A Review on Marine Propeller Performance of High Speed Boat Running on an Outboard Engine

Eugene Gatete, Hiram M. Ndiritu, and Robert Kiplimo

Abstract—This paper presents a review of the marine propeller performance. Currently, water transport is very important and for that marine engines performance is necessary. The use of high-speed boats is increasing because of the population and navy security demands. Propeller blade cavitation, high fuel consumption, and high power absorption are the problems that threaten the life of the high-speed boat. Blade cavitation is caused by the disturbance of the water flow at the leading edge. The propeller blade cavitation affects the outboard propeller performance and leads to the induced vibration, erosion and excess noise of high-speed boats. There are several ways to decrease the blade cavitation, fuel and power consumption of outboard engine running the high-speed boats. Improvement of the propeller performance of an outboard engine is a possible solution for reducing the propeller blade cavitation, high fuel, and power consumption. This study reviews parameters that affect the marine propeller performance, blade cavitation development and its reduction, and improvement in propeller performance of the high-speed boats running on the outboard engine.

Keywords—High-speed boat, Marine Propeller performance, Propulsion system, Outboard engine

I. Introduction

THE conventional internal combustion outboard engine shown in Fig.1 is still the main modern method of marine propulsion and has variety of approaches to be adopted from a direct-injection two-stroke to a four-stroke cycle, with outputs from 2 to 557 horsepower (hp), and weights from a few kilograms to half a metric ton. There are various types of outboard engines in the market which vary in size, weight, output and design. The outboard engine is widely used as a power source for boat or ships due to their high performance, lower cost, simple installation, reduced fire risk, lower weight, higher speed, superior maneuverability, less draft giving better shoal water capability, and easier launching and beaching [1]. Yamaha, Honda, and Suzuki from Japan; and Mercury and Evinrude from America are the leading manufacturers [2]. The outboard engine can be divided into six subsystems base on their functions: the mechanical drive system, the swivel bracket system, water intakes, the propulsion system and the exteriors, as shown in Fig.2. The mechanical drive system includes the engine and transmission shafts to yield the kinetic energy. A swivel bracket system is the supporting and turning base and unloads the thrust from the propeller with its clamp fixed at the ships stern. The water intakes sea water enters at this point and flows through the engine for cooling purposes. The gear box and propeller make up the propulsion system. The exteriors are the covers, connections and decorative pieces. The design of the outboard propeller is the main topic in this review. Therefore, calculation and analysis of the open water propeller performance of propulsion system are needed.

Eugene Gatete, Department of Mechanical Engineering, JKUAT (corresponding author to provide phone: +254 (0) 790249557; e-mail: eugene.gatete@students.jkuat.ac.ke).

Hiram M. Ndiritu, Department of Mechanical Engineering, JKUAT (e-mail: hndiritu@eng.jkuat.ac.ke).

Robert Kiplimo, Department of Marine and Maritime Operations, JKUAT (e-mail: kiprob@eng.jkuat.ac.ke).

Fig. 1. Outboard Engine [2]

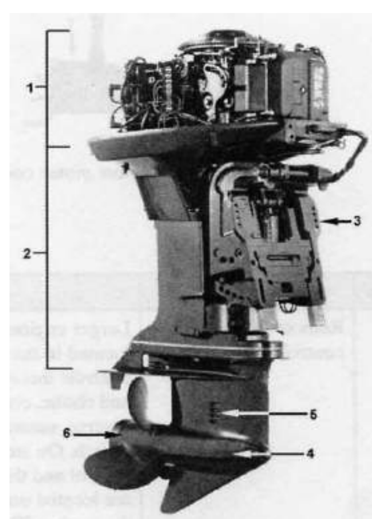

Fig. 2. Outboard Engine Parts [1]

Where in Fig. 2 ;
1 and 2: Mechanical drive system,
3: Swivel bracket system,
4: Gearbox,
5: Water intakes,
6: Propeller.

