DYNAMIC MODELLING OF FLEXIBLE LINK AERATOR WITH EMBEDDED HOLES TO GENERATE DISSOLVED OXYGEN IN TIGER PRAWN POND

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A project report submitted in partial
fulfillment of the requirement for the award of the
Master's Degree of Mechanical Engineering

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JUNE 2015

ABSTRACT

In the aquaculture industry, aerators are used to increase the level of dissolved oxygen in water by mixing the water in order to ensure that the oxygen content is uniformly distributed throughout the pond. This aerator uses a new concept by using flexible link by implementing embedded holes in its design in. The purpose of adding holes in the design is to achieve higher dissolved oxygen level. This research consists on developing a new mathematical model by modification of the Finite Difference Method to suit the irregular boundary of the new design of flexible link aerator. The simulation is done using Matlab SIMULINK and three voltages are chosen to be the input voltage which are 6V, 9V and 12V while the percentage of immerse level were set at 100%, 75%, 50% and 25%. The best result of dissolved oxygen level was achieved by running the simulation at 12V and 25% of immerse level using the 65cm length of PVC link .The simulation of this flexible link was able to oxygen up to 9.65 mg/L with the average Standard Oxygen Transfer Efficiency 2.15 kgO_2/kWhr.

ABSTRAK

Dalam industri akuakultur, mesin pengudaraan biasanya digunakan untuk meningkatkan tahap oksigen terlarut di dalam air dengan mencampurkannya dalam air dan memastikan bahawa kandungan oksigen terlarut secara seragam di seluruh kolam. Dalam kajian ini, mesin pengudaraan yang diketengahkan mempuyai satu konsep pengudaraan baru dengan menggunakan kepingan fleksibel yang telah ditebuk dengan lubang untuk menjana oksigen terlarut. Penambahan lubang pada rekabentuk kepingan fleksibel ini bertujuan untuk meningkatkan kandungan oksigen terlarut. Kajian ini membina model matematik dengan menggunakan kaedah Pembezaan Terhingga yang diubahsuai mengikut rekabentuk dan grid yang tidak sekata pada kepingan fleksibel tersebut. Proses simulasi dilaksanakan dengan menggunakan perisian Matlab SIMULINK dan simulasi dijalankan menggunakan 3 input voltan berbeza iaitu 6V, 9V dan 12V. Ujikaji tahap rendam yang berbeza di dalam air juga dijalankan pada peratusan 100%, 75%, 50% dan 25%. . Bacaan oksigen terlarut yang terbaik didapati ketika menjalankan mesin pengudaraan ini pada voltan bernilai 12V dan tahap rendam 25% dalam air serta panjang kepingan fleksibel PVC ialah 65cm. Hasilnya mesin pengudaraan ini mampu menjana oksigen terlarut sehingga 9.65 mg/L dengan purata Kecekapan Piawai 2.15 kgO_2/kWj .

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LIST OF SYMBOLS AND ABBREVIATION

SAE	-	Standard Aerator Efficiency
SDTR	-	Standard Oxygen Transfer Rate
N/A	-	Not Available
kgO_2	-	Kilo gram oxygen
kW	-	Kilo Watts
kWh	-	Kilo Watts hour
V	-	Voltage
$\frac{d(m)}{dt}$	-	Mass transfer rate
D_m	-	Coefficient of the gas in square centimeters per second (cm^2/sec)
A	-	Area
$\frac{d(C)}{dt}$	-	Concentration gradient of the gas
mg/l	-	Milli gram per liter
τ	-	Torque
E	-	Young’s modulus
I	-	second moment of inertia
ρ	-	Density
l	-	Length

δ	-	Deflection
θ(t)	-	Radian angle
PDE	-	Partial Differential Equation
M_p	-	Mass at end point
F_d	-	Drag force
C_d	-	Drag force coefficient
ν	-	Velocity
DC	-	Direct current
Nm	-	Newton Meter
m	-	Meter
ω	-	Angular velocity
b	-	Width
d	-	Thickness
%	-	Percentage
D.O	-	Dissolved Oxygen
^oC	-	Temperature in Celcius
i	-	Current
K_La_{20}	-	The Oxygen Transfer Coefficient At 20^{o}C
C_{s20}	-	Dissolved oxygen (DO) concentration at saturation, 20^{o}C (mg/L)
V	-	water volume in m^3
C_m	-	Measured DO concentration
rad/s^2	-	Angular acceleration in Radian per second square
a.m	-	*Ante meridiem* mean before midday
p.m	-	*Post meridiem* mean after midday
Hr	-	Hours
C_{ss}	-	Saturated dissolved Oxygen
A	-	Ampere

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CHAPTER 1

INTRODUCTION

1.0 Research Background

Aquaculture business is one of the popular businesses in Malaysia due to high demand in both local and global markets and tiger prawn is an example of aquatic organism harvested in our country (Faiz et al., 2010). It has become a trend for tiger prawn farmers to accommodate a large population of prawns in a cultured environment. Several water qualities such as salinity, water hardness, and dissolved oxygen, temperature and pH level are among the parameters that need to be controlled to sustain the tiger prawn population. In this research, dissolved oxygen is the controlled parameter chosen.

Dissolved oxygen is an indicator to evaluate water quality. Aquatic life like tiger prawns depend on it to survive and if the level of dissolved oxygen drops below the requirement be hazardous to the tiger prawns (Karim et al., 2013). Therefore dissolved oxygen needs to be maintained at the required level. Currently, most aquaculture businesses are using paddlewheel or diffuser type aerators to generate dissolve oxygen. The paddlewheel however is not suitable for shallow ponds as it can disrupt the bottom of the pond and causes the water to be soiled and the diffuser type aerator consume high energy (Boyd, 1998).

One of the alternatives is to use flexible link aerator (Shah, 2012) to generate dissolved oxygen. This approach is more favourable due to its lower energy consumption and cost as well as better flexibility. The existing flexible link aerators were chosen based on its length to weight ratio. According to Boscariol et al. (2013), the weight of the flexible link can affect the energy amount of energy consumption needed to operate it. Therefore a light weight link is preferred for low energy consumption. Shah (2012) also mentions that a longer plate allows wider water surface coverage for dissolved oxygen generation in the water.

Advantages of the flexible link aerator encourage development of new design of flexible link aerator where embedded holes are implemented to increase the level of dissolved oxygen. A mathematical model will be developed using finite difference method for this new design flexible link aerator and precise boundary condition need to be considered to fit the system. The aeration system can be simulated using many types of software. In this case, Matlab SIMULINK will be the software use to simulate the control of the flexible link aerator.

1.1 Problem Statement

In the aquaculture industry, water quality is an important factor to sustain the longevity of aquatic organisms. Dissolved oxygen is one of the parameters that must be maintained at all times to avoid disruption of aquatic organism population. The aquatic organisms required pure oxygen gas to survive but could not extract it.

Aerators are made to generate dissolve oxygen in the water by circulating the water from the surface to the bottom of the pond to make sure that the level of oxygen in the entire pond is stabilized. One of the popular aerator is the paddlewheel but due to its high energy consumption and unbefitting usage in shallow ponds, it is not an ideal method to use to generate dissolved oxygen in the tiger prawn ponds (Boyd, 1998). Another type of aerator is the diffused air system aerators. This system uses high volume low pressure air blower to provide air to the diffusers which is usually located underwater. The diffuse air system release fine bubbles that present a larger surface area and more oxygen is diffused to the surface.

The flexible link aerator can solve the current problem face by farmers in the aquaculture industry since it consume less power compared to other types of aerator. Due to that advantage many studies and new designs have been done. The flexible link is being modelled using finite difference method which has been modified to fit its irregular boundary condition due the addition of a row of circular holes. The system will then be simulated using Matlab SIMULINK software.

1.2 Objective of Study

The main objectives for this study are listed below:

1. To develop a new mathematical model of the flexible link aerator with embedded holes system.
2. To simulate the new modelling of flexible link aerator system.
3. To compare results between flat plat without holes and with embedded holes

1.3 Scope of Study

In order to achieve all the objectives for this study, it is crucial to outline a few scopes to avoid the occurrence of diverted study. Three scopes has been defined and listed as below:

1. The system is modelled using modified Finite Difference Method.
2. Simulation of the system is done using Matlab SIMULINK software.
3. The results from previous research are compared to the current achieved results.

