DESIGN AND ANALYSIS OF COLD FORGED AUV PROPELLER

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2011

DESIGN AND ANALYSIS OF COLD FORGED AUV PROPELLER

by

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**Thesis submitted in fulfillment of the
Requirements for the degree of
Master of Science**

June 2011

ACKNOWLEDGEMENT

In the name of Allah, the most Beneficent, the most Merciful

All praise and glory goes to Almighty Allah (Subhanahu Wa Ta’ala) who gave me courage and patience to carry out this work. Peace and blessing of Allah be upon His last prophet Muhammad (Sallallahu Alaihi Wassalam).

My deepest appreciation and gratitude goes to my thesis supervisor Assoc. Prof. Dr. Zahurin Samad for his guidance and numerous moment of attention he gave throughout this research work. His valuable suggestions made this work interesting and knowledgeable for me. I extend my deepest gratitude to my co-supervisor, Assoc. Prof. Dr. Mohd Rizal Arshad for his guidance and encouragement during my study. Thanks to National Oceanography Directorate (NOD) and Ministry of Science Technology and Innovation (MOSTI), Malaysia, for providing funding to pursue my research in underwater system technology.

I would like to thank to all friends especially those in Underwater Robotics Research Group (URRG) for their favor, encouragement and cooperation.

And last but not least, I would like to thank to my parents, brothers and sister for their support and prayers.

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LIST OF SYMBOLS

J_s Advance velocity

$\bar{\bar{\tau}}$ Stress tensor

μ Molecular viscosity

δ_{ij} Kronecker delta

$-\rho\overline{u_i' u_j'}$ Reynolds stresses

∇^2 Laplace operator

φ Velocity potential

Γ Circulation Strength

ρ Density

C_T Thrust coefficient

C_P Power coefficient

C_R Radial force coefficient

η Efficiency

J Advance ratio

G Non dimensional circulation

P Electrical power

I Current

Q Torque

T Thrust

ω Angular velocity

LIST OF ABBREVIATION

AUV	Autonomous underwater vehicle
EDM	Electric discharge machining
URRG	Underwater Robotics Research Group
PVL	Propeller Vortice Lattice
CFD	Computational Fluid Dynamic
IMU	Inertial measurement unit
MIT	Massachusetts Institute of Technology
MPVL	MIT Propeller Vortice Lattice
CNC	Computer Numerical Control
CMM	Coordinate Measuring Machine
CAD	Computer Aided Drawing
QUICK	Quadratic Upstream Interpolation for Convective Kinematics
SIMPLE	Semi-Implicit Method for Pressure Linked Equations
RANS	Reynolds Average Navier Stokes

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REKABENTUK DAN ANALISA KIPAS AUV TEMPAAN SEJUK

ABSTRAK

Kebanyakan kuasa kenderaan bawah air (AUV) digunakan system tujahan yang terdiri dari kipas dan motor elektrik. Oleh kerana kuasa AUV hanya dibekalkan oleh bateri, maka penggunaan kuasa menjadi pekara penting dalam mengoptimumkan prestasi AUV. Di dalam kajian ini kipas perlu difabrikasi untuk kegunaan AUV yang dibina oleh kumpulan pengkaji robot bawah air (URRG). Rekabentuk kipas yang bersesuaian haruslah dicari bagi membolehkan AUV mengoptimumkan penggunaan kuasa. Kod PVL yang telah dibangunkan oleh Kerwin (2001) telah digunakan untuk menghasilkan kipas yang optimum. Untuk menganalisis kelakuan kipas, simulasi pengkomputeran dinamik bendalir telah dilakukan terhadap kipas. Kajian ini juga melihat penghasilan kipas menggunakan proses tempa sejuk. Untuk menempa kipas, geometri yang komplek telah dimudahkan dengan menggunakan konsep rekabentuk modular. Keputusannya, kod PVL memberikan kecekapan yang tinggi dalam rekabentuk kipas. Nilai kecekapan adalah 76 %. Dengan mengunakan konsep modular, kipas dipecahkan kepada tiga bahagian yang ringkas. Bagi memudahkan fabrikasi mengunakan proses tempa sejuk. Walaubagaimanapun, hanya bilah kipas ditempa kerana kekangan kos pembuatan acuan. Kipas berjaya dihasilkan mengunakan proses tempa sejuk. Keputusan eksperimen menunjukkan simulasi CFD berjaya meramal kelakuan kipas. Perbezaan antara simulasi dan experimen hanya 5.41%. Akhirnya keputusan simulasi menunjukkan bahawa kipas yang dihasilkan cukup baik untuk digunakan oleh URRG AUV.

