Optimum Design of URRG-AUV Propeller Using PVL

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Abstract

Common practice in AUV propulsion system is utilizing the propeller and motor to generate the thrust. The performance underwater vehicle is directly influence by propulsion system efficiency. To increase the efficiency of the propulsion system, the propeller design must be taking into consideration. This paper presented the AUV propeller design based on Propeller Vortex Lifting Line Code (PVL). The propeller is designed specifically for AUV that is being developed in URRG lab. In order to determine the thrust required by the AUV, CFD approach is used. The body motion was simulate with CFD to get the resistance of the AUV hull at maximum design velocity (2m/s). the value of thrust predicted by CFD will be set as the design parameter in PVL techniques. Finally the by using PVL the optimum propeller geometry was produced. The efficiency of this propeller is predicted as 0.8237. The optimum numbers of propeller blade and propeller diameter is 3 and 0.1 meter respectively.

Keywords: Propeller Vortex Lifting Line Code CFD AUV, and Propeller Design.

Introduction

Propeller optimization was popular among aircraft researchers for long time ago. So that, the propeller design is easy with availability of previous data and design. Once the experiment data is available, the performance for each propeller design can be predicted. However this data is not applicable for underwater propeller design. It is because for aircraft, the propeller is working in the air where the density is almost equal to 1kg/m3. But for the AUV propeller the working fluid is in water and the density is 1000 kg/m3.

Because of the density of water, the propeller shape and geometry is totally different from aircraft propeller. The geometry is design based on the effect of hydrodynamic interaction. Since the marine propeller has been studied for a very long time, there are some conventional methods in presenting the propeller performance. One of it is so called Bp-δ diagram and $\eta - \sigma$ diagram.

The Objective of study present in this paper is to design the optimum propeller specifically for AUV that has developed in URRG lab. Figure 1 illustrates CAD drawing of AUV model and table 1 give the basic characteristic of the body. The need of specific design of the propeller is to minimize the energy used in AUV operation.

For optimum design, the PVL code was used with combination of CFD simulation. Firstly CFD simulation was run on URRG-AUV body to determine the resistance of the body at 2 m/s speed. This data is used to calculate the thrust required by the body to move 2m/s in water. This thrust required will be an input to PVL code.

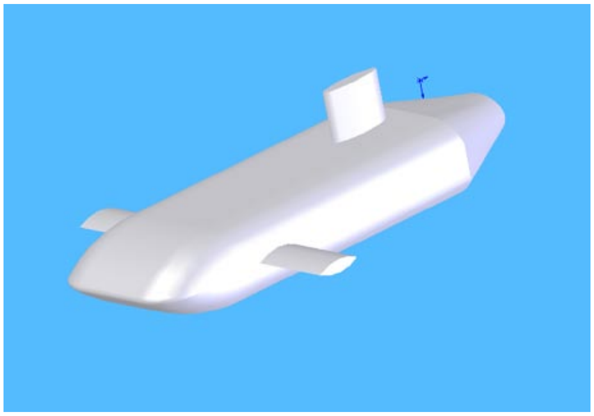

Figure 1: CAD model of URRG AUV

working depth	50 meter
Voyage speed	2 m/s
Length	0.7 meter
width	0.2 meter
weight	Neutral buoyancy

Table 1: URRG AUV specification.

Approach and Methods

The propeller consist of three global parameters that directly influence the performance. These three parameters is, the number of blades, the propeller speed and the propeller diameter. These three parameters give the different in propeller efficiency by different combination. To determined the best combination of these parameters, the parametric study must be conduct . in this paper the parametric study was presenting with varying in numbers of blade, propeller speed, and propeller diameter. For URRG AUV the propeller diameter must not exceed 0.1 meter due to its size. So that the diameter for parameter study was varies from 0.05 meter to 0.1 meter. However, the diameter of propeller is small, the speed of propeller must be high. So that, in this study, the propeller speed was varies from 100rpm to 900rpm with 200rpm increasing. For the number of blades, the minimum is set to two blades and the maximum is five blades.

