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Ship Propeller Performance Prediction under Cavitation

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Abstract: In this study, numerically prediction of the screw propeller design that can overcome cavitation is conducted. The research presents a simplified regression model for the analysis of the geometric area ratio, pitch ratio and open water efficiency of propeller, with the aim of revealing quantitatively the effect of cavitation on propeller open water efficiency. The case study takes into consideration factors that can enhance the performance of a propeller. Area of the propeller disc, propeller pitch ratio, diameter of the propeller, delivered power, thrust coefficient, torque is used as inputs into the model, in prediction of performance for cavitated and non-cavitated propellers. Sensitive analysis is carried out by percentage increase and reduction of the blade area ratio, so as to know the effects on the propeller performance. It is revealed that for every 1% increase in the expanded blade areas, the open water efficiency decreases at 0.12% and 0.15% for the non-cavitated and cavitated propellers respectively. This indicates a performance reduction by a cavitation factor of 0.03. The study further shows that at 7.5% reduction in the expanded blade area ratio, the propeller performance in terms of open water efficiency, increases by 1.85%. The analysis exposed an appropriate and accurate operating envelope for optimal screw propeller performance, thus revealing a way of minimizing cavitation effect.

Keywords: Propeller; Cavitation; Regression model; Efficiency; Ship

1. Introduction

Screw propeller of a ship is regarded as a helical surface which on rotation screws its way through the water. It consists of a hub and blades that are space at equal angle about the axis. As the propeller rotates, the face of the blade increases pressure on the water with the aim of propulsion of a ship. The design and analysis of modern, loaded and highly screw propeller is important in the marine field [1]. The growing demand of heavily loaded, highly efficient propeller that is associated with low level noise and vibration onboard, makes the design of marine propeller more complicated. The propeller converts precious power into forward motion, and if it is mismatched or damaged, optimal ship performance is hindered [2]. Therefore, it is mandatory to choose the correct propeller type and size to prevent cavitation from occurring, which can pose threat to ship propeller optimal operations. However, design of propeller and its efficiency also depends on other several factors [3].

The choice of the number of blades plays a significant role in marine propeller performance. Marine screw propeller usually has two, three, four or five blades. Four blades are the most common, but [4] revealed that most efficient number of blades is the one blade type. This is because the single blade can handle effectively the water flow ahead of it. However, there has been doubt in this conception, because a single blade would be impossible to provide balance loading in operation. The next most efficient is two blades, but this can be impracticable because a propeller with a very large diameter that can accommodate large blade area will be needed for generation of large amount of thrust. In view of this, most propellers have three, four or five blades [2]. Propeller blade normally experience problems such as vibration, noise, cavitation etc. According to [5], noise is experienced when there is displacement of the water by the propeller blade profile; pressure difference between the suction and pressure surfaces of the propeller during rotation; and the periodic fluctuation of the cavity volumes caused by the operation of the vessel behind. Three-bladed propellers have generally proven to be the best compromise between blade area and efficiency [5]. Four or five bladed propellers are useful for two reasons. First their extra blades create more total blade area with the same or less diameter and vibration is reduced to great extent as compared to three blades [6].

1.1. Screw Propeller Performance

A propeller blade shape will affect its performance [7]. Some propellers are progressively pitched. Cavitation does not really affect progressive pitched propeller because the leading edge is a lower pitch, thus water is moved under less pressure differential. The water then flows along the blade surface, increasing the pitch toward the trailing edge and this gives higher efficiency. Performance of a propeller depends on speed of rotation, pitch of the blades, diameters and surface of blades [7]. A combination of these factors creates a thrust which is transmitted to the thrust bearing by the transmission shaft and propels the hull through the water. Before the propulsion system moves the hull, it is mandatory to match the engine and propeller. This entails matching unto the engine on a diagram known as engine/propeller matching curve [8].

1.2. Cavitation Phenomenon

The advancement in the development of high-speed hydraulic machinery and marine propellers has been accompanied by appearance of cavitation [9]. It is a phenomenon that occurs in highly loaded propellers in which beyond certain revolutions results to a progressive breakdown in the flow and consequent loss of thrust [10]. It was first thought to be an oxidation of the metal by free oxygen, liberated from the water at points of low pressure, but investigation has shown it to be a mechanical action. Cavitation do not only cause noise and vibration but pitting in the regions where cavitation bubbles collapse takes place, forming the sponge-lie surface that is characteristics of cavitation erosion [10, 11].