DESIGN AND ANALYSIS OF COLD FORGED AUV PROPELLER

ABSTRACT

Most of power of an Autonomous Underwater Vehicle (AUV) is utilized by its propulsion system. Since AUV power only depends on onboard battery, the power consumption becomes crucial issue in optimizing the AUV performance. In this research a propeller need to be fabricated for AUV that will be developed by Underwater Robotic Research Group (URRG). The specific propeller design must be discovered in order to optimize the AUV power consumption. PVL code that has been developed by Kerwin (2001) was used as a tool to design the specific propeller. To analyse the behavior of the propeller, Computational Fluid Dynamic (CFD) simulation was done on the propeller. This work also looked into propeller fabrication by using cold forging process. To forge the propeller, the geometry complexity was reduced by applying modular design concept. As a result, the PVL code gave high efficiency in the propeller design. The efficiency value was up to 76 %. By applying the modularization concept the propeller geometry was split up into three simple parts to ease the fabrication using cold forging process. However, only the blade was forged due to higher cost in fabricating the die set. The blade was successfully fabricated by using cold forging. The experimental result proved that the CFD simulation can predict the performance of the propeller. The different between simulation and experiment was only 5.41 %. Finally, the simulation result showed that the performance of the propeller was good enough to be used for the URRG AUV.

CHAPTER 1

INTRODUCTION

1.1 Research background

Autonomous underwater vehicles (AUVs) as an unmanned, tether-free, powered by onboard energy sources such as batteries or fuel cells, equipped with various navigation sensors such as inertial measurement unit (IMU), sonar sensor, laser ranger, pressure sensor and so on, and controlled by onboard devices, generally computers with preprogrammed mission (Zhao,2004). Autonomous Underwater vehicle (AUV), become popular among the marine researchers for the last two decades. From the survey made by Yuh (2000), in 1990's 30 AUV was developed by researchers around the world. The ability to doing the job independently draws the researchers to use it in various applications such as ecology survey and sea bed mapping. The reported AUV can working successfully in hazardous condition like deep ocean.

The AUV system is developed by integrating between a few essential subsystems. One of the subsystems is propulsion system. The propulsion system for AUV commonly builds up by propeller and electric motor. Most of the underwater vehicles are used off-the-shelf propellers for their propulsion system. Off-the-shelf designs are easier to obtain than a custom designed propeller, yet they are not optimized for the capabilities of a specific vehicle. It is important to consider that a wide variety of underwater vehicles exist. Unique vehicle characteristics call for a tool that has the capacity to design propellers for a specific application. Underwater propellers are sometimes not optimized due to factors of cost and availability.

In order to increase the efficiency of the propeller, various methods were introduced by the researchers. Most of the methods are based on the lifting line theory. This theory provides the methods to predict the performance of propeller blade. Cairns et al. (1998) utilized the lifting line theory with certain improvement to design the AUV blade. Latest development in AUV propeller design is using the vortex lattice method. The code for propeller design based on this method first developed by Kerwin (2001). The code was writing in FOTRAN and translated into MATLAB as MPVL code released by Chung (2007).

In manufacturing industries, small or medium size products are widely produced by using cold forging process. This type of machine also gives advantages in mass production (Lee et al., 2008). Cold forging also has high potential to reduce manufacturing cost by increasing the speed of manufacturing process cycle time. The accuracy of final product that produced by cold forging is higher than others forging method. Therefore, the cold forging also called precision forging. Precision forging covered the issues of high accuracy, complex and net shape components. If the work material could be completely filled up into the die cavity, desired accuracy of the product can be achieved; hence high productivity can be envisaged (Yuli et al., 2000). Due to the accuracy and some other advantages, this research is focused on AUV propeller fabrication by using cold forging process.

However, the cold forging process is limited to simple geometry and small size. The number of operation will increase with complex geometry of product. Increasing in size, the working force will increase dramatically. To overcome this problem, the modular product architectures must be applied in product design stage. The modular has certain advantages like ease of manufacturing, assembling and disassembling of various section.

1.2 Problem statement

Miniature and high efficiency of propeller must be designed to reduce energy consumption of AUV. High efficiency propeller needs hydrodynamic profile which is very complex geometry. Miniature's propellers reduce the thickness of the blade. This problem lead to difficulties in manufacturing of the propeller.

The most critical stage in AUV propeller manufacturing is fabrication process. Due to small size and complex geometry the conventional method like sand casting and machining failed to produce the propeller with reasonable accuracy (Shan et al., 2005). Thus, other methods were explored to manufacture the propeller. Currently the manufacturing process of AUV propeller is performed by using CNC. CNC machining gives the flexibility in geometry. Most of the complex geometry can be done by CNC machining. Young et al. (2004) show the propeller fabrication by using 5 axis CNC machine. The Propeller diameter is 150 mm and the propeller was machined from raw material which is solid rod.