II. Outboard Propulsion System

The propulsion system of a boat is an assembly of components to drive boats based on rotary motion. One of the most critical propulsion systems is the propeller, which produces the power needed to push water while the main engine is running, as shown in Fig. 3. Its configuration involves a mechanism to push water, with the resultant reaction propelling the boat forward. It plays a great role in the fuel efficiency, thrust, torque and overall efficiency improvement. Due to its role in the performance of the boat as shown in Fig. 4, it is necessary to predict the performance of the considered propeller.

Fig. 3. Propulsion system of an outboard engine [13]

Marine propellers face the problems of blade cavitation which leads to erosion, noise, and vibration. Meanwhile, the propeller configuration influences fuel consumption, efficiency as well as performance of high speed boats [13].

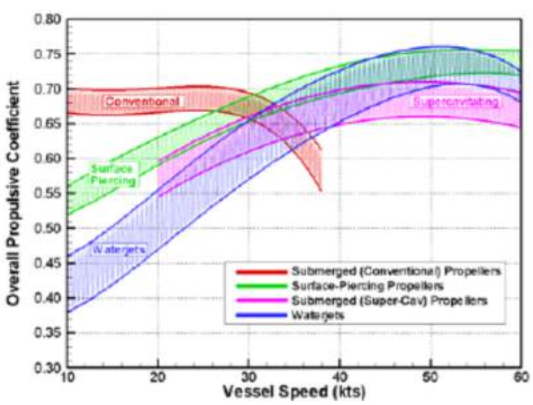

Fig. 4. Overall propulsive coefficient versus ship speed for different propulsor types [12]

A. Outboard Propeller

Propeller design is used to obtain a blade geometry which meets the requirements determined by the operating condition by using various design methods [7], [8]. The optimization of the outboard propeller is to provide the maximum thrust for the minimum torque at a specific rotational velocity (rpm) with a particular boat speed. Initially, propeller design intended to achieve the highest efficiency. Then, the cavitation phenomenon came into focus and now propeller design involves the two factors; efficiency, and cavitation.

Choosing the right propeller is crucial in determining the performance of the outboard engine. Propeller choice can affect boat top speed by as much as 5 to 10 knots. It also has a direct effect on acceleration, cornering, pulling power and fuel economy. Some boats may require change of propellers for different activities, such as high speed cruising, water skiing, or carrying heavy loads. Using the wrong propeller in any of these applications will not only hurt performance, but could also cause engine damage [14]. There are also many types of propeller systems in operation. The right hand fixed blade propeller is still common. Meanwhile, development of controllable pitch propellers, contra-rotating propellers, multi-blade propeller systems, twin, triple and quadruple propeller sets, pod propulsion units, Kort nozzle systems and Azipod systems have also all taken market share in both commercial and boat construction [3].

The propeller is a powerful propulsion device used in a boat. Furthermore, utilizing propeller in high speed boats running on an outboard engine avoids any other damages. Its performance is conventionally represented in terms of non-dimensional coefficients like the thrust coefficient, torque coefficient, and efficiency and their variations with the advance coefficient [15].

It is difficult to determine the characteristics of a full-size propeller in open water by varying the speed of the advance and the revolution rate over a range while measuring the thrust and torque of the propeller, but with the advent of computers, numerical methods developed rapidly since the 1960s onwards. The first numerical methods were based on the lifting line theory and later the lifting surface model were developed by Salvatore et al [16]. Later on, a propeller performance analysis program was also developed and integrated into a genetic algorithm by Burger et al [17].

Sanchez et al. [18] calculated open water flow patterns and performance coefficients for DTRC 4119 propeller using FINFLO code. The flow patterns were predicted by the k-turbulent model. The authors also suggested a better prediction of the tip vortex flow, which required a more sophisticated turbulence model.

Motley et al. [19] investigated a reliability-based global design of self-adaptive marine propellers operating under a range of steady loading conditions, using a Nelder-Mead constraint based optimization technique. An optimized propeller of Vo= 13.0 knots and eq = 17:250 was found to reduce the load variation by approximately 10%, cavitation potential by 2.3% on the back side and 9.7% on the face side. It also increased the total efficiency by approximately 0.3%. For unsteady applications, the authors suggested improvements on propeller performance in terms of reduction of loads, structural strength, delay of cavitation and hydrodynamic efficiency.