These pits are thought to be caused by the repetition of mechanical stress from the impact wave or the micro-jet produced in the liquid as the cavitation bubbles collapses. The erosive effects of these collapsing bubbles mostly affect the propeller blades, struts and rudders [9]. Cavitation damage can also be dominated by the corrosive action of the liquid. Essentially, when cavitation is severe, the cavitation erosion which occurs is due to the surface fatigue created by the alternative mechanical stresses rather than the corrosive action of the liquid [12]. Similarly, when the cavitation intensity is minor, the damage from the cavitation becomes considerably augmented by the corrosive action of the liquid called the “corrosion erosion” effect [10]. At lower levels of cavitation intensity, the damage can be characterized as “flow-corrosion. Experiments at the Massachusetts institute of technology indicate that no metal can long withstand this erosive effect and after a period as short as a hundred hours, steel plate that was previously smooth was found to visibly roughen [13].

The avoidance of cavitation and erosion has therefore become an important requirement in the design of nearly all propellers [12]. Detailed predictions of cavitation performance are now possible using high level mathematical models, but such methods are hardly appropriate at the early design stage. Normally, the blade surface area is selected using empirically derived cavitation criteria, which is a function of the propeller dimensions, the operating conditions and of the immersion of the propeller [13].

The problems related to propeller performance in most cases be traced to a lack of knowledge during the design process of the wake field in which the propeller is operating [13]. When a ship had the benefit of model testing prior to construction, a model nominal wake field is very likely to have been measured. This then allows the designer to understand in a qualitative sense the characteristics of the wake field in which the propeller is to operate. The designer needs to transform the model nominal wake field into a ship effective velocity distribution before it can be used for quantitative design purposes [14]. Although computational fluid dynamics is beginning to address this problem, this transformation is far from clearly defined within the current state of knowledge, and so errors may develop in the definition of the effective wake field [15,16].

In the case where the ship has not been model tested, the designer has less information to work with, and must rely on knowledge of experts from similar ships. In this way, predictions are made empirically based on estimation. Clearly, not all performance problems are traceable to lack of knowledge about the wake field. Other causes, such as poor tolerance specification, poor specification of design criteria and incorrect design and manufacture are common causes of poor performance of ship propeller [12, 14]. Modeling the common causes and effects on the propeller performance using Computational Fluid Dynamics (CFD) presents computational complexity, time and cost. Therefore, this work seeks to present a simplified regression model analysis for propeller performance prediction under cavitation to overcome the challenges of computational time and cost associated with propeller hydrodynamic characteristics CFD models and the unavailability of Model Test facilities. The models were developed from previous predicted test model and analysis, and it show capacity for accurate predictive analysis.

1.3 Methods of Propeller Performance Prediction and Analysis

Propeller performance prediction and analysis can be conducted using any of the four basic methods. The methods are momentum theory, blade element theory, numerical methods and regression model. These theoretical methods are used to predict the action of propellers. The development of these methods started in late nineteenth century. Perhaps, the most notable of these early works was that of Rankine, with his momentum theory, which was closely followed by the blade element theories of Froude [5]. The modern theories of propeller action, however, had to wait for more fundamental works in aerodynamics behavior analysis of propeller [2]. A simple performance analysis flow chart of screw propeller under cavitation is illustrated in Figure 1. The momentum theory, blade element theory, regression method and numerical methods are described as follows:

1.3.1 Momentum Theory

The momentum theory of propeller action is based on the axial motion of the water passing through the propeller disc. Hence, this theory did not concern itself with the geometry of the propeller, which was producing the thrust, and consequently, this method is not very useful for blade design purposes. It does, however, lead to some general conclusions about propeller action which have subsequently been validated by more recent propeller theoretical methods [11].