1.4 Significance of Study

Dissolved oxygen is one of the important parameters to determine quality of water. In the tiger prawn business, aeration system has been widely utilized to generate dissolved oxygen. Unfortunately, the cost to operate and maintain the current system is quite high and it is recommended to find cheaper alternatives that can reduce the cost and also durable. Many engineering discipline can be applied to the aeration system such as control engineering, fluid mechanics and machine design.

In this research, the flexible link aerator will be modelled using finite difference method with suitable boundary conditions. The movement of the flexible link is simulated using Matlab SIMULINK. For future studies, this research can guide the researches to conduct new analysis of the flexible link using a different mathematical model or control approach as well as using different software to simulate the behaviour of the system.

1.5 Flow chart

Figure 1.1 shows a summary of activities in this research. After confirmation of thesis title and proposal submission, an outline of this research is done by setting the objective and the scope of study. Once the objective and scope is confirmed, review of literatures related to this study is done to collect data and information needed followed by choosing a suitable methodology to perform this research such as choosing software, mathematical model and picking a method to validate the data from simulation. After achieving targeted results, all the data and results are recorded and then will be discussed and compared. Finally, the research will be presented for evaluation to the assessment panels.

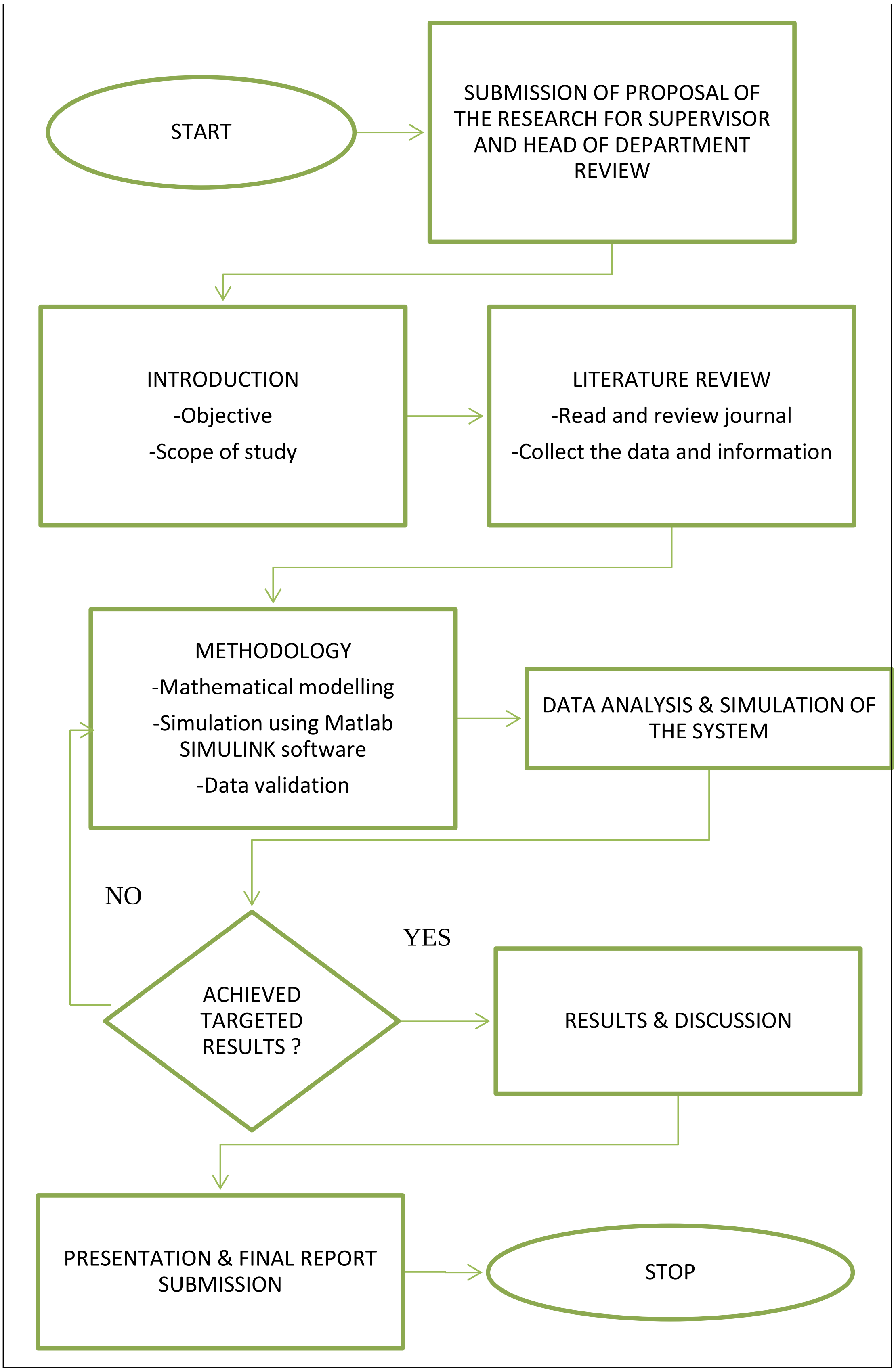

Figure 1.1: Flow chart of this research

1.6 Summary

This thesis contains five main chapters that describes and explains about the research. The first chapter presents a brief introduction about the research background of the tiger prawn, aerators and control methods, statement of problem for this research, objective, scopes and significance of study and flow chart and Gantt charts of the project that indicates activities done during this study as well as its duration.

In Chapter 2, various literature review related to prawn farming, aerator types, dissolved oxygen and controller is presented and some comparison between different aeration systems in other industries apart from aquaculture farming. It is crucial to choose suitable literature review to avoid confusion and getting accurate information.

Chapter 3 explains mostly about methodologies of the research. The processes involved such as mathematical modelling development, methods and the boundary considered as well as equations involved, simulation models, tools and software used to conduct the processes.

Results and discussion will be further explained in Chapter 4. All the results achieved will be described in detail and discussion why such result is obtained also stated in this section.

Finally, Chapter 5 includes conclusion and summary of the whole project as well as some recommendations for future research.

CHAPTER 2

LITERATURE REVIEW

2.0 Introduction

Aquaculture business has been one of Malaysia's potential engine growths and its importance in Malaysia's economy can no longer be denied due to high demand from local and international markets. The tiger prawn or scientifically known as Penaeus Monodon is one of the popular aquatic lives harvested in Malaysia that triggers many farmers to build cultured ponds to accommodate its large population and to maintain the well-being of their harvested tiger prawns, the water quality in these ponds need to be maintained (Food and Agriculture Organization (FAO), 2011).

Generally the farmers will use some parameters to indicate water quality of the ponds. The parameters are salinity, water colour, temperature, ammonia, water odour, pH level and dissolved oxygen (Chen, 1991). However in this research only dissolved oxygen level will be considered to narrow the scope. In order to maintain these parameters, the behaviour of the tiger prawn will be considered as well as the condition of the rearing pond to decide how these parameters can be constantly retained.

The aeration system has been widely used to generate dissolved oxygen in the ponds (Tavares et al., 2007). There are a few types of aerators available but it must be selected carefully according to the physical of the pond and energy consumption needed. The limitations can be a good opportunity for researchers to explore new ideas and concept to overcome them. Due to that, several mathematical modelling of the aeration system and various control methods has been applied to solve the flaws.

2.1 Facts of the Tiger Prawn

Tiger prawn or Penaeus Monodon is one of the popular aquatic species that can be found inhabits in the coasts of Australia, Southeast Asia, South Asia and East Africa. According to the Food and Agriculture Organization (FAO) of the United Nation Fishery Statistic in 2011, Malaysia is one of the major tiger prawn producers along with Thailand, Indonesia, India, Philippines, Myanmar and Vietnam.