B. Geometrical Parts of Outboard Propeller

Marine propeller is a set of identical twisted blades, spaced evenly around a hub. Most propellers have a splined bushing in the hub that mounts on the outboard. Fig. 5 bellow shows an example of marine propeller used in outboard engine [45].

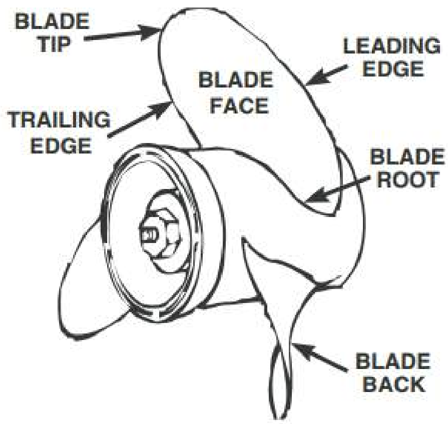

Fig. 5. Parts of an outboard propeller [45]

1) **Hub:** The boss of a propeller is the solid center disc, to which the propeller blades are attached. Since the hub generates no drive, the ideal would be to eliminate it. As a practical matter, though, the hub can seldom be much less than percent of the diameter in order for it to have sufficient strength.
2) **Blades:** The propeller blades are the twisted fins aor foils that project out from the hub. It is the action of the blades that drives a boats through the water.
3) **Blade Face and Blade Back:** The blade face is the high-pressure side, or pressure face of the blade. It is the side facing aft, the side that pushes the water when the boat is moving forward. The blade back is the low pressure side or suction face of the blade, the side facing ahead.
4) **Blade Root and Blade Tip:** The blade root is the point at which the blade attached to the hub. The blade tip is the extreme outermost edge of the blade, as for from the propeller shaft center as possible.
5) **Leading and Trailing Edges** The leading edge of a blade is the edge of the blade that cleaves the water. The trailing edge is the edge from which the water streams away.

III. High-Speed Crafts

A high-speed craft (HSC) shown in Fig. 6 is a vessel for civilian use, also called a fast craft or fast ferry and is called patrol craft for military purposes. A vast increase in the high-speed crafts due to existing needs in the field of fast transport of light and expensive cargo, passengers at the high-speed craft for marine transportation has drawn considerable interest for both ship owners and naval architects. The function of high speed also gives advantages to boats which are designed to be used for a surveillance and patrol in maritime area at open sea. The advanced concept was applied in many types of high speed craft in order to obtain a great performance in Seaway. The design and safety of high-speed craft is regulated by the high Speed Craft Codes of 1994 and 2000, adopted by the Maritime Safety Committee of the International Maritime Organization (IMO) [4].

Savitsky et al. [5] defined that high speed craft are considered to be vessels that can travel at a sustained speed equal to or greater than 35 knots with bursts of high speeds of 40-60 knots. Froude number allows for another way to hydrodynamically classify ships. Naval architects use the Froude number when vessels deal with the interaction of the waters free surface and the hull. High speed vessels are typically defined with Froude number greater than 0.4 which at this speed range the crafts weight is almost entirely supported by dynamic forces and the trim tend to be much lower than hump. It is classified into two categories which are an Air-Supported and Displacement type. Air supported crafts include Air Cushion Vehicles (ACV), Surface-Effect Ships (SES) and Foil Supported craft such as hydrofoils and jetfoils. Displacement type vessels include conventional monohull, catamaran, trimaran, small water plane area twin hull (SWATH), and air lubricated hulls. Each type of craft has its unique characteristics, and they all suffer from the common problem of limited payload and sensitivity to wind and sea state. Besides, they are vessels with a design speed corresponding to a Froude number above 0.45, primarily designed for short distance services such as public transport of passengers and vehicles. An outboard engine, inboard diesel sterndrive, or inboard diesel waterjet can power the high-speed watercraft [9], [10]. Therefore, the improved performance of the high speed boat for the local market is to enhance the operations in green or blue water for support in short distance operations, border actions, and international peacekeeping or disaster relief [11].