1.3.2 Blade Element Theory

The blade element theory is quite different model of propeller action, which took account of the geometry of the propeller blade. In its original form, the theory did not take account of the acceleration of the inflowing water from its far upstream value relative to the propeller disc. This is somewhat surprising, since this could have been deduced from the earlier work of Rankine. Nevertheless, this omission was rectified in subsequent developments of the [15]. Blade element theory is based on dividing the blade up into many elementary strips, as seen in Figure 2 & 3. Each of these elementary strips can then be regarded as an aero foil subject to a resultant incident Velocity w. The resultant incident velocity was considered to comprise an axial velocity V together with a rotational velocity r, which clearly varies linearly up the blade. In the normal working condition, the advance angle β is less than the blade pitch angle θ at the section, and hence gives rise to the section having an angle of incidence α [15, 1].

1.3.3 Regression Method

Regression methodology is a form of predictive modeling techniques which investigate the inter and intra relationship between variables in form of target and predictor. It is applicable in forecasting, time series modeling and used for the causal effect relationship between parameters 17]. This method has demonstrated strength for impact analysis in multiple independency system performance. This technique provides a simplified model that can be used for ship propeller performance prediction. The models can be expressed in the form of linear regression, logistic regression, polynomial regression, stepwise regression, ridge regression, lasso regression and Elastic Net regression.

1.3.4 Numerical Method

Numerical methods are used to predict the performance of ship propeller under cavitation effect. The simulation is based on the viscid-flow theory such as the Reynolds-Averaged Navier-Strokes (RANS) solver [14]. It was used in the performance evaluation of a podded propulsion system to model the unsteady thrust and torque of the pod. The blade boundary parameter and zero pressure conditions are applied for the blade profile modeling using CFD [11, 14]. The performance of a propeller hydrodynamic characteristic can be enhanced using numerical models [14], to improve the live cycle of the propeller for sustainable development [18-20]. However, [14] observed that in most cases, the numerical prediction of propeller under sheet cavitation are not consistent with the generic experimental results. They further used the turbulence model to examine a 3-D cavitation flow propeller to validate the measured observations. This method also presents high computational time and cost in performance based analysis.

2 Research Methodology

In this research, the regression model listed as one of the methods for propeller performance prediction and analysis in sub-section 1.3 is used. The regression model is developed for the modeling of the area ratios and open water efficiencies of propeller at different conditions. The developed regression models were modified from the work of [9, 11] as follows:

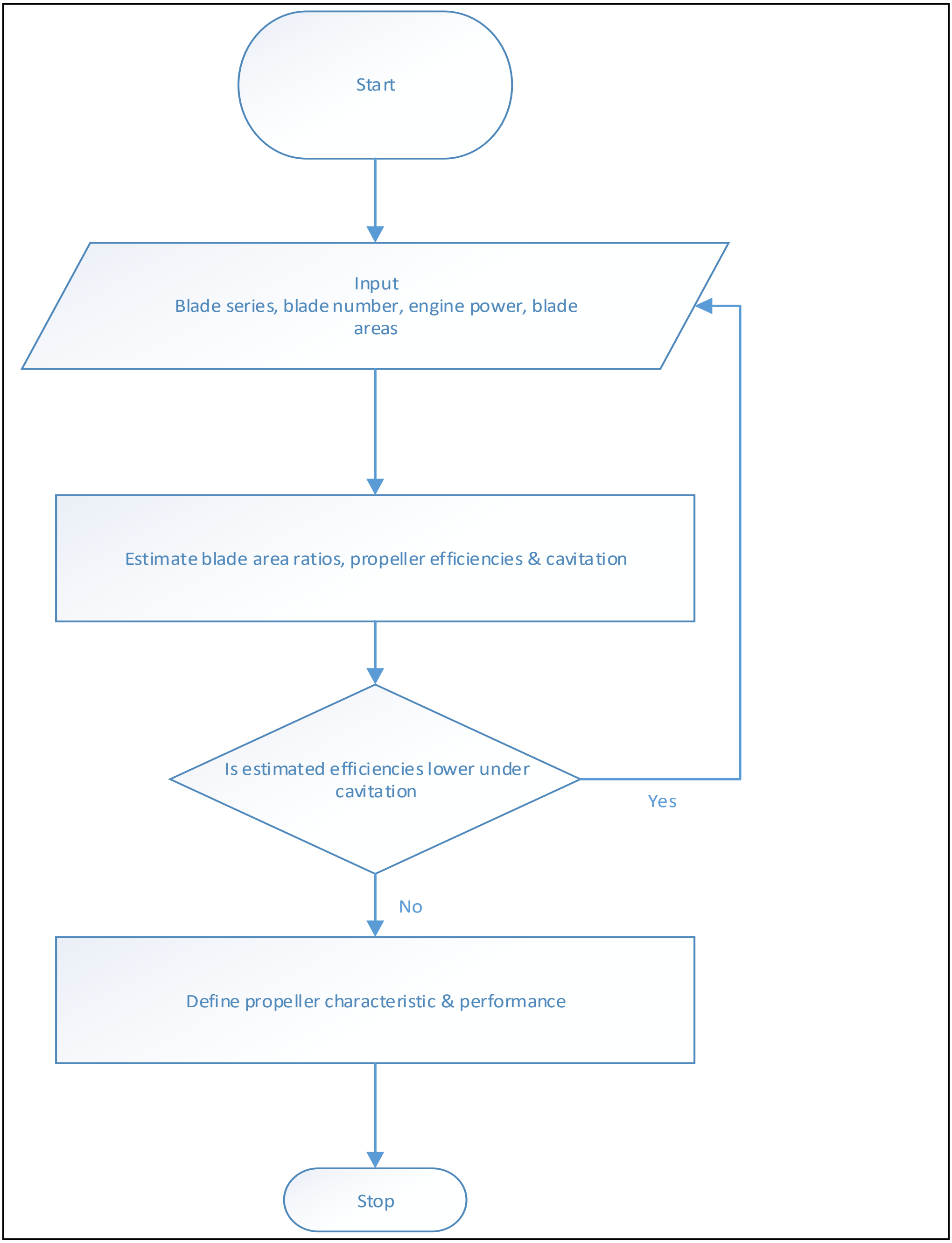

Figure 1: Performance analysis flow chart of screw propeller under cavitation

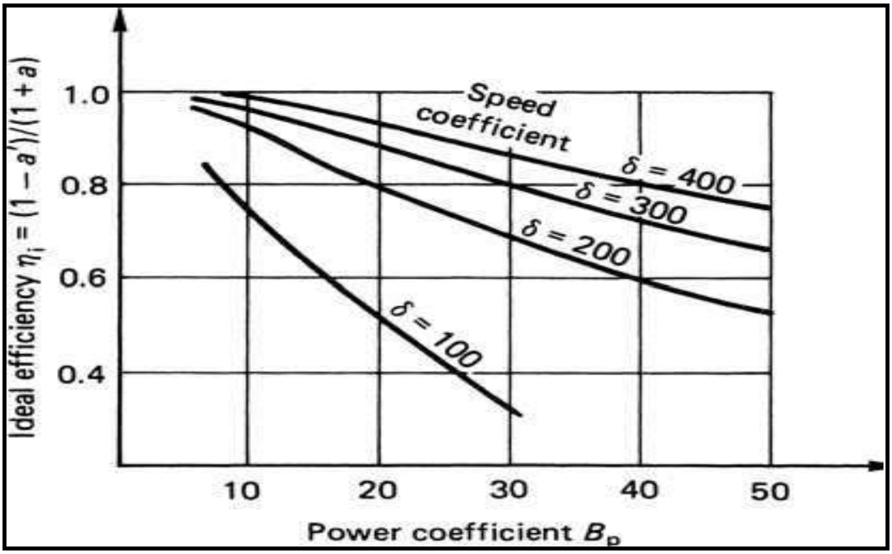

Figure 2: Ideal propeller efficiency from general momentum theory [5]