To move 2m/s URRG-AUV thrust must give the balance to resistance force due to hull move in water, the resistance force is determined by using CFD approach. The propeller produces a thrust force T in the negative x direction, and absorbs a torque Q about the x axis, with a positive value following a right-handed convention. Thrust and torque generated by propeller during it rotation is given by equation (1) and (2):

$$T = \rho Z \int_{r_h}^{R} \left[V^* \Gamma sin\beta_i - \frac{1}{2} (V^*)^2 c \, C_{Dv} sin\beta_i \right] dr \quad (1)$$

$$Q = \rho Z \int_{r_h}^{R} \left[V^* \Gamma sin\beta_i - \frac{1}{2} (V^*)^2 c \, C_{Dv} cos\beta_i \right] rdr \quad (2)$$

Furthermore, the optimum parameter are selected based on the greater efficiency of the propeller. The best combination will show the highest efficiency. the efficiency is given by equation (3) :

$$\eta = \frac{C_T * wake}{C_P} \quad (3)$$

Cp is power coefficient based on torque. Cp is give by equation (4):

$$C_p = \frac{C_Q 2\Pi}{J_s} \quad (4)$$

CQ and CT is propeller torque coefficient and propeller thrust coefficient respectively. Both of CQ and Ct can be compute by equation (5) and (6):

$$C_{T_S} = \frac{8}{\pi} \frac{K_T}{J_S^2} \quad (5)$$

$$C_{Q_S} = \frac{16}{\pi} \frac{K_Q}{J_S^2} \quad (6)$$

Js is advanced velocity , KQ and KT is thrust coefficient and torque coefficient.

Vortex lattice method

To solve the equation (1) until (6) the propeller vortex lattices method was used. This method conceptually used to solve the propeller lifting line. The propeller blade first is divide into panels extending. In this method, the radial distribution of circulation (Γ), is approximated by set the vortex element has a constant strength of (Γ) in particular panels. From the lifting line theory, it convinient to consider that the vortex system is built from horseshoe elements. Each consisting of a bound vortex segment of strength (Γ) and two free vortex line ±Γ. The horseshoe vortex element induces an axial and tangential velocity at a specified control point, $r_c(n)$ on the blade. The total induced velocity at control point , $r_c(n)$ is given by equation (7) and (8).

$$u_a^*\big(r_c(n)\big) = \sum_{m=1}^{M} \Gamma_m \, \bar{u}_a \, (n,m) \qquad (7)$$

$$u_t^*\big(r_c(n)\big) = \sum_{m=1}^{M} \Gamma_m \, \bar{u}_t \, (n,m) \qquad (8)$$

Here, Ua and Ut are the horseshoe influence functions.

For spacing the vortex and control points, the cosine spacing are used. Equation (9) and (10) give the spacing relationship:

$$r_v(m) = r_h + h[1 - \cos(2(m-1)\delta)] \qquad (9)$$

$$r_c(n) = r_h + h[1 - \cos(2(n-1)\delta)] \qquad (10)$$

where $h = 0.5(R - r_{h)}$ and $\delta = \Pi/2\mathrm{M}$.

for solving the circulation distribution, propeller vortex lattice was used. In this method equation (9) and (10) are used to compute the vortex lattice grid. The items tabulated at input radii are interpolated to the vortex lattice grid by cubic spline procedure. The unknown circulation is given by equation (11)

$$\sum_{m=1}^{M} \left[\bar{u}_a \, (n,m) - \bar{u}_t \, (n,m) \, tan\beta_i(n)\right] \Gamma_\mathrm{m} =$$

$$\frac{\mathrm{V_a}\,(\mathrm{n})}{\mathrm{V_s}} \left(\frac{\tan\beta_\mathrm{i}(\mathrm{n})}{\tan\beta(\mathrm{n})} - 1\right) \quad \mathrm{n} = 1, \ldots \ldots \mathrm{M} \qquad (11)$$

Where $\tan\beta$ is given by equation (12).

$$tan\beta(r) = \frac{V_a(r)}{\frac{\Pi r}{J_s} + V_t(r)} \qquad (12)$$

β_i is obtain by using the 90 percent of the efficiency of the actuator disc as a first guess.

Numerical method

To determine the value of thrust need to generate by propeller to push the URRG-AUV for moving in 2 ms CFD approach was used. The AUV body was simulated to move in fluid domain. For the simulation process the body is stationary and the fluid is set to move 2 m/s. the design depth is set to 50 meter.