Fig. 6. Example of high speed craft (HSC) [11]

Black, et al. [12] developed new blade section concepts that have the efficiency characteristics of conventional submerged sub-cavitating propellers at low and intermediate speeds but can transition to a super-cavitating mode for high speed operation without encountering thrust breakdown.

IV. Marine Propeller Performance Characteristics

A propeller is normally fitted onto the lower unit of an outboard engine where it runs in water that has been disturbed by the boat as it moves ahead. The performance of the propeller is thus affected by the boat to which it is fitted. Hence, in order to determine the performance characteristics of a propeller unaffected by the boat to which it is fitted, it is necessary to make the propeller operate in open water. Therefore, some of the parameters that can affect the performance while designing are subdivided into two categories, that is, open water characteristics and propeller-hull interaction characterization [20].

A. Open Water Characteristic

The forces and moments produced by the propeller are expressed based on non dimensional characteristics. These non-dimensional terms explaining the general performance characteristics are established using dimensional analysis [20]. Thrust (T) and Torque (Q) can be represented by the following functions depending upon the physical quantities involved;

$$T = f_1(\rho, D, V, g, N, P, \mu) \tag{1}$$

and

$$Q = f_2(\rho, D, V, g, N, P, \mu). \tag{2}$$

An efficient propulsion system relies on propeller performance which depends on the thrust force, torque, and efficiency. These were determined by non-dimensional quantities through propeller performance, which are, thrust coefficient(Kt), torque coefficient (Kq), coefficient of cavitation and open propeller efficiency(η_o) with respect to the advance coefficient (J). The expressions for K_T,K_Q, σ, η_o and J are given in Equations 3 to 8 as shown by Techet et al [21], [22].

$$K_T = \frac{T}{\rho N^2 D^4} \tag{3}$$

$$K_Q = \frac{Q}{\rho N^2 D^5} \tag{4}$$

$$\sigma = \frac{P_0 - P_v}{2\rho N^2 R^2} \tag{5}$$

$$J = \frac{V_a}{ND} \tag{6}$$

The efficiency of the propeller is the ratio of useful power produced by the propeller, the thrust horsepower (THP), to the input shaft power, the delivered horsepower (DHP):

$$\eta_o = \frac{THP}{DHP} = \frac{TV_a}{2\pi NQ} \tag{7}$$

Additionally, the efficiency can be written as:

$$\eta_o = \frac{K_T \rho N^2 D^4 V_a}{2\pi N K_Q \rho N^2 D^5} = \frac{K_T}{K_Q}.\frac{V_a}{2\pi ND} = \frac{K_T}{K_Q}.\frac{J}{2\pi} \tag{8}$$

Where;
T= Thrust [N],
Q= Torque [Nm],
D= Diameter [m],
V_a=$J.N.D$ (Advanced Speed)[m/s],
N= Rate of rotation[rps],
ρ= Mass density of water[kg/m^3],
μ= Dynamics viscosity of water[Pa/s],
P= Total static pressure[Pa],
P_o= Absolute pressure at shaft centre [Pa],
P_v= Vapour pressure at ambient temperature [Pa].

Taheri et al. [23] developed a propeller design method based on a vortex lattice algorithm to optimize the shape and efficiency. The analysis of the hydrodynamic performance parameters based on a vortex lattice method was used to implement two computer code. The first code was sequential unconstrained minimization techniques for minimizing the torque coefficient considering the thrust coefficient constant as a constraint and chord distribution as a design variable. The second was a modified genetic algorithm to maximize efficiency by considering the design variables as non-dimensional blades chord and thickness distribution along the blade. The comparison between experimental data and the solution of the optimization problems were found to be near 13% improvement in efficiency and a nearly 15% decrease in torque coefficient for the propeller.

Senthil et al. [24] investigated a computational method for the determination of open water performance of a marine propeller using the RANS solver and unstructured meshes and compared the results to experimental ones. The result of thrust, torque and open water efficiency found using CFD (based on RANSE) were not accurate compared to the existing propeller chart. This inaccuracy was due to the challenge of handling a large number of cells in the flow domain and incorporating a rotating flow over propeller simulation. The author suggested the structured meshes and proper modeling of the hub to get an accuracy result of thrust, torque and open water efficiency in Computational Fluid Dynamics.