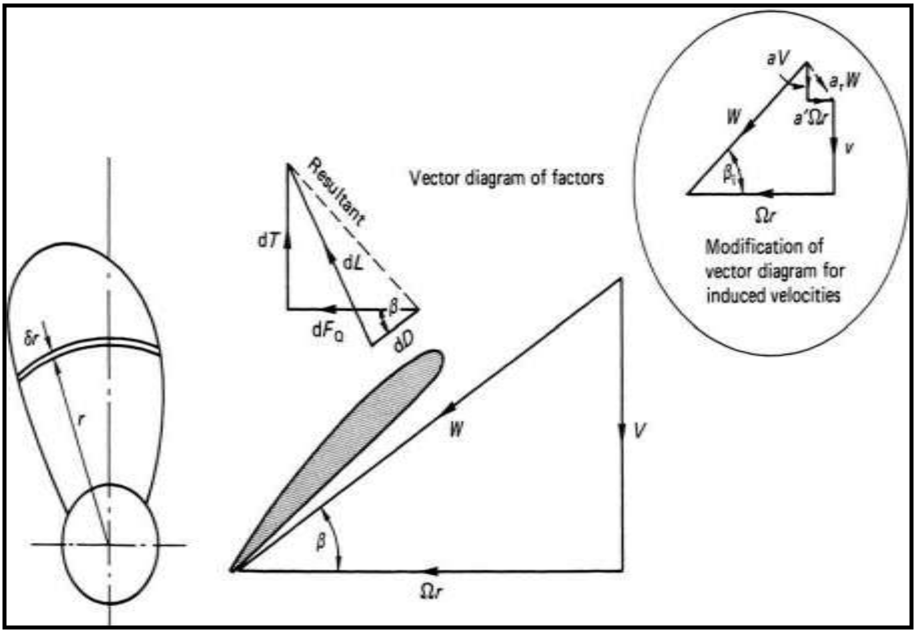

Figure 3: Blade element theory [1]

$$Developed\ Blade\ Area\ Ratio = \frac{A_D}{A_O} = 0.0876D^2 - 1.1657D + 4.4272 \quad (1)$$

$$Expanded\ Blade\ Area\ Ratio = \frac{A_E}{A_O} = 0.012812D^2 - 0.3306D + 2.1871 \quad (2)$$

$$Projected\ Blade\ Area\ Ratio = \frac{A_p}{A_O} = 0.0658D^2 - 0.8924D + 3.4852 \quad (3)$$

$$Pitch\ Ratio = 0.0521D^2 - 0.57883D + 2.5521 \quad (4)$$

$$Cavitation\ Number\ \sigma_O = \frac{P_O - P_S}{1/2V_A^2} \quad (5)$$

$$\eta_{O} = -0.133\left({}^{A_E}/_{A_O}\right)^2 + 0.133\left({}^{A_E}/_{A_O}\right) + 0.61 \quad (6)$$

$$\frac{d\eta_O}{d\left({}^{A_E}/_{A_O}\right)} = -0.266\left({}^{A_E}/_{A_O}\right) + 0.133 \quad (7)$$

where,

A_D is the developed blade area

A_O is the propeller disc area

A_E is the expanded area

D is the blade diameter

V_A is the advance velocity

$P_O - P_s$ is the pressure differential on the blade surface.

A_P is the projected blade area

η_O is the open water efficiency

3. Application of Regression Model in Propeller Performance Prediction and Analysis

The study uses regression model to analyse and predict the performance of a screw propeller for a marine vessel under various assumptions. The prediction is hypothetically evaluated at different blade diameters and geometric blade areas ratio. The results of the analysis at the given range of blade profile and blade area ratios are shown in Figures 4-9.

The result of the analysis in Figure 4 &5 show the trend of the open water efficiency for the selected blade area ratio. As the ratio increases, the open water efficiency decreases at a steep rate with blade diameter of 7.00m. This further revealed that for every 1% increase in the expanded blade areas, the open water efficiency decreases at 0.12% and 0.15% for the non-cavitated and cavitated propellers respectively. This indicate a performance reduction factor of 0.03. This factor, though minimal, over time can results to performance deterioration, especially when the propeller is fully loaded. The consequences may result to catastrophic failures.

