions. Image editing is performed based on users' needs. There are some cases where image editing is necessary. Common image editing includes converting the colour image to a monochrome image, adjusting the image brightness, trimming the image or changing the image file format. There are a few possible softwares that are capable to perform the jobs above such as MATLAB photo editing software, Photoshop, IrfanView etc. The selection of software to perform the image editing depends on the user's personal preference.

To perform analysis on the raw images acquired during the PIV experiment, either crosscorrelation or autocorrelation can be performed depending on the operating mode of PIV experiment conducted. The results obtained include velocity flow field, flow velocity magnitude, vortex strength, fluid shear rate, fluid strain rate etc. The results presented are in the form of either vector plot or contour plot. Commonly used software which are possible to generate reliable results include PIVLab, a MATLAB based software, Open PIV, PIV View, Dynamic Studio etc.

All software have similar functions except that some might be different on the interface.

Other than performing analysis on the PIV images, other basic functions of a PIV analysis software include applying masking on the images, selecting region of interest (ROI) and editing the plot appearance of the final results obtained. Masks are applied to the region where flow is not present, which is usually applied to the model in the images. Correlations are not performed on the masked region. Selection of ROI can also be done to selection desired flow region to perform the analysis. Correlation will only be performed on the selected region. Calibration can also be performed to calibrate the image pixel into desired units. After the correlation is completed by the software, the plot appearance can be changed so that it can be better presented. Vector validation can also be performed to remove spurious vectors. Statistical information can also be obtained while the software performs the analysis.

PIV analysis software has eased the process of image analysis, helping one to have a better understanding of the flow field. However, for PIVLab which is operated under MATLAB, it is also possible to edit the original coding in order for the software to perform analysis that suits the user. Customized programme coding that suits the analysis requirements can be constructed and performed on PIV analysis through computational programming software such as MATLAB, C++ etc. if a user refuses to use the readily available PIV analysis software. The key thing is correct equations must be used in order to achieve accurate and reliable analysis results.

Slightly different from other PIV analysis software, besides analyzing the PIV images, Dynamic Studio, a software developed by Dantec Dynamics at the same time is also the control center of the illumination and imaging systems. It is possible to define the pulse rate and length for both the illumination and imaging systems depending on the fluid flow velocity of the PIV experiment. Live view from the imaging system is directly displayed on the screen and raw images acquired can be saved for further analysis. These capabilities have directly eased the PIV operation.

1.2.4 Test Section

Unlike the other system, a test section is not included in a PIV system. However, it is an essential component for every fluid flow experiment. It provides a platform to hold the model, at the same time generate desired fluid flow for the experiment. It is the location where the PIV measurement on the target fluid flow is conducted. It commonly refers to the transparent section where models are placed in the wind tunnel or water tunnel. The presence of experimental model depends on the research topic.

However, it is not necessary for a test section to be part of a wing tunnel or water tunnel. A water tank, pipes or any model which experiences internal fluid flow which is intended to be measured can be the test section. For cases like water tank as shown in Figure 1.4, the fluid in it is static where flow is not present. In this case, the model will have to move in order to generate the fluid flow, as the working principle is the same for the fluid to flow across a static model. For a big model where test section of a wind tunnel or water tunnel is not big enough to accommodate it, it can also being placed in an open test section but the PIV setup will be slightly more complex.

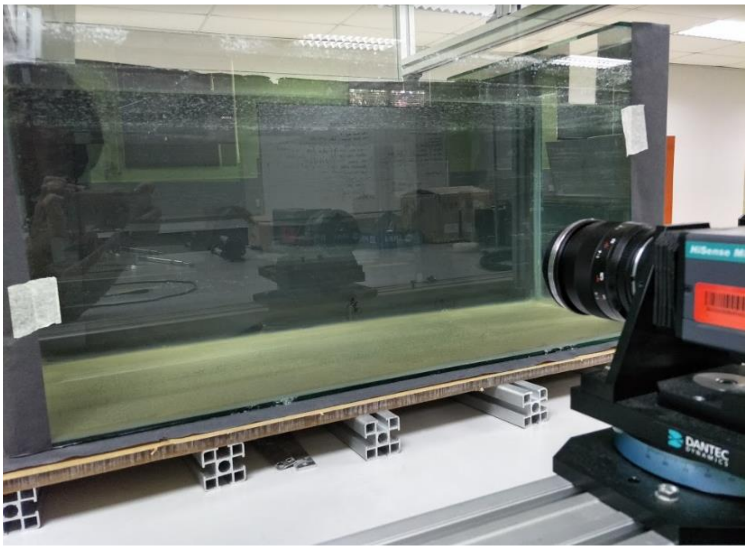

Figure 1.4: The imaging system is placed at the side of water tank which acts as the test section

The most important criterion of the test section is its transparency. Other than the open test section, a test section that is required for PIV experiment is that it must be optically transparent. This is to ensure that the light scattered by the particles can be clearly ‘seen’ by the imaging system. The PIV would be able to achieve a better performance if the background of the test section is covered, so that less stray light can enter the test section, and introducing noise into the measurement.