The governing equations for mass and momentum are witen as below:

$$\frac{\partial\rho}{\partial t} + \nabla.(\rho \underset{v}{\leftarrow}) = 0 \qquad (13)$$

Mass conservation:

$$\bar{\bar{\tau}} = \mu\left[(\nabla\vec{v} + \nabla\vec{v}^{T}) - \frac{2}{3}\nabla.\vec{v}\boldsymbol{I}\right] \qquad (14)$$

Momentum conservation:

$$\frac{\partial(\rho\underset{v}{\leftarrow})}{\partial t} + \nabla.\left(\rho \underset{v}{\leftarrow}\underset{v}{\leftarrow}\right) = -\nabla.p + \nabla.(\bar{\bar{\tau}}) \qquad (15)$$

In this equation, $\vec{v}$ represent the velocity vector in Cartesian coordinate. P the static pressure and $\bar{\bar{\tau}}$ the stress tensor given by equation (16):

$$\bar{\bar{\tau}} = \mu\left[(\nabla\vec{v} + \nabla\vec{v}^{T}) - \frac{2}{3}\nabla.\vec{v}\boldsymbol{I}\right] \qquad (16)$$

μ is molecular viscosity, ***I*** the unit tensor and the second term of right hand sight is volume dilation. In this paper k-ε turbulent model was used. This turbulent model are based on Reynolds averaging approach. After apllied Reynolds averaging term, the

Navier Stoke equation can be written in Cartesian Form as in equation (17) and (18):

Mass conservation:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u_i)}{\partial x_i} = 0 \qquad (17)$$

Momentum conservation:

$$\frac{\partial(\rho u_i)}{\partial t_i} + \frac{\partial(\rho u_i u_j)}{\partial t_i} = -\frac{\partial p}{x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial u_i}{\partial x_j}\right]\right. + \frac{\partial}{\partial x_j}\left(-\rho\overline{u'_i u'_j}\right) \qquad (18)$$

Here δ_{ij} is the Kronecker delta, and $-\rho\overline{u'_i u'_j}$ the Reynolds stresses.

This governing equation will be descretized by using Finite volume approach which support by FLUENT package.

Result and discussion

Numerical solution of AUV body

The thrust is required by URRG_AUV body is show in table 2:

Velocity (m/s)	Resistance force (N)
0.1	0.0643
0.5	0.3973
1.0	0.9315
1.5	1.5302
2.0	2.0595

Table 2: CFD simulation result of URRG-AUV resistance force.

The maximum resistance affecting the body is when the velocity 2m/s. major of the resitance in this condition was contribute by the variation of pressure. For the 3D calculation the resistance of the body is given by equation (19):

3D resistance = Pressure drag + skin friction + induce Drag. (19)

Parametric analysis

Graph 1 and 2 in figure 2 and 3 show the efficiency plot for the 2 and 3 numbers of blade. While the graph 3 and 4 in figure 4 and 5 show the efficiency plot for 4 and 5 numbers of blades. Each plot is consider different rotation per minute in range 100rpm to 900rpm with increasing in 200rpm. In the figure 2 until 5 the highest efficiency is obtained at numbers of blade is three and the rotation per minute is 900rpm. The efficiency at this combination of parameter is 0.8237. this parameter is set as optimum parameter. However the percentage of different of efficiency for each combination is very closed. The different in percent is 0.007% for 2 numbers of blades, 0.008% for 4 numbers of blades and 0.022% for 5 numbers of blades. From the graph also the highest efficiency occurred at each number of blade is at 900 rpm. However, from the graph, the efficiency for the operation at 700rpm and 500rpm increase by increasing in propeller diameter. This phenomenon is important to consider caused the fact that if propeller running at lower rpm it can save more energy rather than higher rpm. But for this case the maximum propeller diameter is set to 0.1 meter due to limitation in size of AUV. As a result, the optimum parameter for design the propeller is still 3 numbers of blade and 900rpm for propeller rotation.

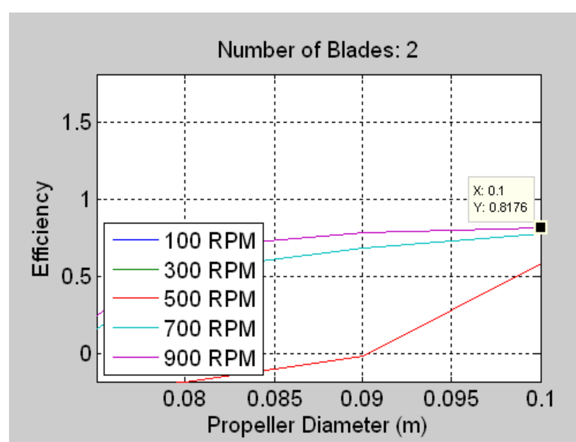

Figure 2: efficiency of propeller at 2 numbers of blade and speed.