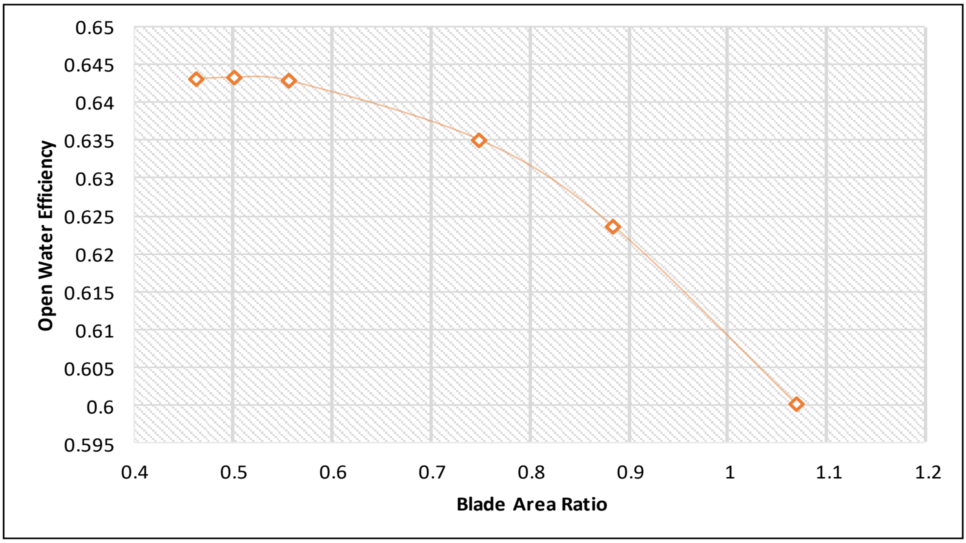

Figure 4: Effect of blade area ratio on open water efficiency

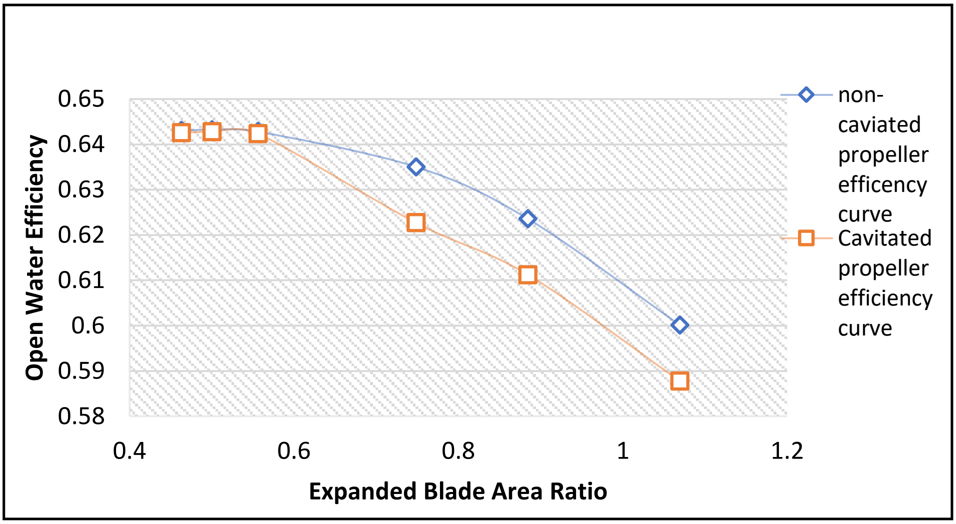

Figure 5: Comparative prediction of open water efficiency for non-cavitated and cavitated propeller

Figure 6 describes the effect of expanded area ratio reduction on the performance of the propeller. Selected percentage reduction ranges from 2% to 10%, where used to evaluate the optimal percentage incremental effect on the open water efficiency. The result show that at 7.5% reduction in the expanded blade area, the open water efficiency has the optimal percentage increment. That is at 7.5% increase in the expanded blade area, the propeller performance increase by 1.85%. This is an indication that the blade area ratio is a factor to be considered in propeller choices and performance criteria. Although, the cavitation effects decrease as blade area ratio increases. Beyond certain allowable pressure fluctuation, this increment may result to the overall propeller performance deterioration over time. It is therefore of concern that selection and prediction should be done within the optimum performance envelope for safer operation in fully loaded propeller. From the result analysis of this study, the predicted propeller performance optimizing range is $0.46 \leq {}^{A_E}/_{A_o} \geq 0.70$ and $0.62 \leq \eta_o \geq 0.65$.