In Malaysia, many indoor cultured tanks and earthen ponds are built to meet the demands in both local and global markets. There are a few types of method to rear the tiger prawns. In his research, Apud (1985) categorized three different methods for tiger prawn breeding. The methods are extensive, semi-intensive and intensive. For larger scale business, Intensive method is best practiced to produce higher population of the tiger prawn. However, this method required higher investment as it might need higher energy consumption to maintain the cultured ponds. Semi-intensive method is the most common method in breeding the tiger prawn where water pump is used to maintain the desired water quality. This method can accommodate about 10-30 prawns per square meter and suitable for ponds with depth ranging from 70 to 100 cm. The extensive method is more suitable for shallow ponds ranging from 40 to 70 cm depth and the capacity is limited to 2 to 3 prawns per square meter.

Despite the breeding method chosen, the main purpose to maintain the longevity of the tiger prawn is to maintain the water quality. There are several parameters that need monitoring. These parameters includes dissolved oxygen rate in the water, pH level, temperature, salinity and ammonia level. In aquatic business, dissolved oxygen is very important to boost the growth of the prawn (Debnath et al. 2012). Generally, the dissolved oxygen level varies between 4 to 9 ppm in semi intensive ponds and 4 to 7 ppm in traditional ponds (FAO, 2011). Another factor that needs consideration is the mechanism to conserve all the water quality parameters needed to sustain the tiger prawns. One of the most common mechanisms is the aeration system to generate dissolved oxygen in the water. It is crucial to choose a suitable mechanism as some aeration mechanism can worsen the water quality due to the unbefitting characteristic towards the physical of the pond. Another reason is some mechanism is not economical for a small scaled business due to its high energy consumption. Figure 2.1 shows the physics of the tiger prawn that can be found in Asia.

Figure 2.1: The physics of a tiger prawn (http://cairnsoceanproducts.com.au, 2014)

2.2 Dissolved Oxygen

Dissolved oxygen concentration is an indicator of the aquatic ecosystem's well-being. Dissolved oxygen is not only meant for aquatic organisms but also useful to humans, animals and all living creatures. Streeter and Phelps (1925) first modelled the dissolved oxygen of the Ohio River in U.S and since then many modifications and extensions have been done towards the model which is also known as DO sag equation.

Main source of dissolved oxygen in aquatic environment can be classified into three (Floyd, 2003). The sources are by direct diffusion from atmosphere, wind wave action and photosynthesis by aquatic plants. The dissolved oxygen fluctuates throughout the day and varies with temperature and altitude changes. Normally, dissolved oxygen rate will be reduced due to many reasons such as temperature and weather changes where higher temperature can reduce the amount of oxygen in water.

It is also believed that excessive algae growth contributes to the cause of low dissolved oxygen level because die-off and decomposition of algae at the bottom of the pond can suffocate aquatic organisms and reduce the amount of dissolved oxygen especially at the bottom of the pond. Figure 2.2 shows sources of dissolved oxygen.

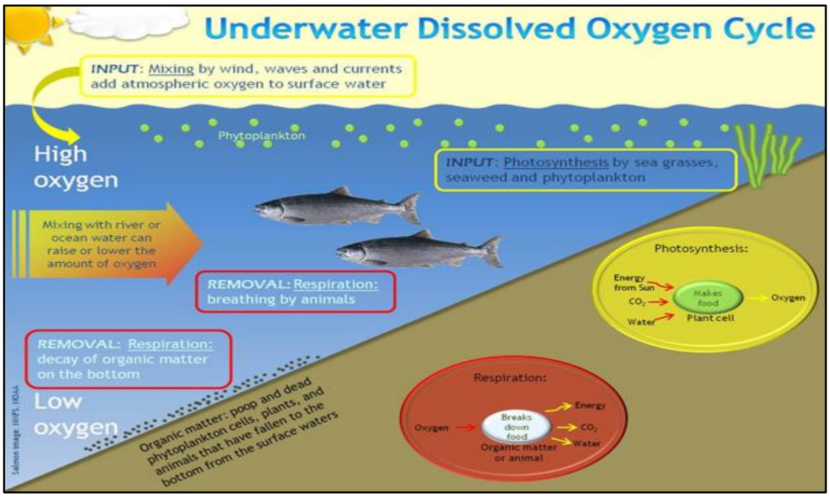

Figure 2.2: Source of dissolved oxygen (http:// www.globalspec.com, 2014)

2.3 Aeration

Generally, aeration is a process where air is circulated and mixed or dissolved with a substance such as water. This process is generally applied in industries such as waste water management, food industries, oil and gas, agriculture and aquaculture. Although the mechanism used might be different, the purpose is similar which is to eliminate constituents face in each industry.

In the agricultural industry, aeration is a process where the soil is mechanically since compact soil reduces the ability of the roots to grow. Soil aeration has been done to reduce compaction and allow oxygen and water to penetrate through the soil and absorbed by the plants.

Drew (1992) mentioned in his research that the roots of plants can experience shortage of oxygen when the soil becomes flooded or waterlogged and causes a fraction of the roots to be anaerobic in order to survive. In their research, Armstrong and Boatman (1967) attempt to further the aeration measurement conditions and relate them to plant behaviour in the Yorkshire valley and they revealed that plant distribution was found to vary with state reduction of soil and concluded that aeration is important to alleviate the soil. Laurenson and Houlbrooke (2012) indicate in their research that mechanical aeration can provide a short term improvement towards the porosity of the compacted soil and can contribute to a higher pasture growth rate. Figure 2.3 shows a roller type aerifier used to aerate lawns.

Figure 2.3: Roller type aerifier (http://www.ipm.ucdavis.edu, 2014)

In food technology, aeration is not an estranged process. In bread making industry, the bread making process consists of three major operations which are mixing a process where the dough is kneaded and developed and air bubbles introduced followed by proving, during which the yeast produces carbon dioxide gas causing the bubbles to inflate and the dough to rise and baking the process that sets the aerated structure of the bread. Nowadays, the mixing stage determines the final bread texture.

Aeration of the dough when mixing process is done is crucial since it will decide the quality and appeal of the bread loaf (Chin and Campbell, 2006). In wine making industries, aeration technique is practiced to expose the wine with air for a short period in order to improve the flavour. Aeration can also be applied in ice cream making process as higher aeration can produce smoother and tastier ice cream. In cereal making process, stored grains were aerated to combat pests and slow down mould development as well as maintaining germination of the seeds. Figure 2.4 shows an example of aeration technique in grain storage.

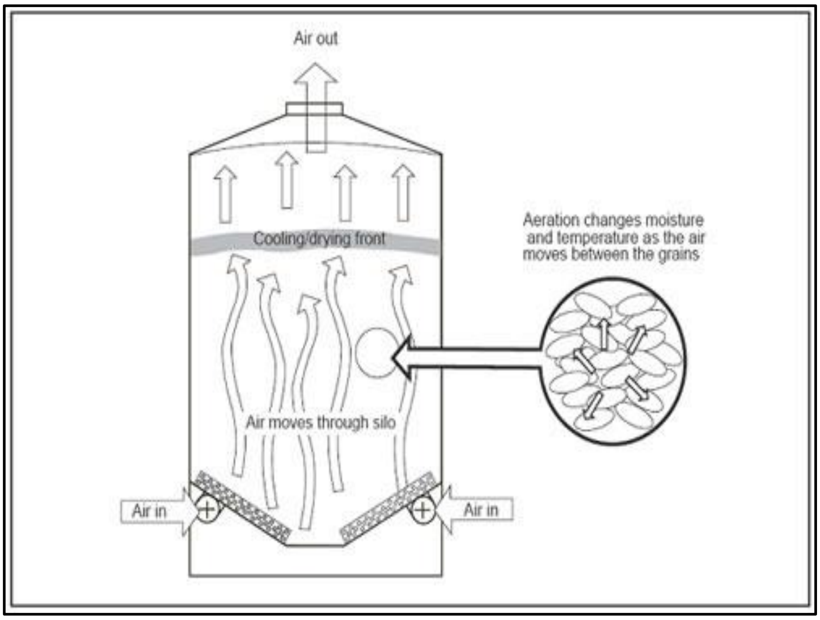

Figure 2.4: Aeration technique in grain storage (https://www.daff.qld.gov.au, 2014)

Waste water management also apply aeration technique by introducing air bubbles to liquid in order to build an aerobic environment for microbial degradation of organic matter. The purpose of aeration is to supply the required oxygen to the metabolizing microorganisms as well as provide mixing so that the microorganisms come into intimate contact with the dissolved and suspended organic matter (Pescod, 1992). Figure 2.5 shows an example of aeration practice in waste water management.