D'Epagnier (2007) produced the AUV propeller by using rapid prototyping. The rapid prototyping method gives the flexibility in complex shape. This capability guarantees the production of complex geometry of the blade. However, rapid prototyping failed to give strength to the blade. This is because the material commonly used in rapid prototyping is plastic like ABS. Besides that, the surface roughness of the product is very poor. The strength and surface roughness are very important parameters to ensure the good performance of AUV propeller. Due to the limitation in the process mentioned, new manufacturing process must be identified to produce the AUV propeller.

The propeller consists of number of blades attached to the hub. This complex shape becomes difficult to forge by forging process. To make the propeller possible for forging process, the shape must be redesigned but at same time the geometry of the propeller should not change.

1.3 Objective of Research

Goal of this research is to fabricate the propeller for the URRG AUV. To achieve this, the following objectives are considered.

- To design efficient cold forged AUV propeller.
- To validate the propeller performance by experiment.
- To predict the efficiency of AUV propeller in various advance ratio using CFD.

1.4 Approach

As discussed previously, the AUV propeller design is an important factor in fact to reduce the power consumption of AUV in its operation. Therefore, optimum design of the propeller must be performed to overcome this problem. Optimum propeller with complex geometry tends to increase the difficulty in manufacturing process. The approach was aim at introducing the AUV propeller fabrication using cold forging process. The intent is to improve the development of underwater vehicle especially AUV by optimizing it’s power consumption. This research consists of propeller design and manufacturing process described in four phases. Figure 1.1 shows the approach in this research.

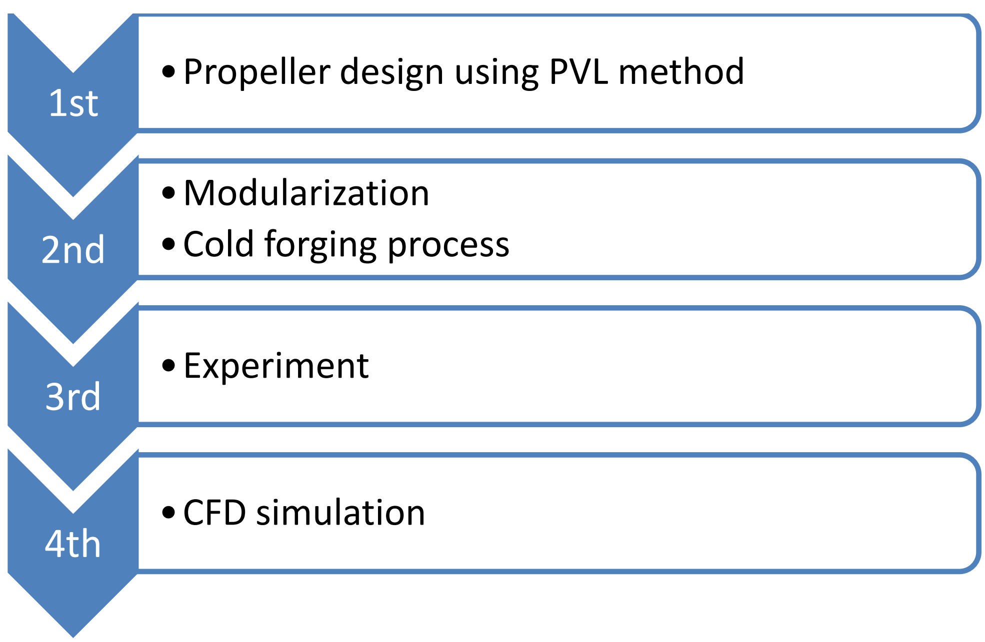

Figure 1.1: Research approach flow chart.

The first phase was aimed to provide easy step to design the optimum propeller. This was done by using the PVL method that introduced by Kerwin (2001). The Matlab code created by Chung (2007) was used to input the specification of the propeller for the design process. The second phase was aim at the manufacturing process of the designed propeller. The chosen process for propeller fabrication is cold forging. This process hopefully can increase the accuracy of the AUV propeller. However, cold forging has limitation in complicity of the geometry. For this reason, the propeller must be designed modularly. Modular design approach helps in minimizing the complexity of the geometry by separating the propeller into three parts. These three parts are propeller blades, front and back hub.

The third phase was aim at experiment the finished propeller for performance validation. In this phase the propeller was test under bollard pull condition. The finished propeller will fit to the underwater motor shaft for experiment purpose. Result from the experiment will be used to validate the CFD analysis. The final phase of this research is CFD analysis for propeller performance. The simulation is run to determine the performance of the propeller under different advance velocity. The CFD simulation was needed because it is difficult to run the experiment for varies in water speed.