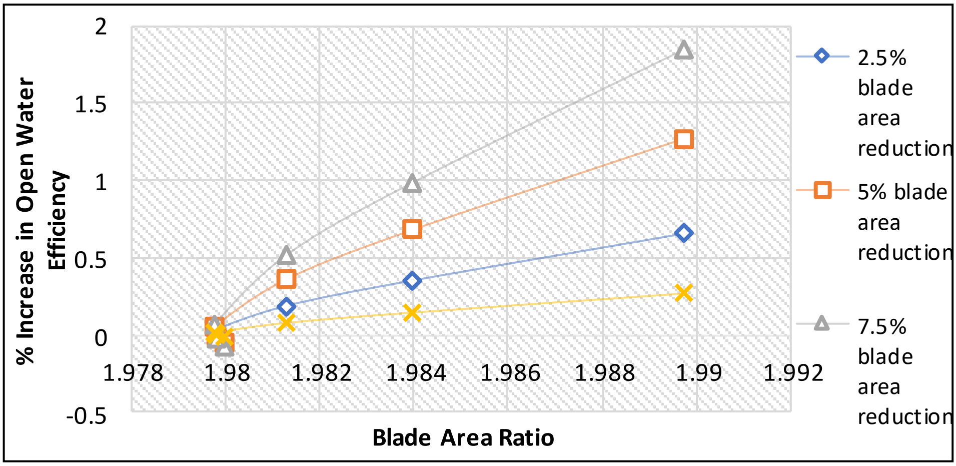

Figure 6: Effect of percentage reduction in blade area ratio on the open water efficiency

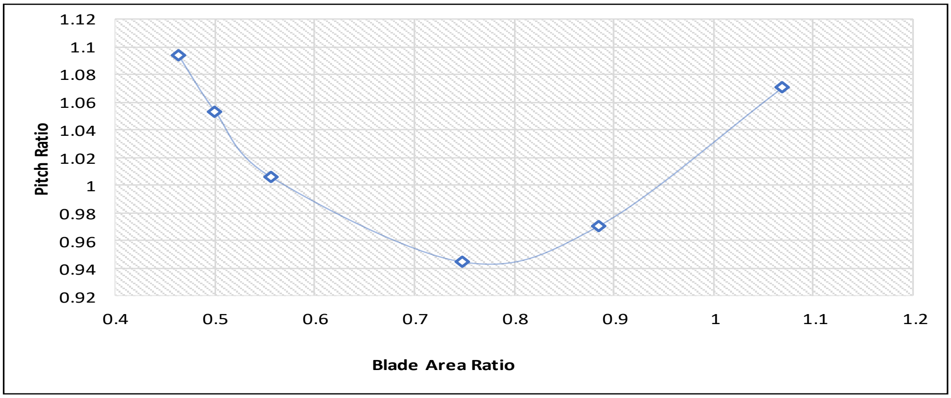

Figure 7: Effect of blade area ratio on pitch ratio of a screw propeller

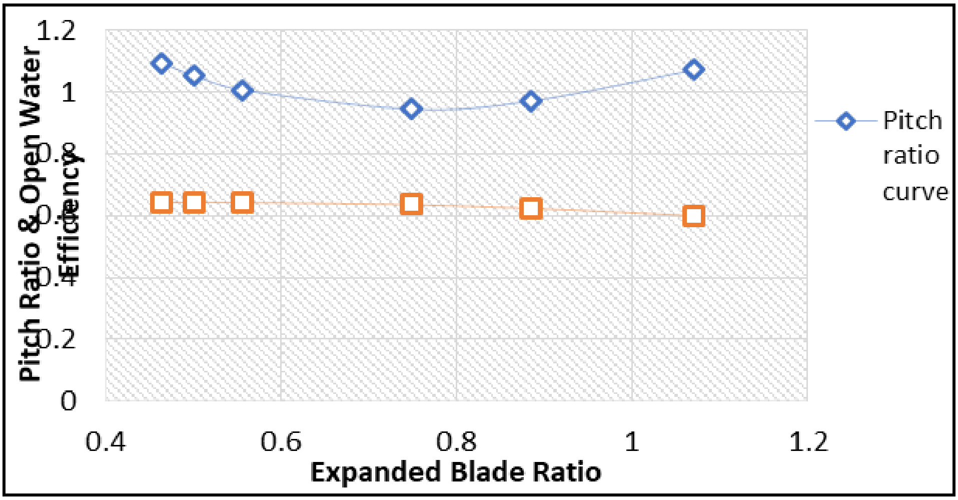

Figure 8: Comparative effects of blade area ratio on pitch ratio and open water efficiency

The result of the study as shown in Figures 7 and 8, show the effect of blade area ratio on the propeller pitch ratio. This described theoretically the advances during the complete cycle and how pitch ratio may lead to an increase in the propulsive efficiency. It also shows that the propeller propulsive efficiency is dependent on propeller pitch ratio. It is therefore important for propeller performance analysis to predict the pitch ratio during propeller design. For the proper performance of a screw propeller, the propeller pitch ratio prediction should be holistic for an optimum output.