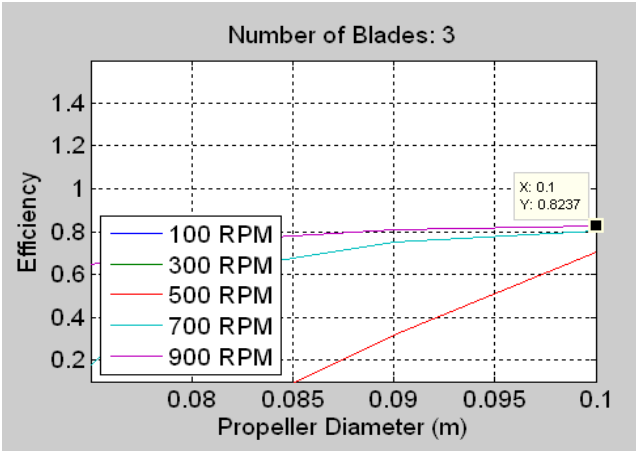

Figure 3: efficiency of propeller at 3 numbers of blade and speed.

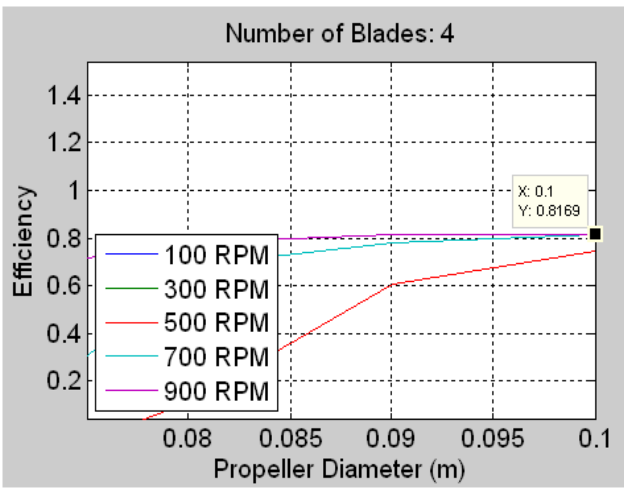

Figure 4: efficiency of propeller at 4 numbers of blade and speed.

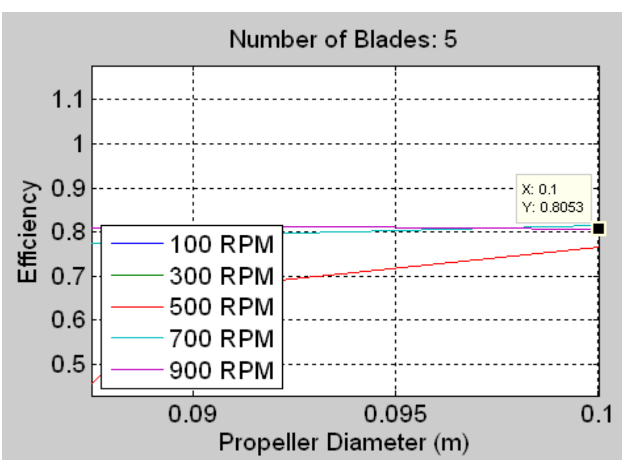

Figure 5: efficiency of propeller at 5 numbers of blade and speed.

Propeller design

In design stage, the optimum parameter that generated in parametric study was used to design the propeller. The propeller was design shown in figure 6. this propeller performance was calculated and the result was shown in figure 6. Figure 7 show the propeller cross sectional at different radius. This plot is important to draw the propeller in CAD software. Beside that this data also can be used for further analysis when the 2D CFD analysis needs to do.

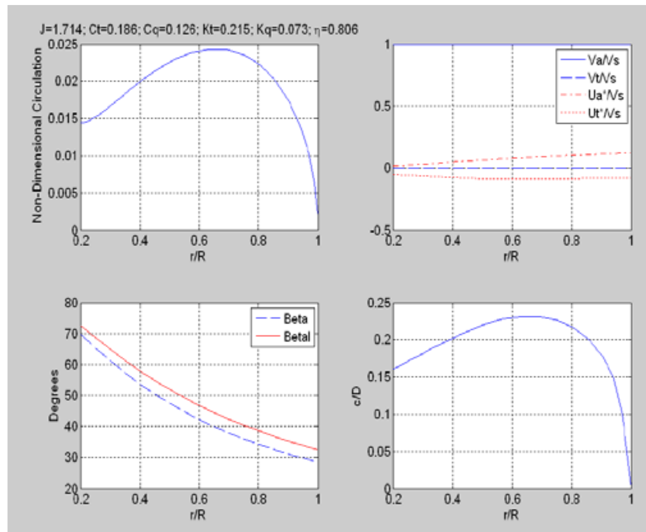

Figure 6: graphical report of blade performance.