1.5 Scope

In this research work, AUV propeller was design using MPVL code that has been developed by Chung (2007). Work was present in this thesis did not include the development of new method in propeller design. Currently, various methods were used to fabricate the propeller. However, in this thesis cold forging process was used. The study was stress on capability of the process to fabricate propeller blade. The front and back hub was not fabricated using cold forging process. This is because; the blade profile was the most difficult part in propeller to forge. Thus, if the blade can be forged so can are with the hub. Due to cost constraint in making mold, only the propeller blade was forged. The hub was fabricated with conventional lathe and EDM process. In experimentation stage, the blade was fit to underwater motor that has been developing in the URRG laboratory. The speed limitation was depend on the motor characteristic. Because of difficulty in developing the facility, the experiment only runs for static water. Thus, the bollard pull test was done on the propeller. CFD simulation was done to study the performance of the propeller while the water is moving. The result from experiment was used in this stage to validate the numerical model. The numerical study was limited to steady simulation. The simulation was run using commercial CFD package know as $FLUENT^{TM}$.

1.6 Thesis outline

This thesis consists of a total of five chapters. Chapter 1 discusses the issues address in this work. The relevant background, problem statement, objective, approaches and the scope of the study was presented in this chapter. Literature review which focused on previous study was present in Chapter 2. This chapter consists of the review of propeller design, CFD, propeller manufacturing, and also the modular design. In Chapter 3, research methodology was mentioned in detail. In the methodology, the design method using PVL was explained. Besides, the cold forging process for propeller fabrication and experiment setup for performance analysis are presented here. Chapter 3 ends with propeller simulation setup. From the methodology, the thesis continued with result of the research. Chapter 4 in this thesis, stressed at the CAD drawing of the propeller and the dimensional measure of the finished part. CFD simulation also presented in Chapter 4. Finally, the conclusion and future work was presented in Chapter 5.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

This chapter is a literature review of the selected topics related to marine propeller design; propeller fabrication and computational fluid analysis of propellers. A review is carried out of the various methods to design the marine propeller and to get the most efficient propeller. This work is concerned with miniature sized propellers as stated in the previous chapter, so that the literature covers the fabrication and forging processes of propellers. Finally, the CFD analysis of propellers was surveyed to determine the most suitable setup for propeller simulation. The literature survey will give the basic idea of the research and clarify the suitable methodology for the research.

2.2 Propeller

Starting from horizontal water milling, which was explained by Robert Hook his in Philosophical collection, the screw type propeller was evolved over the last century (Carlton, 2007). As we can see, this idea was later applied to propel ships. Nowadays there are two types of screw propeller widely used in marine applications that are either constant or variable pitch. Commonly screw type propellers have between 2 to 6 blades. In a constant pitch propeller the blade is fixed with a hub, but in controllable pitch propeller, the blade angle can be changed depending on the application. The propeller that is designed and analyzed in this study is a fixed pitch propeller.

2.2.1 Propeller Design

In industry there is a standard method used to design the propeller. The method always uses a chart which has been developed by previous researchers. This method was based on the b-delta diagram (Carlton, 2007). The parameters, such as blade area ratios, thrust required, rotation of the propeller etc. are considered as design factors. An optimum propeller design was selected after considering this parameter in the calculation. This method can finally give the performance of a propeller by comparing it with the standard series available. The most popular series amongst propeller designs is the Waginingen B-series, in addition to the other series, such as; Gawn, Newton radar etc. However, this method is only available in a certain range of propeller diameters (Cairns et al., 1998; Chen and Shih, 2007; Neocleous and Schizas, 1995). In AUV applications, the propeller size is always less than 20 centimeter, and this method will fail to design and predict the behavior of the propeller. This constraint leads to AUV propeller designers to explore new methods of designing the propeller.

The rise of computers makes propeller design possible to be optimized by using complex optimization algorithms. Several researchers have tried to apply optimization algorithms to propeller design. Optimization algorithms were applied to propeller design in order to find higher efficiency of the propeller. Most of the researchers optimized the geometry of the blade to get maximum efficiency. Cho and Lee (1998) first introduced the application of optimization algorithms to optimize propeller design. The chord length and blade thickness was distributed, in order to minimize the propeller mass in this prior work. Camber geometry, propeller pitch, and chord distribution was optimized by Mishima and Kinnas (1996) and Takekoshi et al. (2005) to give a maximum allowable cavity area or a maximum cavity volume velocity in a non-uniform flow. They also provided an option for optimum skew. Their method was further improved by (Jang et al., 2001; Takekoshi et al., 2005; Kim et al., 2009a) who optimized the pressure distribution in a non-uniform flow. More recently, Kim et al. (2009b) optimized the pitch distribution in order to maximize the propeller efficiency.