Shiu-Wu Chau et al. [25] investigated the hydrodynamic performance of high-speed craft rudders via turbulent flow computations with non-cavitating characteristics, by focusing on the numerical analysis of non-cavitating hydrodynamic characteristics of practical rudders used for high-speed crafts, which is valid in the low-speed region. Thrust, torque, and efficiency, the lift, drag and stock moment coefficient of rudder were evaluated to investigate the influences of profile shape and profile thickness. The result showed that, the location of maximum thickness is the most important factor to influence the non-cavitating hydrodynamic characteristics.

B. Propeller Hull Interaction

Kim et al. [26] in their studies on high-speed planning hulls for improving the seaworthy performance, designed three planning hulls namely deep-V planing straight (VPS), deep-V wave-piercing concave (VWC), and deep-V wave-piercing straight (VWS) having almost the same displacement and principal dimension. The hydrodynamic characteristics were compared with each other through the model tests. It was found that among the three model boats, VWS model had favorable seaworthy performance due to its reduced wetted surface area. However, its hull form needed to be optimized in order to improve its hydrodynamic performance.

An experimental and numerical investigation on hydrodynamic and aerodynamic characteristics of a plan boat was performed by Jiang et al. [27]. The comprehensive series of viscous CFD simulations considering free-surface and 2-DOF motion of the hull was used. The result showed that the variation between the calculated and experimental resistance increased from 2.99% to 14.66% as the Froude number increased from 3.16 to 5.87. In the numerical simulation, the total resistance increased up to the value of

Froude number for which wave surface separated from the tunnel roof and the total resistance decreased. Finally, the calculated results were validated by comparing experimental and numerical data and this showed a good agreement.

V. Parameter Affecting the Outboard Propeller Performance

There are three most significant factors affecting the propeller performance and efficiency which include diameter, rotational speed, and pitch. Pitch is the distance that a boat is propelled forward in one propeller rotation. Many other variables are needed for selection of suitable propeller which include the pitch to diameter ratio, rotation speed, blade number, blade area ratio, skew angle, blade shape and blade thickness [1], [6].

A. Propeller Diameter

The diameter is a crucial geometric parameter in determining the amount of power that a propeller can absorb and deliver, and thus dictating the amount of thrust available for propulsion. With the exception of high speed (35 Knots+) vehicles the diameter is proportional to propeller efficiency (i,e. Higher diameter equates to higher efficiency). In high speed vessels, however, larger diameter equates to high drag. For typical vessels a small increase in diameter translates into a dramatic increase in thrust and torque load on the engine shaft, thus the larger the diameter the slower the propeller will turn, limited by structural loading and engine rating. For optimum efficiency, the propeller diameter determination is a complex procedure involving various empirical formulas [6]. In high speed craft, with regards to cavitation, a larger diameter is beneficial as the rotational speed of the propeller could be reduced and still achieve the required forward movement. A reduced rotational speed would mean that the pressure unbalance on the blades would be reduced with the reduction of the inflow forces and so cavitation would be decreased. So for a certain engine output or desired forward speed, a large diameter propeller would allow for slower rotation and reduced cavitation [3].

B. Rotational Speed

For vessels operating under 35 Knots speed, reduction of speed and increase in diameter results to higher torque. For high speed boat, RPM is ranging from 2000 to 6000 rpm and from that it is possible to get the inflow velocity for a given advance coefficient [28].

C. Pitch to Diameter Ratio

The pitch of a propeller indicates the distance the propeller would drive forward for each full rotation. In reality since the propeller is attached to a shaft it will not actually move forward, but instead propel the ship forward. The distance the boat is propelled forward in one propeller rotation is actually less than the pitch. For high speed craft, pitch ranges from 9 inch to 24 inches. Typically blades are twisted to guarantee constant pitch along the blades from root to tip. Often a pitch ratio will be supplied. This is simply the ratio of pitch to diameter, usually in millimeters, and typically falls between 0.5 and 2.5 with an optimal value for most vessels closer to 0.8 to 1.8. Pitch effectively converts torque of the propeller shaft to thrust by deflecting or accelerating the water astern simple Newtons Second Law [6], [29].