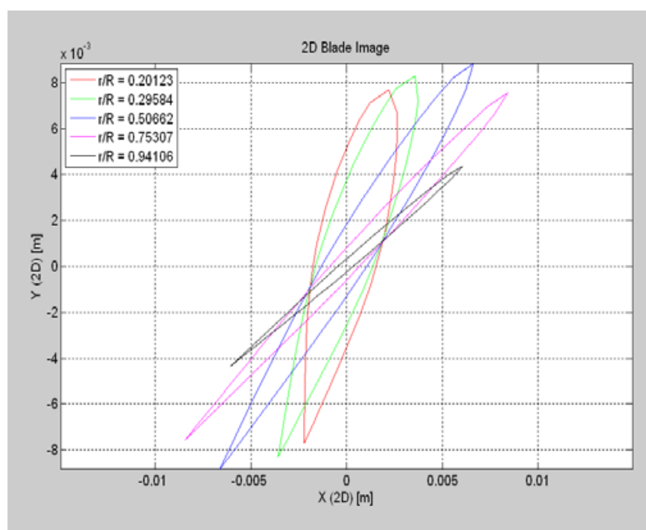

Figure 7: 2D blade image.

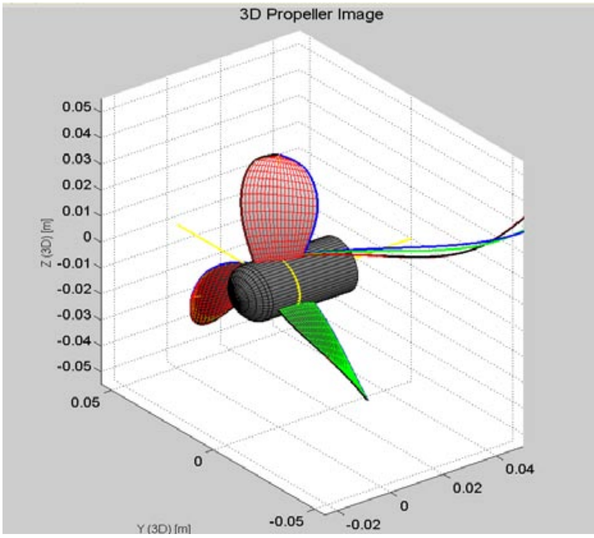

Figure 8: propeller 3D.

Conclusion and future work

From this work, the optimum propeller for URRG – AUV is developed. The efficiency of this propeller is up to 0.8237. the diameter of the propeller is 0.1 meter and the operating speed is 900 rpm. This propeller is consisting of three blade. From the CFD simulation the required thrust is only 2.5 Newton for maximum speed. This value very important in term to avoid the over expecting in design. The information from CFD also important to reduce the value of optimum speed required, where the speed required is proportional with thrust required.

In future, this work will be extended to manufacturing process and validation of the prediction value. Beside that the CFD analysis of design propeller will be conducted to find the pressure distribution on propeller blade. This study is important to determined the failure mode of the propeller.

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References

1) A. J. Healey, S.M. Rock, S. Cody, D. Miles , and J. P. Brown, 1994, Toward an Improved Understanding of Thruster Dynamics for Underwater Vehicles. IEEE conference.

2) C. Constantinos Neocleous and N. Christos Schizas,1999, Marine Propeller Design using Artificial Neural Networks, IEEE conference.

3) W.M.J. Batten , A.S. Bahaj, A.F. Molland, J.R. Chaplin ,2006, Hydrodynamics of Marine Current Turbines, Renewable Energy 31 (2006) 249–256.

4) D. F. Scharpf, T. J. Mueller, An Experimental Investigation of The Sources of Propeller Noise Due To The Ingestion Of Turbulence At Low Speeds, 1995, Experiments in Fluids 18 (1995) 277-287.

5) Ralf. Bachmayer, L. Louis, and Whitcomb, 2003, Adaptive Parameter Identification of an Accurate Nonlinear Dynamical Model for Marine Thrusters, Journal of Dynamic Systems, Measurement, and Control.

6) Jinsoo Cho and Seung Lee, 1998, Propeller Blade Shape Optimization For efficiency Improvement,computers & Fluids Vol. 27. No. 3 pp. 407-419.