Earliest work on AUV propeller design was begun by Healey (1995) after discovering that it is important to get the appropriate propulsion device for AUV. This approach was almost similar to the conventional propeller design. However, the tool for estimating the thrust required, was different. In the proposed method, the thrust was estimated by applying the potential flow analysis around the AUV body. For the propeller design the lifting line theory was applied to find the optimum propeller geometry. Cairns et al. (1998) continued the AUV propeller design. The method used was the blade element method. In this approach, the input for propeller design was the thrust required to move the vehicle at a certain speed. From the input the program will calculate the optimum propeller model. This propeller model will be used to calculate the different combinations of geometry parameters to determine the optimum propeller geometry. These geometry parameters include thickness distribution, chord length, and chord profile. One major factor that contributes to the performance of the propeller is the blade. By realizing these factors, Cho and Lee (1998) developed a technique to design the optimum propeller blade. In their work, two numerical methods were used, which were the vortex lattice method and the 3D panel method.

The elasticity behavior of the propeller during its operation was studied by Young and Shen (2007) in order to design the propeller. The aim of that study was to develop the new numerical tool to design the propeller, with consideration of the cavitations effect and elasticity of the propeller. In this study, the BEM and FEM were utilized for solving the fluid structure interaction problem. As a result, the code shows a good agreement with the experiment.

Koronowicz et al. (2009) considered various parameters in marine propeller design. Their proposed method was based on both modified lifting and vortex lifting surface theories. The parameters were considered to influence the propeller with rudder effect, maximum efficiency, blade geometry and spindle torque. Amongst the previous marine propeller designs, this method was very attractive as many parameters were considered in one time. All the parameters considered were applied by the computer system. This system also included the numerical tool that is able to solve the 3D fluid flow.

Another factor that gives significant effects to propeller efficiency is hub geometry (Kim et al. 2009b). The hub geometry can also be optimized as an energy saving device. Choi et al. (2009) conducted a study to find an optimum design of hub geometry to reduce the energy consumed by the propeller. The boss, at the front of the hub, was declared as an energy saving device. CFD was used as a tool to analyze various configurations of the boss. From that study, pitch and fin installation angles were recognized as the main factors that affect the energy saving device.

Most researchers developed the optimum design of the propeller by predicting its performance (Felli et al., 2008). Various techniques were explored in order to predict the propeller performance, such as the blade element method (Cairns et al., 1998), neural network (Neocleous and Schizas, 1999), the panel method (Koronowicz et al., 2009), the boundary element method (Jang et al., 2001) and the vortex lattice method (Chung, 2007).

From the literature survey above, many of the researchers conducted studies to find the optimum parameters for propeller geometry. Most of the work was aided by computer systems and it was a good approach to reduce the time for propeller design. Comparing with conventional methods that were commonly used in marine propeller industries, the new method introduced was more practical. This is because the range of the propeller sizes are wide, and the performance of the propellers are already predictable and in agreement with experiments. The vortex lattice method proposed by D'Epagnier et al. (2007) is very useful in reducing the propeller design time, which is also capable of designing for a wide range of blade applications.

2.3 Propeller Simulation Using CFD

With an increasing demand for optimum propeller designs, propeller behavior becomes even more important. This situation has accelerated researchers desire to understand the behavior of fluid around the propeller during its operation. To do this with low cost and less effort, the CFD approach was introduced in propeller modeling. This section will review some of the previous works related to propeller simulation by using CFD. The review will only cover the application of CFD in specific propeller problems, such as; cavitations effect and the unsteady simulation of propeller behavior.

In order to highlight the significance of blade element theory in propeller performance prediction, Benini (2004) made the comparison between Combined momentum-blade element theory (CMBET) with the three dimensional Navier-Stokes calculation. The CMBET representation of the propeller model was validated with a four blade Waginingen B series propeller. Fluid flow around the same type of propeller geometry was simulated by using the FLUENT 6.2 software. Furthermore, the result of the CMBET and CFD simulations were compared with theoretical explanations. The result showed that CMBET was only true to experimental values if the fluid-flow was in 2D, but for CFD the performance of the propeller can still be predicted, with certain degrees of agreement with the experiment, even though the flow is three dimensional.

Rhee and Joshi (2003) conducted a study to validate the flow around a marine propeller using unstructured mesh based on the Navier-Stokes solver. The study was conducted based on the P5168 propeller type with a diameter of 0.402 metres, which were designed at the David Taylor Model Basin. For computational study the propeller blades were simply mounted on an infinitely long constant radius cylinder, which served as the hub. There are two types of computational domains developed, which are; base domain and extended domain. The purpose of these two different domains is to examine the influence of exit boundary distance from the blade. For the baseline domain, the upstream is 0.5D from blade, downstream at 0.72D and the outer boundary is 1.43D. While the extended domain upstream and outer boundary remained unchanged, but the downstream was extended to 2D. To minimize the computational cost, only one blade was simulated with the domain divided into 4 parts of 72 degrees each. To model the turbulent flow, there are two turbulent flows applied in this study, which are k-omega and RTSM. Fluent 6.2 was used to solve the Navier-Stokes equation and gambit as mesh generator.