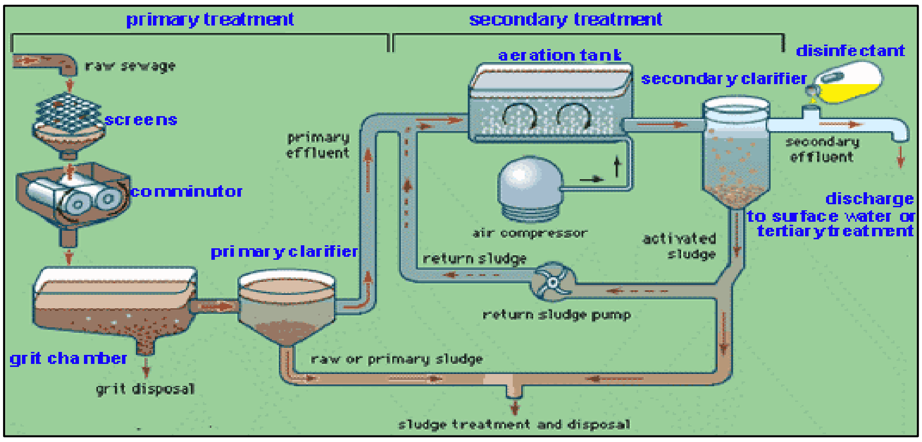

Figure 2.5: Aeration in waste water (http://www.blueplanet.nsw.edu.au, 2014)

In aquaculture business, aeration technique is applied to generate dissolved oxygen. Water can only hold a limited amount of oxygen. In natural setting, oxygen is added to water by atmospheric diffusion, photosynthesis of plants and by wind circulation. However, a few factors can contribute to the depletion of oxygen level in the water. These factors include weather changes, temperature, pollution and waste decomposition. Many aeration techniques have been practiced to generate oxygen in order to sustain the harvested aquatic organism. Among the methods used are the paddlewheel aerators and diffused type system. Figure 2.6 shows how aeration process of a fish pond is conducted.

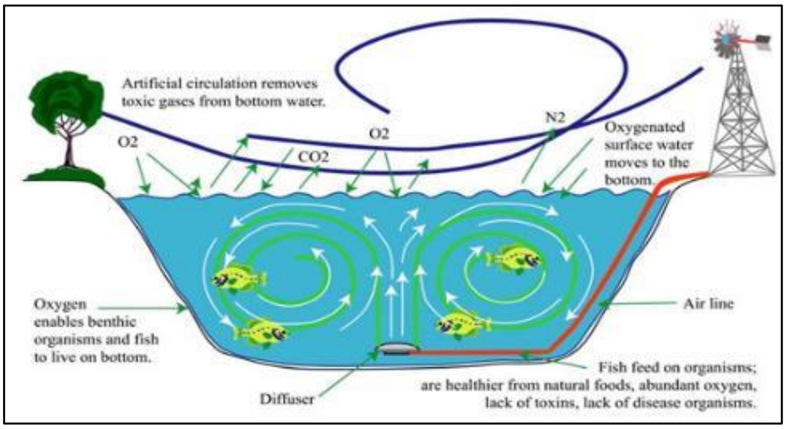

Figure 2.6: Aeration of fish pond (http://www.marlowsfishingpark.com,2014)

2.4 Aerators for ponds

Many types of aerators are invented to suit its usage in the industry. In pond aeration, there are several types of aerator used. One of the common aerator is the paddlewheel. Paddlewheel aerators can be classified as one of the most efficient aerator due to its ability create larger surface areas of air-water interface and allow oxygen to be absorbed and release harmful gas (Boyd 1998). Large paddlewheel aerators of 15 kW capacities or higher are typically used with freshwater catfish culture in the US while 1.5 kW or smaller paddlewheel aerators of Taiwanese design are typically used in marine shrimp culture (Fast et al., 2000). An example of the paddlewheel used in fish and prawn farming is shown in Figure 2.7.

Figure 2.7: Paddlewheel aerator (http://www.aquaculture-aerator.com.tw, 2014)

Another type of aerator used in the aquaculture business is the diffused air system. This method is effective in ponds that are deeper than 8 feet. Typical diffused air systems have an air compressor that has a tube that connects to a diffuser located at the bottom of the pond. As air is forced down the tubes, the diffuser converts it into small bubbles that are released into the pond. This action caused the water to de-stratify as of the air rising to the surface and oxygen deprived water at the bottom of the lake is mixed with the oxygen rich water above and eliminates harmful gases to the atmosphere. At the surface, where the bubbles break, additional oxygen transfer is made by adding to the overall oxygen content of the water. As shown in Figure 2.8 the process of air diffusion in ponds is illustrated.

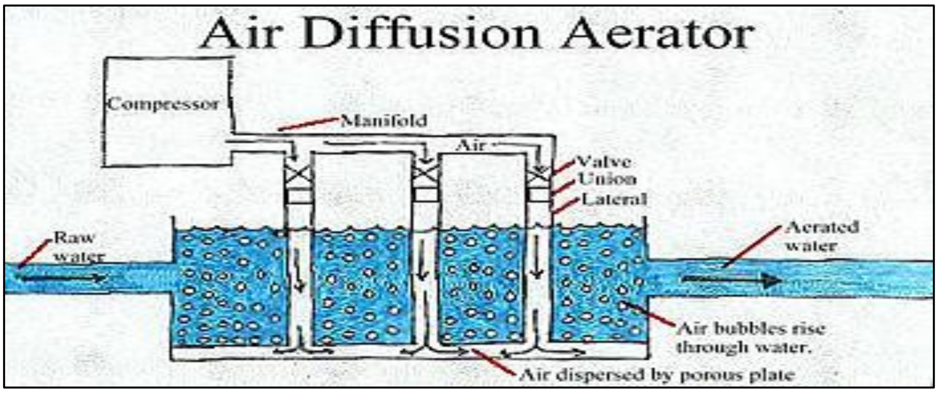

Figure 2.8: Air Diffusion in Ponds (http://water.me.vccs.edu, 2014)

Submersible pump aerator is another popular method in pond aeration. This method is recommended in small nursery ponds but not advisable in larger ponds (Boyd, 1995) and usually the aerator is placed at the bottom of the pond with its outlet pointed to the surface.

This type of aerator provides circulation and mixing of the water and oxygen is added to the water by diffusing the poorer quality of water to the surface. In the aquaculture industry, surface aerators is more popular compare to submersible aerators because it has better efficiency and more convenient in terms of maintenance (Rao and Kumar, 2007). In Australia it can be said that surface aerator such as paddlewheel is a popular choice to aerate ponds (Peterson et al. 2001).

Aeration and circulation of the water is very important to ensure the safety of aquatic environment and well-being of aquatic organism. Therefore it is important to choose a suitable aerator that can eliminate unwanted gasses and substance and maximize the oxygen level in the water. Factors such as pond design, costs and energy consumption as well as specification of the aerator should also be considered in choosing aerators. This is due to certain type of aerator might not suit shallow ponds as it will cause the water to be muddy and certain type of aerator consumes a lot of energy and will increase the cost to operate the pond and not suitable for small aquaculture business.

2.5 Flexible manipulators

Flexible manipulators have been studied extensively due to their importance especially in robotics research and have been applied in many engineering application nowadays. The advantages of flexible manipulators over rigid manipulators such as greater manoeuvrability and less power consumption as well as fast motion and less material usage attracts many researchers to focus on the study of its development (Mansour et al. 2010).

In their research, Mansour et al. (2010) mentions that flexible manipulators can be beneficial in space exploration due to their advantage of having high payload to weight ratio. Jia et al. (2007) also emphasize the importance of flexible robot manipulators in underwater research and explore the possibility of tuning and controlling the flexible robot grasping strength and manipulation. This kind of research is important since the attempts of grasping an object using a flexible robot without controlling the grasping force applied to the object can result in damaging the object if excessive force is applied.