1.3 Reynolds Number

Conducting experiments to establish the relationship between variables of interest such as lift, drag and other flow properties are often necessary. Only certain problems of interest in fluid mechanics are solved using differential and integral equations. In order to save cost, it is necessary to keep the required experimentation to a minimum. Models of a different scale are often developed to be used in experiments in order to replace prototypes that are not possible to be used in the test due to their size. In this case, dynamic similarities between model and prototype need to be achieved to predict the associate quantity on the prototype. Dynamic similarities of an incompressible fluid flow experiment are usually represented by Reynolds number, *Re*.

Reynolds number is a dimensionless parameter that is commonly used in fluid dynamics experiments. It represents the ratio of inertial force and viscous force. It is an important parameter that is often used to determine the dynamic similarities of the flow across the model and prototype. To achieve dynamic similarities of both prototype and model, the Reynolds number must be the same. It is represented by the equation below:

$$Re = \frac{\rho v D}{\mu} \tag{1.1}$$

where ρ refers to the density of the fluid; v refers to the fluid flow velocity; D refers to the dimension of the model while μ refers to the dynamic viscosity of the fluid.

Besides, determining the dynamic similarities of the fluid dynamic experiments is also a key parameter that helps to determine the state of flow of the fluid. Some flows are laminar where they are smooth and orderly while others are rather chaotic, which is known as turbulent. The state of flow that is alternating between these two conditions is known as transitional. These states of flow mainly depend on the ratio of inertial force to viscous force, as discovered by Osborne Reynolds in the 1880s (Reynolds, 1883). The Reynolds number where the flow becomes turbulent is known as the critical Reynolds number.

The critical Reynolds number differs with different flow cases and conditions. For example, for normal or internal flow in a circular pipe, the flow remains laminar when the Reynolds number is less than or equal to 2300 but it can be maintained at a higher Reynolds number in a very smooth piper by avoiding flow disturbance and pipe vibrations (Cengel and Cimbala, 2010), where in such carefully controlled laboratory experiments, laminar flow can be maintained up to Reynolds number at 100000. On the other hand, the critical Reynolds number for flow past a cylinder and flow across a flat plate are 30000 and 500000 respectively (Anderson, 2017).

It can be clearly observed that the turbulent Reynolds number is always greater than the laminar Reynolds number regardless of flow cases. This is because for small or moderate Reynolds number, the viscous force is dominant in the flow, i.e. it is large enough to suppress the fluctuations in the flow, keeping it 'in line'. For large Reynolds number, the inertial force tends to amplify the disturbance and fluctuations are more dominant in the flow. It is proportional to the fluid density and the square of fluid velocity is large relative to viscous force. As the inertial force tends to amplify the disturbance and fluctuations in the flow, thus the viscous force cannot prevent the random and rapid fluctuations in the flow (Cengel and Cimbala, 2010). Therefore, the flow is laminar in the first case while turbulent in the latter.

1.4 Motivation

Normal off-the-shelf PIV system commonly employs high power laser as the source of its illumination system. The main concerns with the laser-based illumination system are its safety and cost. First of all, it can be hazardous if it is not handled with care. Altering the beam path of the laser, tripping over the cable which usually happens in the dark, inserting reflective objects into the beam path, bypassing the interlock accidentally turning on the power and accidentally firing the lasers are common causes of accidents when handling laser. It is reasonable to develop a safer and user-friendly illumination system as alternatives for the PIV system.

In addition, the purchasing and maintenance cost of the laser system is very high. It might cost up to a few hundred thousand (ringgit Malaysia). This means that not all institutions are able to own a PIV system. Therefore, an alternative light source which is feasible to replace the laser system is required. Looking at the cost of different light sources, a HPLED illumination system is relatively cheap which might cost less than five thousand (ringgit Malaysia). The development of HPLED illumination systems will be able to make the PIV technology more affordable and can be utilized by these institutions.

Recent development in solid state illumination which resulted in mass production of HPLEDs is capable to provide an average radiant power of 100 W. This has added some value to the use of HPLEDs as an alternative PIV illumination system. HPLEDs also promise some attractive advantages other than costing. Firstly, it has a longer lifespan and can be operated beyond its damage threshold when operating in pulsing mode (Willert et. al, 2010). HPLEDs provide incoherent light over a rather wide wavelength range which reduces many related issues on speckle artifacts found in laser-based illumination. Compared to laser, HPLEDs are easier and safer to operate. There are also no laws and restrictions on the usage of HPLEDs. The improvement of radiant power for HPLEDs led to the possibility of it being used as the illumination source in PIV system, at the very least for low Reynolds number applications.