Mojtaba et al. [30] designed a marine propeller to generate the thrust with lower torque, highest efficiency and reducing cavitation. The author used numerical method based on Blade Element Theory (BET) to get the thrust and analyze how it depends on the shape of the marine propeller. The parameters such as pitch ratio, blade area ratio and skew angle were used as the input variables to achieve the optimum propeller with high propeller performance. It was found that various pitch ratios such as 0.4, 0.6, 0.8, 1.0, 1.2, and 1.4 used satisfy the propeller performance characteristics. The skew angle effect also showed its capacity to estimate the propeller efficiency in limitation of cavitation problem. This research did not consider diameter, blade number and material selection for optimization.

Kiam et al. [31] investigated the marine propeller performance characterization through CFD to predict a three blade marine propeller performance characteristics. Five propellers with a pitch to diameter ratio values of 0.6; 0.8; 1.0; 1.2; and 1.4 were used for the computational flow analysis through RANS solver to compute the propeller performance characteristic to the advance coefficient(J). It was found that efficiency, torque, and thrust increased as the pitch diameter ratio increased.

M.Bernitsas et al. [32] designed the Wageningen B-Series propeller to test the open water characteristics using the multiple polynomial regression analysis. The derived polynomials expressed thrust and torque coefficients in terms of the number of blades, the blade area ratio, the pitch-diameter ratio and the advance coefficient. It was shown that the derived polynomials valid for the pitch-diameter ratio varying between 0.5 and 1.4 for the Reynolds number of 2×10^6. It was also found that the thrust coefficient displayed a local maximum for high pitch-diameter ratio, high number of blades, low blade area ratio and low values of advance coefficient. However, the extremes of the above ranges were not considered in this research.

D. Number of Blades

Blades are the twisted fins or foils that protrude from the propeller hub. The shape of the blades and the speed at which they are driven dictates the torque a given propeller can deliver. The primary effect that is to be avoided with propeller blade number selection is resonance, as the number of blades affects the frequency of vibrations and the strength of vibrations that occur during operation. There is also a strong interrelation between propeller diameter, blade area and blade number, where a greater diameter requiring fewer blades and a greater area requiring more blades. An increase in propeller number can reduce sheet cavitation of the suction side due to a reduced load per blade, however it can increase root cavitation due to reduced clearance between each blade [29]. It is recommended that the number of blade should be in range of 2 to 6 blades to reduce the resonance. An area ratio of 16-18% should be also assigned to each blade, with a decrease of 4% in the diameter per each additional blade. This guideline has been obtained with both performance and cavitation efficiency in mind [33].

Kiam et al. [34] also investigated the effects of number of blade on marine propeller performance. Five propellers with number of blades of 2, 3, 4, and 5 were utilized for the computational flow analysis through RANS solver to investigate the propeller performance. It was seen that the efficiency decreased as number of blades increased while torque and thrust increased as the number of blades increased. It was concluded that, although higher number of blades reduced the efficiency and leads to higher fuel consumption but it provided better velocity.

Boucetta et al. [35] carried out a numerical simulation of the flow around marine propeller using RANS method of the commercial CFD code fluent to examine the effect of skew magnitude, thickness and blade number on the hydrodynamic performances. The number of the blades were changed from three to four and five to investigate its effect on the open water characteristics of the marine propeller. It was concluded that the increase of blade thickness generated a rise in propeller efficiency, and the adoption of skew angle on the blade improved the hydrodynamic performance of marine propeller. In addition, the propeller with four blades gave the best efficiency. However, this work did not consider the effect of blade materials, pitch diameter ratio and rotational speed on propeller performance.

Xueyin Wu [28] in his development process for marine propeller through design, simulation and prototyping explained the effect of the number of blade on propeller performance. The author showed that propellers normally have a number of blades within the range from two to six. In his study, it was found that more number of blades increased thrust which caused cavitation and which also led to propeller vibration. It was also shown that less number of blades avoided cavitation and decreased thrust. Therefore, the author concluded that, a good propeller has a large diameter, slow speed, low number of blades and high efficiency.