The major problem of the marine propeller study is the cavitation effect, where in conventional modeling, such as the momentum theory and the blade element theory, this effect was ignored (Wald, 2006). However, Young and Shen (2007) showed that there is some change in the performance of the propeller due to the cavitation effect. Therefore, the modeling of propeller must consider this effect to ensure that the performance of the propeller can be predicted accurately. CFD can significantly predict the thrust and torque of the propeller under the influence of cavitation. Mishima and Kinnas (1996) showed the predicted value of thrust and torque in cavitating and non-cavitating values by using Reynolds-averaged Navier–Stokes (RANS) simulation, agreed with experiment values. Two geometry domains were created in this study, which were for steady and unsteady simulations respectively. For the steady simulation, the domain geometry was the same as that of Rhee and Joshi (2003) where only one blade was simulated. But for the unsteady domain, a complete propeller was simulated with an infinite cylinder in the middle of the blade to serve as a hub. Two types of propeller were investigated in this study, which were the MP017 and Sien Maru propellers. For both cases, the turbulent model (k omega) was used to model the turbulent flow. The solver was segregated, the pressure velocity coupling was SIMPLE and the descretezation method was QUICK scheme. To solve the problem FLUENT 6.2 was used.

Besides the propeller itself, the performance of the propeller was also investigated by the presence of the stator. The stator in front of, or at the back of, the propeller will increase the efficiency of the propeller (Kerwin, 2001). The stator will act by cancelling the swirl at the hub, which will increase the torque of the propeller. The study of the propeller stator interaction, using CFD, was presented by (Rhee and Koutsavdis, 2005). In their study, 3D incompressible RANS equations were solved on the non-orthogonal multi-blocked grid system to analyze the flow of ducted marine propulsion.The 3D incompressible code was validated with a turbine blade, where the experiment result was already available. The time averaged pressure coefficient was compared with the experiment and a fairly good agreement was obtained. After the code validation, the flow field around the single-stage ducted marine propulsion was simulated, followed by the plotting of pressure distributions, streamlines and changes of velocity components. The hydrodynamic coefficients and propulsive efficiency were also obtained. The main contribution of Rhee and Koutsavdis (2005) is that the CFD code can be used to study the behavior of the fluid around the propeller in the presence of other structures.

The study of turbulence started in the 18th century, after Reynolds introduced the study of fluid behavior in a tube channel. Reynolds differentiates between these two types of fluid behavior by using the Reynolds numbers. These numbers actually represent the ratio between inertia and viscous forces. At low Reynolds numbers, the inertia force is smaller than the viscous force. In this case, the disturbances are dissipating and the flow remained laminar. At high Reynolds numbers, the inertia force is sufficiently large to amplify the disturbances, and turbulence occurs.

In the CFD simulation of the propeller, the selection of the turbulent model was crucial in order to get an accurate result of the propeller’s behavior. Singhal et. al. (2002) solved the Navier-Stokes equation for viscous flow around the propeller and used a k epsilon turbulence model to represent turbulent behavior. Later, Celik and Gunner (2007) and Phillips et al. (2009) also used a k epsilon turbulence model to solve the turbulent flow around the propeller. However, Li (2006) followed by Guo et. al. (2009) applied a k omega to model the turbulence flow. From literature, both of these turbulent models give a good agreement with experiments. The simulations carried out by the researchers above were in both steady and unsteady domains. This shows that the k epsilon and k omega are also available for unsteady simulations. Beside these two turbulence models, Vysohlid and Mahesh (2006 and 2007) was specifically working on unsteady simulation proof, that the Large Eddy Simulation (LES) was also good for modeling the turbulent flow around a propeller.

2.4 Propeller Fabrication

The most difficult stage is propeller fabrication. There are some constraints that must be faced by the fabricator. The complex geometry, due to the skew of the blade, always becomes the main challenge to produce a complete propeller. Another issue is the size of the blade, and finally, the production rate of the conventional method used. In general, propeller fabrication can be divided into two methods, which are the casting method and the CNC machine. But these two methods have their own drawbacks, which will be explained in this section.