The interest of conducting research work on low Reynolds number application originated from the demands on smaller unmanned-aerial-vehicles (UAVs) are increasing for the past few decades (Abas et. al., 2016). With rapid development of micro-structure methods (Felton et. al., 2015), flapping wing micro air vehicles (FW-UAVs) are built by imitating natural flyers while designing (Meng, Liu and Sun, 2017). Reduction in size of UAVs is equivalent to reducing the size of the wing, thus reducing the forces generated and Reynolds number experienced by the wing. This poses interest to study the complex flow condition within the low Reynolds number regime. In this case, winged insects are often of research interest which may be found in the dynamic range of Reynolds numbers from 1 to 10000 (Yao and Yeo, 2018).

To put things into perspective, this work focused on the flow diagnostic system involving standard PIV system which falls in the category of (2, 2, 0) based on Hinsch classification. The illumination system of the PIV system was developed using HPLEDs. Evaluation of HPLEDs properties were performed by qualitative and quantitative image comparisons acquired by both illumination systems. An experiment on impulsively started airfoil model at various angles of attack with Reynolds numbers ranging from 7000 to 10000 is conducted for the experimental case study. This range of Reynolds numbers are selected due to the experimental setup constraint, as well as its value towards the development of micro air vehicles (MAVs). The experiment is conducted under a condition where all the lights in the laboratory were switch off to obtain images with better signal to noise ratio.

1.5 Research Objectives

The primary goal of this research is to investigate the use of HPLEDs as the illumination source for PIV applications to replace laser illumination source. To achieve this aim, the objectives of this work are to:

1. Develop an illumination system for particle image velocimetry (PIV) measurement using high power light emitting diodes (HPLEDs). The system includes LEDs driver circuit and optical components.
2. Characterize the driver circuit and HPLEDs properties with respect to PIV application.
3. Evaluate the overall system usability with a real world test case. The test case selected is low Reynolds number flow around airfoil.

1.6 Thesis Organization

This thesis is structured into six chapters to discuss the details of the entire work performed. Chapter 1 starts with the present introduction and sets the scene for the rest of the work. It also briefly describes the components and working principle of the PIV system.

Chapter 2 is the literature review. It discusses briefly the historical development of PIV techniques, advanced PIV techniques development and its recent applications in various fields. Several modifications performed on existing PIV systems are also discussed.

Chapter 3 is the methodology. This chapter describes the methodology employed in this work in detail. It is basically divided into two parts which are development of the PIV illumination using HPLEDs and evaluation of the developed PIV illumination system on an impulsively started NACA 0018 airfoil.

Chapter 4 presents selected results obtained from the experiments and measurements conducted in this work. It starts with the characterization of the HPLEDs driver circuit, followed by the HPLEDs. The characterization results obtained are the signal output from the Metal Oxide Semiconductor Field Effect Transistor (MOSFET) and the illuminance and wavelength of the HPLEDs. Qualitative and quantitative comparisons of the HPLEDs illumination system and laser-based illumination system are also shown. The evaluation of the HPLED illumination system is the analyzed results obtained from steady state flow and unsteady state flow. The latter was performed using time resolved PIV.

The last chapter concludes the work presented in this thesis. This chapter consists of two parts. The first part discusses and concludes the performance of the HPLED illumination system while the last part suggests some future research avenues that can be undertaken.

CHAPTER TWO

LITERATURE REVIEW

2.1 Historical Background

Human senses are sensitive to moving objects in many cases, and thus simple experiments are designed to have a better understanding of the characteristics of a moving object. This also applies to the flow of fluid. Historical interest in flow measurement can be traced back to more than a thousand years (Medlock, 1986). However, the limitations of technology in the early days restrict the description of flow properties to qualitative descriptions. A great step forward in the investigation of flow field was made after the well-planned experiments to extract information about flow utilizing visualization technique replaced the passive observations of nature as time goes on (Raffel et. al., 2007).

Back in 1904, Ludwig Prandtl, a German aero-dynamist studied the aspect of unsteady separated flow behind the wing and other objects by rotating a blade wheel in his water tunnel to manually drive the flow (Albring, 1991). The tunnel comprises two sections, which are an upper and lower section separated by a horizontal wheel. The water re-circulates from the upper open channel back through the lower closed duct. Two-dimensional models such as cylinders, prisms and wings can be mounted vertically in the upper channel, thereby extending above the level of the water surface so that flow could be observed.