According to Jiang (2008), force control is very important for many practical manipulation tasks of robot manipulators, such as, assembly, grinding, de-burring that associate with interaction between the end-effector of the robot and the environment.

Nguyen et al. (2013) also studied the implementation of flexible link in the form of flexible tail fin of a robot fish which is able to create propulsion forces as well as moving forwards and backwards easily. This ability possessed by the flexible tail is characteristic of a flexible link.

The application of flexible links manipulators is worldwide trending in technologies nowadays. Thus, various application of flexible link in industries has been study to improve its ability and many researches are implementing its good characteristic for greater use.

2.6 Mathematical Modelling

Mathematical modelling can be described as a representation of real objects or devices in mathematical terms. Mathematical modelling has been increasingly important subject especially in engineering or applied science especially in the era where computer technology expands and demanding the requirement of translating more mathematical formula and equation.

In engineering application, many mathematical models have been applied such as partial differential method, neural network, recursive least square and genetic algorithm and finite difference method. Tian et al. (2004) in their research investigates the force control of constrained flexible manipulators. They proposed a new control method by introducing recursive neural network to approximate the dynamics of the flexible manipulators.

Solis et al. (2009) implement the Euler-Bernoulli beam equation to design an effective control method for the end tip of their flexible link robot. Shah (2012) makes use of the finite difference method to model his flexible link aerator and introduces a new boundary condition for the system.

The idea of applying mathematical model into a system can be useful to engineers or researchers to predict the system's behaviour. Meng and Chen (1988) stated in their research that since several vibration modes of a flexible arm must be identified with adequate precision to predict the plant dynamics for the design of a competent controller, many techniques are suggested to identify the dominant modes of the plant.

These approaches can be divided into two categories which are the model analysis method where experiments are being used to identify dominant Eigen modes solving the governing partial differential equations to obtain approximated modes. Another method is using the finite element method which is discretizing the actual system into elements whose elastic and inertial properties are obtained from the actual system. These two methods will provide the approximated static and dynamic properties of the actual system.

Shawky et al. (2007) make use of the Lagrangian mechanics for their proposed dynamic model of a single link flexible manipulator with revolute joint. They assumed the link as an Euler Bernoulli beam that is subjected to a large angular displacement to establish the model of the flexible link.

Mathematical modelling is an expression of things that can happen, possible to happen and impossible to happen. It is the crucial part especially for control engineers and researchers to accomplish in their design or analysis. Just like stated in their research, Duka and Zeidman (2013) quoted that mathematical competence is an imprescriptible part of any engineering education and almost all branches of engineering rely on mathematics as a language of description and analysis. This strengthened the statement that an accurate model of a system is essential especially in control engineering.

Many dynamic models have been proposed to represent the flexible link. Some use the Euler-Bernoulli beam configurations and others assumed that the link as clamped-free, pinned-free or perhaps pinned-mass. Mansour et al. (2010) stated that the flexible link can be modelled by assuming it as pinned free flexible link and employing the simple link theory. This assumption is only valid when ratio between the length of the link and its height is relatively large (>10) and only if the link dose becomes too wrinkled due to flexure.

Equation 2.1 represents the total (net) displacement or y (x, t) of points along the flexible link at a distance of the hub for angular displacement θ and elastic deflection, ∂, can be described as a function of both the rigid body motion (t) and elastic deflection ∂(x, t) measured from the line OX shown in the schematic of flexible link which can be seen in Figure 2.9

$$y(x,t) = x\ddot{\theta}(t) + \delta(x,t) \quad (2.1)$$

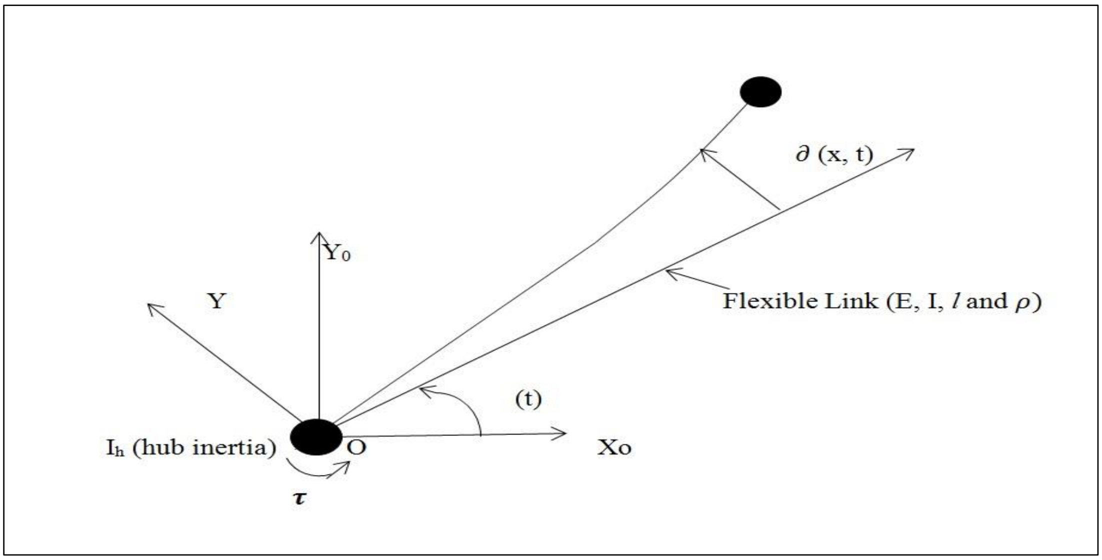

Figure 2.9: Schematic of the Flexible link

The fourth order partial differential equation (PDE) of the flexible link motion from Equation 2.1 is obtained. Md Zain (2010) and Azad (1994) stated that by associating the kinetic, potential and dissipated energies of the system the principle of dynamic equation of motion for the flexible link can be extended and rotary inertia and shear deformation effects can be ignored. The governing equation is shown in Equation 2.2:

$$EI\frac{d^4u(x,t)}{dx^4} + \rho\frac{d^2u(x,t)}{dx^2} = -\rho x\ddot{\theta} \quad (2.2)$$

In order to establish the boundary conditions the assumptions below is taken into account

- The displacement at hub (x, t) must be zero.
- Total applied torque must be the same force at the hub.
- Mass, M_p at the end point is equal to the shear force.
- The end point should not have external force and stress at the end point is zero.

The corresponding boundary conditions for Equation 2.2 can be seen in Equation 2.3 and represents the dynamic equation of motion of the system and it assumes that there is no existence of the water as the flexible link moves. However to implement the link in the water, the boundary conditions must be change. This is due to the existence of drag force that can slow down the movement of the flexible link

$$
\begin{aligned}
&u(0,t) = 0\\
&I_h \frac{\partial^3 y(0,t)}{\partial t^2 \partial x} + EI \frac{\partial^2 y(0,t)}{\partial x^2} = \tau(t)\\
&M_p \frac{\partial^2 y(l,t)}{\partial t^2} - EI \frac{\partial^3 y(l,t)}{\partial x^3} = 0\\
&EI \frac{\partial^2 y(l,t)}{\partial x^2}
\end{aligned}
\tag{2.3}
$$

Shah (2012) conducted a research on his new concept of flexible link aerator to generate dissolved oxygen in water by making full use of the manoeuvrability of flexible link as well as ability to cover more surface area to generate waves in water and increase the level of dissolved oxygen by both simulation and experimental method. The flexible link will be employed in the water therefore the fluid will apply a reaction forwards from the movement which will contribute to added mass.

According to Van Deyzen (2008) the drag force is caused by fluid such as water, air or any liquid or gas that strikes on an object and corresponds with the object’s reference area and coefficient. In fluid dynamics, it is used to measure the resistance of an object in fluids such as air or water. Benson (2010) stated that shapes can influence the amount of drag produced and different shapes has different coefficient. Figure 2.10(a) and Figure 2.10 (b) shows common value for drag coefficient for various shapes.