VI. Marine Propeller Blade Cavitation on Propeller Performance

Propeller cavitation is phenomenon which begins when a disturbance creates a low-pressure area in the water flow. As speed increases, the low pressure intensifies enough to vaporize (boil) some of the surrounding water. When the vapor bubbles approach a high pressure area, they collapse, releasing energy and causing damage. Cavitation is caused by a disturbance of the water flow in front of the propeller. It is also caused by an irregularity in the boat bottom or gearcase, and a misplaced transducer or speedometer pickup [36]. The results of cavitation usually appear as burned areas on the propeller blades as it is shown in Fig. 8;

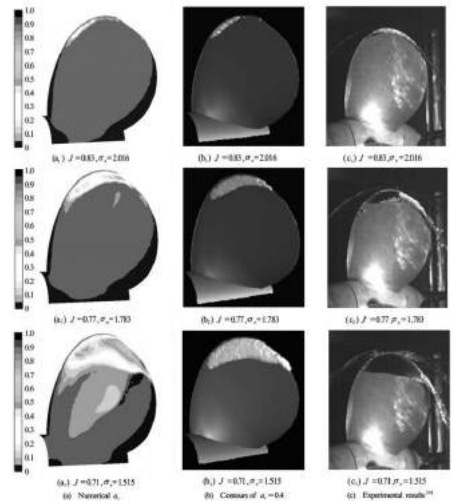

Fig. 8. Variation of propeller blade cavitation [47]

Propeller Cavitation shown in Fig.7, also referred to as ”cold-boiling”, is the phenomenon of the formation of vapour pockets -cavities- within a fluid, caused by pressure reduction below a certain value named vapour pressure”. When the cavities find themselves back in a higher pressure environment they implode, causing the liquid to rush towards its center to fill it, hence generating large pressures (up to 1 GPa). These are subsequently propagated in the form of pressure waves to their surroundings [48].

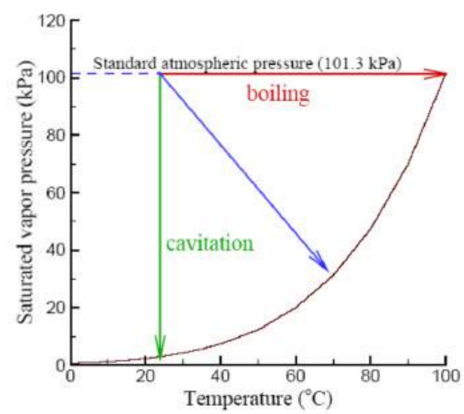

Fig. 7. Difference between cavitation and boiling phenomena [48]

In marine hydrodynamics this phenomenon is especially present in pumps, turbines and propellers, which often comprise of multiple hydrofoils. As pressure is a decreasing function of velocity, according to Bernoulli, the flow around each propeller blade section experiences rapid pressure changes, which lead to the inception of cavities around them. This effect is amplified at high inflow speeds but is also dependent on the body geometry [2], [40].

This phenomenon occurs also in many fields such as automotive industry, chemical engineering, cleaning technologies, the biomedical applications and, of course, has developed a dedicated research branch under fluid mechanics. The effect of cavitation on propellers was first investigated by Reynolds et al. [39] in the laboratory, and by Barnaby et al. [41] using full scale trials of the destroyer daring. They found

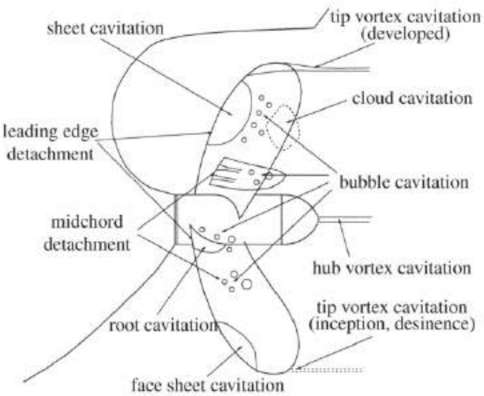

Fig. 9. Various types of cavitation [44]

that the formation of vapor bubbles on the blades reduced the power of the propeller. Later investigators also found that cavitation can lead to undesirable effects such as blade surface erosion, increased hull pressure fluctuations and vibrations, acoustic energy radiation, and blade vibration.