In early development of propellers, the geometry was a simple shape and made from either cast iron or steel. Traditionally, the propeller was fabricated through the casting method and still works in today's foundries. But when the demand for high quality propellers increased, the material and the geometry of the propeller become more complex. This situation meant that the casting method was not significant anymore, due to accuracy of the final propeller (Carlton, 2007).

Nowadays in industry, a five-axes CNC is used to cut solid work pieces into a propeller's geometry. Commonly, the cutters path is generated using commercial CAM software. However, this method becomes less significant when overcoming the work holding problem in propeller machining, (Kim et al., 2009a). In machining of propeller, the propeller geometry must be cut into two faces from a solid work piece. The first face the geometry can be cut easily because there is still a solid work piece at the back. But for the second face, the work piece is only left with the thin blade. The problem arises when there is no place to hold the work piece (Kuo and Dzan, 2001; Kuo and Dzan, 2002; Young et al., 2004 ; Shan et al., 2009).

2.4.1 Propeller Forging

Forging is the working of metal into a useful shape by hammering or pressing and is the oldest of the metalworking arts (e.g. primitive blacksmith). Replacement of machinery occurred early during the industrial revolution. Forging machines are now capable of making parts ranging in size from a bolt to a turbine rotor. Most forging operations are carried out hot, although certain metals may be cold-forged. Zhan (2002) characterized the forging process into 5 types, namely: open die, closed die, blocker die, conventional type, and precision type. Precision forging is employed to obtain a part, which is very close to its final dimensions, and requires little or no additional finishing operations

(Bariani et al., 2004). In this section, the blade fabrication using the forging process is reviewed.

Currently, propeller fabrication by a forging process applies a modular design concept. As an example, in the marine industry, a ships propeller was divided into several components. The blade and the hub were separated to make the manufacturing process easier. Another example is in the space industry, where the engine impeller was separated into small parts. Compared to the marine propeller, the jet impeller blade commonly used a forging process for fabrication, (Na et al., 2003). Due to large sizes, the forging processes used are hot or warm forging (Yuli et al., 2000; Ou et al., 2003; Zhan et al., 2004). However, there is a limitation in hot forging, where the dimensional accuracy is difficult to achieve. This problem is due to shrinkage of the work piece after the forging process (Bruschi and Ghiotti, 2008). Many studies were conducted to minimize this problem with the studies focused on optimization in die design and also the forging steps (Ou et al., 2004; Zhan et al. ,2004; Shan et al., 2005; Gao et al., 2006).

While the study of hot forging was still getting interest by researchers, other techniques that promise dimensional accuracy in the forging process were explored (Zhan et al., 2002; Lee et al., 2008). Another forging option was the cold forging process (Shan et al., 2005). Cold forging can eliminate the shrinkage problem because the work piece in this type of forging is already at room temperature. However, the cold forging process required more force compared to hot forging (Lu et al., 2009). This factor makes this process unpractical for large sizes of product. But for propeller blades, their size and features make cold forging possible. Shan et al. (2005) studied the cold forging process in aluminum rotors. As a result, the blade dimensions were almost similar to the design shape, with deviation of only less than 5%. Besides that, the mechanical properties, such as surface roughness and surface hardness, also increased.

To get the best performance from cold forging for blades, Lu et al. (2009) optimized the die shape for cold forging. The study applied a finite element method to simulate the die set. An experiment conducted, using the optimum die, showed that the dimensions and tolerance for blade fabrication can be improved. Cold forging can also be used for fabricating the micro thickness of a blade. Lee et al. (2008) fabricated a micro magnesium impeller by using cold forging. As a result, with a few changes in die design, the micro impeller can be fabricated with acceptable tolerances. The disadvantage of the cold forging process is that it requires large amounts of force to forge a product. To overcome this problem, Lv et al. (2008) explored a multi-stage forging process, also known as progressive forging. This method can reduce the load required to forge the material. Experimental results show that this progressive forging can reduce the load without effecting dimensional accuracy.

2.4.2 Modular Design

The Design For Manufacturing (DFM) concept was not new in the product development field. This concept has already been applied since the 18th century within forging industries. DFM is a philosophy and mind set in which manufacturing is used during the early stages of design in order to design parts and products that can be produced more easily and economically (Poli, 2001). In this thesis, the DFM concept that has been applied was via a modular design. This concept is important for this work because it can make propeller forging possible. In this modular design the best option for forging of the blade will be explored.

Product variety can be achieved by combining discrete functional units. The process used for producing the functional unit is known as “modular design”, which emphasizes the minimization of interactions between components, in order to design and produce those components independently. In modular design, the component must be able to support one or more functions. Finally, when the component is assembled together, it will perform a larger or more general function (Salhieh and Kamrani, 1999). Chun-Che and Kusiak (1998) refer to modular products as; machines, assemblies and components that fulfil various overall functions through the combination of distinct building blocks or modules. In other words, modular products are designed as building blocks that can be grouped together to form a variety of products. This approach promotes standardization and re-use of existing modules to develop new products.