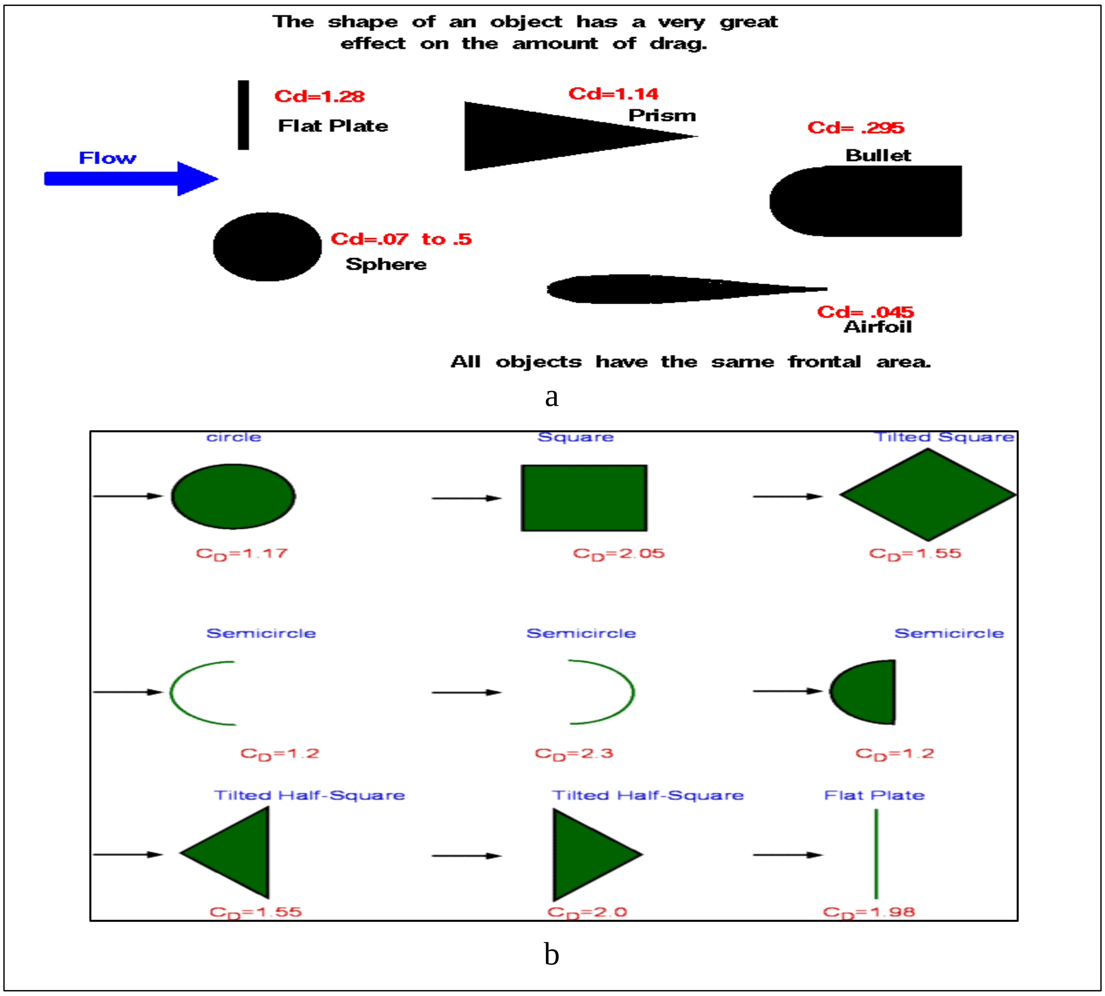

Figure 2.10: Common value for drag coefficient (Benson, 2010; Maxemow, 2009)

Shah (2012) in his research implement the drag coefficient which is considered as flat plate (C_d=1.28) Figure 3.5 shows the basic outline of the flexible link and the flexible plate. The symbols E, I, ρ, I_h and τ are the Young's Modulus, area moment of inertia, mass density per unit length, hub's inertia and input torque. The drag coefficient can be expressed as shown in Equation 2.4 (Benson, 2010). In this equation, F_d is representing the drag force of component in direction of the flow's velocity. Mass density is represented by ρ and υ represents the velocity of object relative to the fluid. Reference area of object relative to fluid is represented as A and C_d represents the drag coefficient. In this research, the reference area of interest is shaded in grey as seen in Figure 2.11.

$$F_d = 0.5\, \rho\, \upsilon^2 C_d A \qquad (2.4)$$

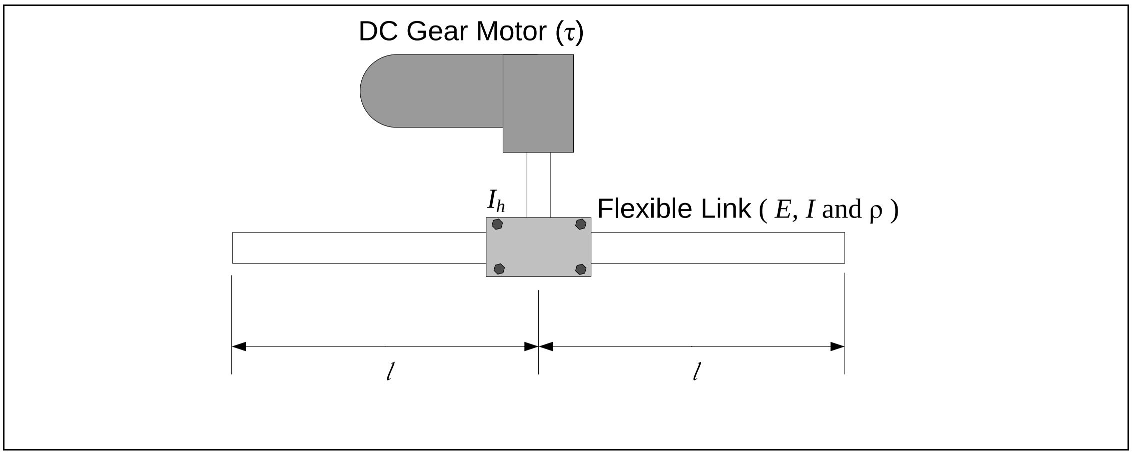

Figure 2.11: Outline of the flexible link aerator

Due to the existence of drag force, modification to Equation 2.3 is done by taking the drag force into consideration which is shown in Equation 2.5. The symbol L denotes the length of the flexible link and F_d (t) is the drag force that changes with time.

$$u(0,t) = 0$$

$$I_h \frac{\partial^3 y(0,t)}{\partial t^2 \partial x} + EI \frac{\partial^2 y(0,t)}{\partial x^2} = \tau(t) - F_d(t)L$$

$$M_p \frac{\partial^2 y(l,t)}{\partial t^2} - EI \frac{\partial^3 y(l,t)}{\partial x^3} = 0$$

$$EI \frac{\partial^2 y(l,t)}{\partial x^2} = 0 \quad (2.5)$$

The assumption made for this new boundary conditions in Equation 2.5 are:

- The displacement at hub (x, t) must be zero.
- Total applied torque must be the same force at the hub after water resistance is included
- Mass, M_p at the end point is equal to the shear force.
- The end point should not have external force and stress at the end point is zero.