Propeller cavitation has been found to manifest itself in different locations of the propeller and with certain unique forms as show in Fig. 9. Thin string-like cavities at the tip of the blade and from the hub of the propeller are called vortex cavities and are fully developed. On the other hand, the sheet cavities encounter were relatively stable and present the least modeling difficulties in numerical methods. Sheet cavities start from the leading edge of the blade whereas if they start from mid-chord they tend to turn into bubble cavitation from there and aft ward. Root cavitation may appear just forward of the hub at certain rotation angles of the propeller and often joins the hub vortex. Finally, cloud cavitation is visually similar to sheet cavitation, however is very unstable and presents many modeling difficulties. Other type of cavitation which can also occur include bubble cavitation [40].

In Yin Lu Young's study [44], the cavity on a propeller blade is treated strictly as sheet cavitation. She states that the pressure inside the sheet cavity is assumed to be constant and equal to the vapor pressure. The rationale behind using the sheet cavity model includes: It provides a relatively simple mathematical model where potential flow theory can be applied. Tulin et al. [43] found that sheet cavity is the first-order contributor to dynamically varying blade loads; and other forms of cavitation (such as tip or hub vortex cavitation) and other neglected phenomena (such as wake roll-up) can be added as refinements to the current models.

Kuiper et al. [42] proposed propeller design techniques to delay the tip vortex cavitation inception. Important parameters in the tip region including thickness, plan form, skew, chord distribution and rake were systematically varied while maintaining a constant radial loading distribution. A systematic series of 2 bladed propeller designs was evaluated using a panel method for pressure distribution near the tip. An extreme tip rake towards the pressure side was used in the investigation. The measurements showed a trailing vortex coming from the corner of the raked tip. There was still too much cross-flow over the area of strong curvature, leading to separation and vortex formation. Local and leading edge tip vortex inception were delayed significantly, while the width of cavitation bucket for the trailing tip vortex inception was reduced moderately. The authors believe that the strong curvature in the tip region should be avoided.

Gaggero et al. [46] designed a propeller for a high-speed craft using a multi-objective numerical optimization approach based on boundary element method. The efficiency was numerically investigated using RANSE calculation. The design improved the propulsive efficiency, reduced blade cavitation and simultaneously maximized the ship speed. It was also found that the proposed approach was able to deal with main objectives and to derive trade-off designs with high performance simultaneously concerning suction and pressure side cavitation. However, the author did not investigate the improvement of the quality of the design regarding the risk of leading edge, the pressure side, and blade cavitation.

Numerically, Zhi-feng et al. [47] investigated the cavitation and hydrodynamics performance of the propellers to predict the thrust, the torque and the vapour volume fraction on the back side of propeller blade for a uniform inflow. The authors used a viscous multiphase flow theories based on RANSE formulation of advance rate (J) and cavitation number (n) to validate the result. It was found that for the high value of advance rate the cavitation was relatively weak and had the little effect on the hydrodynamic performance while the sixteen small value of advance rate the cavitation was strong. In addition, the increase of cavitation number improved the propeller performance characteristics. However, Blade number and area ratio, rotational speed, and blade material were not considered in this work.

VII. Conclusion

1) From the review, it is evident that sufficient research has not been done to determine the optimum propeller design for high-speed boats running on an outboard engine while reducing the propeller blade cavitation as low as possible. Hence, there is a need to improve the quality of propeller design in the cases of the original rake distribution with regards to the risk of leading edge, the pressure side, and blade cavitation.
2) Due to limited literature on propeller geometry and material, there is a need to investigate the effect of propeller geometry such as pitch diameter ratio, rotational speed (rpm), and blade number on propeller performance.
3) The use of outboard engine as an alternative propulsion for high speed boat remains a challenge due to the propeller blade cavitation. Thus, an investigation on the parameter affecting the propeller blade cavitation is needed to get a marine propeller with the high-performance application.

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