Cavitation also affect the propeller pitch ratio as shown in this analysis. It revealed that as there is an increase in the cavitation number, the propeller pitch ratio decreases. Also, the result shows that for a nominal pitch ratio of 0.944 at the blade area ratio of 0.748, the corresponding open water efficiency is 0.635. This further explain the mean performance of the propeller at the given normal pitch. There is an even distribution of the pitch at the right and left sides of the nominal value as shown in Figure 8. So critical decision making is needed to operate within the acceptable criteria considering the decline in the open water efficiency.

Figure 9 indicate that the open water efficiency increases as the blade diameter reduction ratio decrease towards the zero axis. The result show that between the ratio of 0.55 and 0.40, the efficiency has a peak value, which gradually decline as we move toward the zero axis. It also means that the propeller disc area will also affect the propeller efficiency in operation. The propeller disc area is also a major factor of consideration in screw propeller performance due to its significant on propeller efficiency prediction. So, to enhance propeller efficiency during propeller design, the area of the disc should be accurate predicted to avoid errors that can limit performance. Furthermore, a predictive profile for operational decision making and proactive planning can be deduced from the curves shown in Figure 9. It was observed that operating within the acceptable limit under cavitation can prolong the life of the propeller and minimize the maintenance downtime in operation.

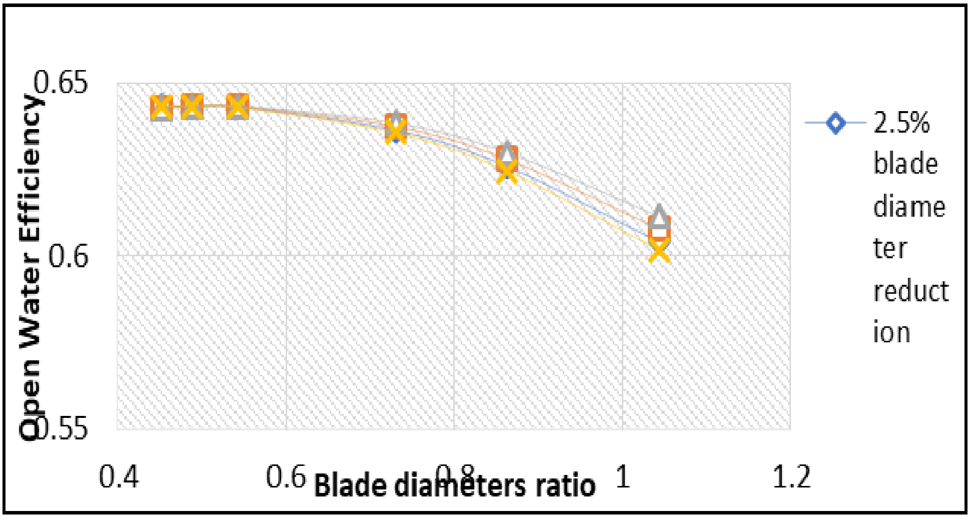

Figure 9: Effect of percentage reduction in blade diameter on open water efficiency

4. Conclusion

In this research, the regression model was utilized in propeller performance prediction, when cavitation is experienced. The model shows accurate predictive result with minimum associated error. It was identified that the cavitation reduces the performance by a factor of 0.03 in the open water efficiency. This factor overtime enhances reduction in the propeller effective power and causes performance deterioration and frequent breakdown. Therefore, an effective operating envelope of $(0.46 \leq A_E/A_o \geq 0.70$ and $0.62 \leq \eta_o \geq 0.65)$ was proposed for the operation, considering the consequences of the effect of cavitation when the propeller is fully loaded.

Furthermore, for operational safety and design consideration, cavitation reduction or monitoring should be integrated into the design for safety of ships. Increasing propeller immersion, introduction of ventilation, increase of clearances from the hull and application of skewed bladed propeller can serves as cavitation reduction measures that can minimize propeller failure in operation and optimize the performance.

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