In order to solve the Partial Differential Equation (PDE) in Equation 2.5, Finite Difference (FD) method will be used. The FD schemes are shown in Equation 2.6

$$\frac{\partial^2 u(x,t)}{\partial t^2} = \frac{u_{i,j+1} - 2u_{i,j} + u_{i,j-1}}{\Delta t^2}$$

$$\frac{\partial^2 u(x,t)}{\partial x^2} = \frac{u_{i+1,j} - 2u_{i,j} + u_{i-1,j}}{\Delta x^2}$$

$$\frac{\partial^3 u(x,t)}{\partial x^3} = \frac{u_{i+2,j} - 2u_{i+1,j} - 2u_{i-1,j} + u_{i-2,j}}{2\Delta x^3}$$

$$\frac{\partial^3 u(x,t)}{\partial t^3} = \frac{u_{i,j+2} - 2u_{i,j+1} - 2u_{i,j-1} + u_{i,j} - 2}{2\Delta t^3}$$

$$\frac{\partial^4 u(x,t)}{\partial x^4} = \frac{u_{i+2,j} - 4u_{i+1,j} + 6u_{i,j} - 4u_{i-1,j} + u_{i-2,j}}{\Delta x^4}$$

$$\frac{\partial^4 u(x,t)}{\partial t^4} = \frac{u_{i,j+2} - 4u_{i,j+1} + 6u_{i,j} - 4u_{i,j-1} + u_{i,j-2}}{\Delta t^4}$$

$$\frac{\partial^3 u(x,t)}{\partial t^2 \partial x} = \frac{u_{i,j+1} - 2u_{i,j} + u_{i,j-1} - u_{i-1,j+1} + 2u_{i-1,j} - u_{i-1.j-1}}{\Delta x \Delta t^2}$$

$$\frac{\partial^3 u(x,t)}{\partial x^2 \partial t} = \frac{u_{i+1,j} - 2u_{i,j} + u_{i-1,j} - u_{i+1j-1} + 2u_{i,j-1} - u_{i-1.j-1}}{\Delta t \Delta x^2} \quad (2.6)$$

In this mathematical model, the FD process will divide the length of the link with n sections to become a *Δ*x section of length and consider the deflection of each section at a sample time *Δ*t. The discretization can be seen in Figure 2.12.

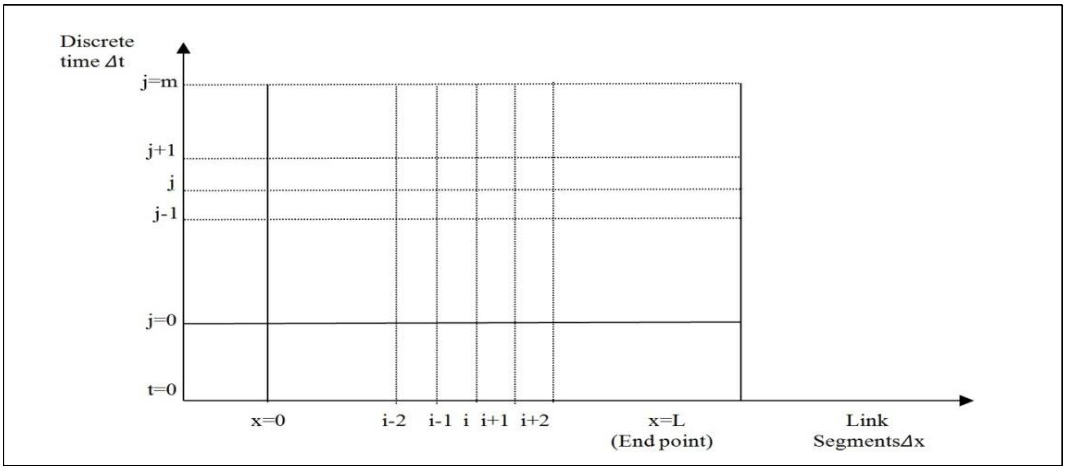

Figure 2.12: Finite difference discretization in time and space variable

2.7 Advantages of surface alteration.

Shah (2012) invented the flexible link aerator and in his research he is able to conclude that his design is able to generate an acceptable level of dissolved oxygen with less power consumption compared to the Paddlewheel. Due to that reason another design of flexible link done by Zain et al. (2014) has been developed. The design implements a row or embedded circular holes and the experiment proved that it can achieve better results in generating dissolved oxygen compared to the previous design.

Research done by Yajima and Sano (1996) in the study of drag reduction also indicates the advantage of adding holes in their experimental apparatus where double row of holes were made across the diameter of a hollow circular cylinder and a remarkable of 40% drag reduction was found compared to a smooth surface cylinder. Low drag surfaces are often desired in applications such as ship hulls and pipe flows and can have substantial energy savings, resulting in ecological and economical benefits. Due to that reason, Greidanus et al. (2015) apply riblet surfaces which are small surface protrusions aligned in the flow direction to observe the drag change compared to a smooth reference surface. In their research, they manage to reduce drag by disturbing the span wise motion of the flow at the surface. Walsh (1983) in his research concluded that micro surface geometry variation can reduce drag and contribute to cost reduction.

2.8 Summary

The tiger prawn farming is an important aquatic business in Malaysia and triggers many aquatic farmers to harvest them in a cultured pond using various technique. For sustaining their longevity, water quality must be in an ideal condition. Among the parameters being monitored are dissolved oxygen and pH level. Dissolved oxygen can be generated using many ways. Some farmers opt to use the paddlewheel and some might choose a diffused system type for their pond aeration. The decision is based on the suitability of their pond's physics because some aerators are not suitable for shallow ponds.

Due to the inconvenience face by the current aerators, Shah (2012) proposed a flexible link aerator as a new aeration concept. However it is not easy to control a flexible manipulator. Therefore, in order to get a good control of a system it is crucial to get its accurate model. Flexible manipulators are no exceptions. Researchers all over the world have been modelling their flexible manipulators using various mathematical models. Among their favourite method is the finite difference method due to its approximate solution method and its ability to handle nonlinear conditions and solve complex problems (Korayem et al. 2011). On the other hand there are some researchers, who opt to use a different modelling method such as Neural Network and Genetic Algorithm.

After getting an accurate model, the flexible link manipulator can be simulated using various type of software such as LabView or Matlab SIMULINK. However, according to Patel et al. (2002) Matlab SIMULINK is favoured in researches since it is user friendly and it has an interactive environment for modelling, analysing, and simulating a wide variety of dynamic systems as well as providing graphical user interface by utilizing the drag and drop operation when constructing a block diagram.

REFERENCES

Air Diffusion Aerator Retrieved October 21, 2014, from *http://water.me.vccs.edu/*

Apud, F. D. (1985). Extensive and semi-intensive culture of prawn and shrimp in the Philippines. In *Proceedings of the First International Conference on the Culture of Penaeid Prawns/Shrimps, 4-7 December 1984, Iloilo City, Philippines* (pp. 105-113). Aquaculture Department, Southeast Asian Fisheries Development Centre.

Alam, & Tokhi. (2007). Dynamic modelling of a single-link flexible manipulator system: a particle swarm optimisation approach. *Low Frequency Noise, Vibration and Active Control*, *26*(1), 57-72.

Armstrong, W., & Boatman, D. J. (1967). Some field observations relating the growth of bog plants to conditions of soil aeration. *The Journal of Ecology*, 101-110.

Azad K.M. Analysis and design of control mechanisms for flexible manipulator systems. PhD thesis, *Department of Automatic Control and Systems Engineering, The University of Sheffield*, 1994

Banks, R.B. and Herrera Of (1977). Effect of wind and rain on surface reaeration, Journal of the Environmental Engineering Division, Vol. 103, No. 3, May/June 1977, pp. 489-504

Billings, S.A and Voon, W.S.F. (1985). Correlation based model validity tests for non-linear models. Research report no. 285, Department of Automatic Control and System Engineering. University of Sheffield, U.K. International Journal of Control Volume 44, Issue 1, 1986.

Bhuyar L.B, Thakre S.B and Ingole N.W (2009), Design characteristics of curved blade aerator w.r.t aeration efficiency and overall oxygen transfer coefficient and comparison with CFD modeling. International Journal of engineering, science and technology Vol 1, no. 1, 2009, pp.1-15

Boscariol, P., Gasparetto, A., Vidoni, R., & Romano, A. (2013). A model- based trajectory planning approach for flexible-link mechanisms. In *Mechatronics (ICM), 2013 IEEE International Conference on* (pp. 219-224). IEEE.

Boyd, C.E. (1990). Water Quality in Ponds for Aquaculture. Birmingham *Publishing Company, Birmingham, Alabama.*

Boyd, C. E. (1998). Pond water aeration systems. *Aquacultural Engineering*. doi:10.1016/S0144-8609(98)00019-3

Boyd, C. E. (1995). Deep water installation of a diffused-air aeration system in a shallow pond. *Journal of Applied Aquaculture*, *5*(1), 1-9.