Jose and Tollenaere (2005) survey papers showed the complete review of modularization in the product family. This paper clearly defined various definitions of modular products as stated by Braha et al., 2006 and Huang et al., 2009. The different definitions may be due to various perspectives of the researchers. These differences also give an important sign that modularization was widely accepted as a design approach. In order to achieve modularization, various methods are explained briefly in (Dobrescu and Reich, 2003). However, no standard method has been suggested for modularization. This is because the modularization method of production strongly depends on the type of the product itself.

The idea that covers the modularity for X was first proposed by (Braha et al., 2006). However, early work only covered modular in use, modular in production and modular in design. Except for modular in design, the other concepts were less reported in literature. This constraint makes this concept unpopular amongst the other topics of modular design. Additionally, the concept was proposed by Poli (2001) only in general and there is no specific method to achieve the design goal. A clear method for modularization was reported by (Huang et al., 2009). In this paper, the modularity of the design is indicated in the matrix system. This systematic approach gives great impact within modular design. The decomposition technique was used to solve the modularity problem. Huang et al.(2009) looked at modularization from different perspectives. The modular concept was used in certain terms to solve electrical component design for testability. As a result, the modular design gives an advantage in mechatronic system design. This modular design approach gives an opportunity for the designer to review the testability factors in their design.

The modular concept was arising parallel with the development of computer systems. Development of computer algorithms, such as optimization techniques, gives advantages in modularization. Nepal et al. (2005) used a metaheuristic approach to optimize platform development. The optimum combination, of component modules that were generated by product modularization of the platform, was determined by applying a metaheuristic approach. The use of computer systems for optimizing the modular product was developed by many researchers, such as; (Yigit et al., 2002; Salhieh, 2008; Yujia et al., 2009).

In robotic systems, modular design also gives a significant impact, in terms of improving system design. Yujia et al. (2009) used the modular concept in both mechanical and electrical designs for underwater robots. In their paper, the method of modular partitions, based on function is adopted, and the modules of structure and hardware are designed, which include the structure of a functioning modular unit, modular interface and the reconfiguration of module combinations, etc. Another important example of applying the modular design in robotic systems was shown by Moody, (2001) and Salhieh, (2007) . Their work showed the design process of a gripper using the modular design concept. Modular design can finally give a solution for the requirements for a gripper. The problem statement for this robot arm is that the gripper must be able pick up different components as proposed by the customer.

As a conclusion, modular design is widely used in current design processes. The concept of modularity for certain factors (like the design for X) already exists, but these factors were very limited and less explored by researchers. For this reason, this thesis will cover a new concept in modularity that is known as “modularity for manufacturing”. Besides that, a few researchers have also looked at the advantages of modularity to support robotic systems design. Previous work shows that the modular concept can improve robot design and increase the variety of robot tasks.

2.5 Summary

This chapter has stated overview of current stage in AUV propeller design and fabrication. There are various method in designing the optimum propeller suggested by researchers as in (Neocleous and Schizas, 1995;Cairns et al., 1998;D'Epagnier, 2006;Chen and Shih, 2007; Kim et al., 2009; Koronowicz et al., 2009). However, most of the method was specifically for marine propeller where the diameter always more than 200 millimeter. As mentioned before, the AUV propeller always has smaller in size. Because of this limitation the vortex lattice method that has been suggested by D'Epagnier (2006) is the most suitable in designing the AUV propeller. This method provided the flexibility in term of diameter selection and was proven can give the satisfied result. After the design of the AUV propeller the discussion was move into fabrication. In this chapter, the problem in fabrication of the small AUV propeller was explained. In order to reduce the complexity of the geometry so that the fabrication becomes simpler, the modularization of the design was explored. From the literature, the modularization was shown can support the manufacturing process. In the propeller case, the decomposition technique promising the best result (Yigit et al., 2002). From the review, the performance of the propeller was studied by the previous researchers by using numerical method. This approach is to ensure the design propeller can give desired result in real situation (Young and Shen, 2007). Many such as Rhee and Koutsavdis (2005), Vysohlid and Mahesh (2006), Celik and Gunner (2007) and Guo et al. (2009) used finite volume method to simulated the behavior of the propeller in various cases. Li (2006) showed CFD simulation can represent the propeller during it operation with small error compare with experimental result. From the review, the simulation of propeller operation by using CFD will be used in this researched in order to reduce the numbers of experiment. Beside that from the previous work there is only few researchers (Singhal et al., 2002; Phillips et al., 2009) simulated the small scale propeller by using the CFD. Finally the review goes to forging manufacturing process. The review show