Prandtl visualized the flow by adding micaceous iron ore particles onto the water surface to visualize the flow. The setup enables Prandtl (1928) to study the flow structure for both steady and unsteady flow cases. However, only a qualitative description was possible but no quantitative data about the flow could be determined at that time. In fact, this flow visualization procedure was originally developed by Ahlborn, while Prandtl utilized it to study the separated flow behind wings and other models by closely following these visualization procedures (Raffel et. al., 2007).

In scientific studies, other than qualitative descriptions, quantitative data is always an important outcome. Thus, wide varieties of instruments were invented over years to quantitatively study the properties of fluid flow. According to Medlock (1986), there are about sixty different flow measurement techniques in use to meet the ever-increasing demands for domestic, custom transfer and industrial flow measurement of liquids, gases, vapors and solid in single or multiphase forms. The earliest quantitative measurement of the fluid flow was the flow velocity, which was obtained by using a Pitot static tube (Prasad, 2000a). The Pitot tube operated using the Bernoulli's principle, where it measures the velocity at a given point of a flow by measuring the pressure difference (Anderson, 2016).

A subsequent probe was invented in the 1920s, which was the hot-wire anemometer (Prasad, 2000a). It was significantly advanced, especially in probe miniaturization, frequency response and the ability to measure multiple velocity components. It operates by inserting a thin hot wire into the fluid flow. The fluid flow changes the temperature of the hot wire and hence, the velocity components of the flow are calculated based on temperature changes.

Both the techniques mentioned above are reliable to quantitatively measure the fluid flow. However, these methods are intrusive which requires a physical probe to be inserted into the flow. This leads to flow interference which might have the tendency to disrupt the flow especially at high Reynolds number applications. It is also difficult to provide the instantaneous measurement of the flow using both techniques mentioned above. The invention of PIV had solved these issues as it offers a non-intrusive method (Hyun et. al., 2003) and is capable of providing instantaneous flow measurements (Cely et. al., 2017).

It has been more than 30 years since the term ‘particle image velocimetry’ (PIV) first appeared in literature (Adrian, 2005). Tracing back the history - when the first person possessing the concept of velocity by watching small debris moving on the surface of moving stream would probably be the most rudiment form of PIV. It can be said that PIV is old and simple from this point of view. The present state of art of PIV is reliable and capable of measuring various flow applications. The rapid evolution of PIV was aided by parallel development in optical measurement techniques, flow visualization, image processing and speckle metrology (Merzkirch, 1987; Lauterborn and Vogel., 1984; Adrian, 1991; Sirohi, 1993).

In the 1960s, the technology of PIV started to grow with the invention of lasers, leading to the development of Laser Doppler Anemometer (LDA) (Park et. al., 2008). However, the first investigator to realize PIV measurement concept actually used the method of laser speckle and showed that it could be applied to fluid measurements. In fact, speckle metrology is a technique developed in solid mechanics. It measures the solid surface by illuminating a diffused laser beam on an optically rough surface leading to multiple light scattering, forming a ‘speckle’ interference pattern in the image plane of the observation optics (Archbold and Ennos, 1972). As an extension of speckle metrology, the measurement of the motion of fluid flow with high concentration of particles was conceived by Barker and Fourney in 1977 (Barker and Fourney, 1977).

Barker and Fourney (1977), Grouson and Mallick (1977), Dufferar and Simpkins (1977), three different groups of researchers independently demonstrated the feasibility of applying laser speckle phenomena to fluid flow measurement in

1977. They had measured the parabolic velocity profile in the laminar flow. They formed the Young's interference fringes from many pairs of displaced laser speckles in small interrogation spots on the speckle-grams by using a double-exposure photograph and a planar laser light sheet illumination. Liquid was chosen in their study at that time because of the high scattering efficiency of typical seed particles such as aluminum powder and latex sphere.

Since then, development of PIV techniques continues to advance. In 1978, using the laser speckle photography method that is adapted for fluid mechanic study, Simpkins and Dudderar (1978) quantitatively measured the velocity of unsteady convection in a Bénard cell suddenly cooled from above to a supercritical Rayleigh number. Using this technique, the two-dimensional full-field velocity information is able to be obtained solely from a selected plane within the volume of moving liquid at any given instant in time.

In 1980, Meynart (1980) employed the laser speckle photography techniques to obtain a 2-D map of the velocities in a Rayleigh-Benard flow, a more complicated problem of non-stationary convection. Slightly different recording techniques and spatial filtering of the recorded photograph was used for comparison. Multiple exposures were obtained with an electro optical shutter while recorded images were analyzed by using two distinct methods which are coherent plane waves and spatial filtering setup. The latter method successfully yields a whole-field picture of the velocity field directly. Later in 1983, Meynart (1983a & 1983b) applied the speckle velocimetry method to measure unsteady air flow. These publications were particularly interesting since a pulsed Ruby laser was used for measurement in air was first reported.