Benson, T. (Mar. 16, 2010). "Shape Effects on Drag." NASA Webpage:

http://www.grc.nasa.gov/WWW/K-12/rocket/shaped.html

Cairns Ocean Products. (2014). *Retrieved from http://cairnsoceanproducts.com.au/*

Cancino, B., Pedro Roth, Manfred Reub, (2004). Design of high efficiency surface aerator, Part 1. Development of new rotor for surface aerators. Aquacultural Engineering 31, 83-98

Chen, S. N. (1991). Environmental problems of aquaculture in Asia and their solutions. *Revue scientifique et technique (International Office of Epizootics)*,*10*(3), 609-627.

Chin, N. L., & Campbell, G. M. (2006). Modelling of bread dough aeration during mixing: Experimental investigations using scale-up mixers.

Debnath, P.P., Karim, M., Quazi, A.Z.M. and Kabir, K.E. (2013). Comparative Study on Growth Performance of Bagda (p. monodon, Fabricius, 1798) in Traditional and semi-intensive culture systems. Science and Technology 2013,3(1) 1-16

Department of Agriculture, Fisheries and Forestry. (2014.). Retrieved from *http://www.daff.qld.gov.au*

Drew, M. C. (1992). Soil aeration and plant root metabolism. Soil Sci. 154, 259–267. Armstrong W. & Boatman D.J. (1967) Some field observations relating the growth of bog plants to conditions of soil aeration. *Journal of Ecology* 55, 101–110

Faiz, A. N. A., Khairuddin, I., Jegak, U., Azril, M. S. H., & Jeffrey, L. S. (2010). Aquaculture industry potential and issues: a case from cage culture system entrepreneurs: suggestions for intensification of aquaculture industry. *Journal of Social Sciences*, *6*(2), 206.

Fast, A. W., & Menasveta, P. (2000). Some recent issues and innovations in marine shrimp pond culture. *Reviews in Fisheries Science*, *8*(3), 151-233.

Fishery Statistics from the Food and Agriculture (FAO) of the United Nations (2006,2011). Retreived from http://www.fao.org

Floyd, R.F (2003). Dissolved Oxygen for fish production, Fisheries and aquatic sciences Department, Florida Cooperative Service, Institute of Food and Agricultural Sciences, University of Florida

Greidanus, A. J., Delfos, R., Tokgöz, S., & Westerweel, J. (2015). Riblet Drag reduction and the effect of bulk fluid rotation in a fully turbulent Taylor-Couette Flow *Physical Review Letters*,*114*(1), 014501.

Home Page - UC Statewide IPM Program. (2014.). *Retrieved from http://www.ipm.ucdavis.edu*

IHS Engineering360 - Engineering Search & Industrial Supplier Catalogs. (2014.). *Retrieved from http://www.globalspec.com*

Jia, P., Meng, Q., and Wang, L. (2007). Dynamic analysis on fingers of the underwater multi-fingered robot hand. In Proc. IEEE Int. Conf. on Mechatronics and Automation, 757 -762.

Jiang, Z. H. (2008). Vision-based Cartesian space motion control for flexible robotic manipulators. *International Journal of Modelling, Identification and Control*, *4*(4), 406-414.

Karim, M., & Kudrat-E-Kabir, Q. A. (2013). Comparative Study on Growth Performance of Bagda (P. monodon, Fabricius, 1798) in Traditional and Semi-intensive Culture Systems. *Science and Technology*, *3*(1), 1-16.

Korayem, M. H., Vatanjou, H., & Azimirad, V. (2011). New hierarchical method for path planning of large-scale robots. *Latin American applied research*, *41*(3), 225.

Laurenson, S., & Houlbrooke, D. J. (2012). The effect of soil aeration on the recovery of soil structure in the North Otago Rolling Downlands following winter grazing of sheep and cattle. *Fertiliser and Lime Research Centre*.

Mansour, T., Konno, A., & Uchiyama, M. (2010). Vibration Based Control for Flexible Link Manipulator. *Tohoku University*.

Md Zain, B.A.(2010), Dynamic Modelling of a Single-Link Flexible Manipulator Using Particle Swarm PhD thesis, Department of Automatic Control and Systems Engineering, The University of Sheffield, UK, 2010

Maxemow, S. (2009). That's a Drag: The Effects of Drag Forces.*Undergraduate Journal of Mathematical Modeling: One+ Two*, *2*(1), 4.

Meng, C. H., & Chen, J. S. (1988, April). Dynamic modeling and payload-adaptive control of a flexible manipulator. In *Robotics and Automation, 1988. Proceedings., 1988 IEEE I nternational Conference on* (pp. 488-493). IEEE.

Nguyen, P.L., Do, V.P and Lee, B,R, (2013). Dynamic Modelling and experiment of a fish robot with a flexible tail fin. Journal of bionic engineering 10(2013) 39-45

Paddle Wheel Aerator. Retrieved October 21, 2014, from http://www.aquaculture-aerator.com.tw/en/2_1443/manufacturer/PADDLE_WHEEL_AERATOR_id9542.html

Patel, R., Bhatti, T. S., & Kothari, D. P. (2002). MATLAB/Simulink-based transient stability analysis of a multi machine power system. *International Journal of Electrical Engineering Education*, *39*(4), 320-336.

Pescod, M. B. (1992). Wastewater treatment and use in agriculture.

Peterson, E. L., Wadhwa, L. C., & Harris, J. A. (2001). Arrangement of aerators in an intensive shrimp growout pond having a rectangular shape. *Aquacultural engineering*, *25*(1), 51-65.

Pond services. (n.d.). Retrieved October 21, 2014,

from http://www.marlowsfishingpark.com/pond-services /

Rao, A. R.; Kumar, B., (2007). Neural modeling of square surface aerators., *J. Environ. Eng. 133(4), 411–418*.

Rogers, L.G. (2001). Aeration Offers Dealers More Than They May Realize, Vol 43 No. 6, June 2001

Shah, M. A.M (2012). Modeling flexible plate as an aerator to generate dissolved oxygen. doi:10.1109/CSPA.2012.6194705

Shawky, A. M.; Ordys, A. W.; Petropoulakis, L.; Grimble, M. J.(2007) "Position control of flexible manipulator using non- linear with state-dependent Riccati equation". Proc. IMechE, 221 Part I: *J. Systems and Control Engineering*, 475- 486,

Solís, J. F. P., Navarro, G. S., & Linares, R. C. (2009). Modeling and tip position control of a flexible link robot: experimental results. *Computación y Sistemas*, *12*(4), 421-435.

Streeter, H. W. and Phelps, E. B., (1925), "A Study of the Pollution and Natural Purification of the Ohio River, III. Factors Concerned in the Phenomena of Oxidation and Reaeration," *U.S. Public Health Service*, Bulletin 146.

Tavares-Sipauba, L.H.; Braga, F. M. de S. (2007) The feeding activity of Colossoma macropomum larvae (tambaqui) in fishponds with water hyacinth (Eichhornia crassipes) fertilizer. *Brazilian Journal Biology*, São Carlos, v. 67, n. 3, p. 459-466

Tian, L., Wang, J., & Mao, Z. (2004). Constrained motion control of flexible robot manipulators based on recurrent neural networks. *Systems, Man, and Cybernetics, Part B: Cybernetics, IEEE Transactions on*, *34*(3), 1541-1552.

Van Deyzen, A. (2008). A nonlinear mathematical model of motions of a planning monohull in head seas. *Delft University of Technology, The Netherlands*

Water Issues. (2014.). Retrieved 2014, from http://www.blueplanet.nsw.edu.au/wi--saw--the-wastewater-treatment-process/.aspx

Walsh, M. J. (1983). Riblets as a viscous drag reduction technique. *AIAA journal*, *21*(4), 485-486.

Yajima, Y., & Sano, O. (1996). A note on the drag reduction of a circular cylinder due to double rows of holes. *Fluid dynamics research*, *18*(4), 237.

Zain, B. A. M., Kamarrudin, M. H., Omar, Z., & Wahab, M. S. (2014, November). New Design Flexible Link Aerator to Generate Dissolved Oxygen in Water. In *Applied Mechanics and Materials* (Vol. 660, pp. 857-862).

Zeidmane, A., & Duka, V. (2013, September). Students' perceptions on practical problem solving in mathematics in e-environment. In *Interactive Collaborative Learning (ICL), 2013 International Conference on* (pp. 82-87). *IEEE.*