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A Review of the Surface Drives Employed for High Speed Planing Craft

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Abstract Marine propulsion systems are the core of high speed planing craft (HSPC), a major factor in creating acceleration, and speed retaining therein. HSPC have used many surface drives to drive the craft. The propulsion systems installed on these vessels are always an important factor for buyers and users, This article reviews and compares the several different of surface drives system been designed for planing boat and the important factors to evaluate a surface drive system have later been investigated, The overall results show that the best propulsion system have higher safety and reasonable price and lower maintenance cost per year and can provide more speed for boats. Hence, the articulated surface drives while having high hydrodynamic efficiency will be a priority for installed on most new planing craft.

Keywords: *high speed planing craft, surface drive, SPP, Q-SPD, Levi drive, arneson, Topsystem*

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1. Introduction

The popularity of HSPC continues to grow, especially in countries with extensive maritime borders. In the last two decades, designers have provided a wide range of HSPC with various drive systems and bodies to marine Communities, each of them with is related advantages and disadvantages and the number and types of these craft are increased every year. But the changing rate of designing drive systems of these craft is relatively lower compare to changing rate of their hull and side equipment designing, because creating a new drive system is one of the costly steps in the design process, in terms of price and time and HSPC manufacturers prefer to provide the drive systems of these craft from related specialist companies because increase in costs leads to a reduction in the rate of sales and competitors' surpass. In addition, the cost of a HSPC with the capability of water skiing is about three times more expensive than conventional displacement HSPC. There are two main options to select a proper drive system for planing craft with internal-installed diesel combustion engine which will affect the next parameters. One of these options is to purchase a fixed surface drive system and another one is to purchase an articulated surface drive system for planing craft. One of the most important features of articulated surface drive systems is to utilizing from surface piercing propeller (SPP). Studies have been conducted on designing and analyzing of these propellers, as well as on surface drive systems are divided in two groups of numerical and experimental researches. Current knowledge of the SPPs is mostly on the basis of experimental tests conducted on their models. The first effort to model partially sub-merged propeller was carried out by Oberembt [1]. He used a lifting line approach to calculate the characteristics of partially sub-merged propellers. The blades were reduced to a series of lifting lines and method was combined with a 2-D water entry-and-exit theory developed by Wang [2,3] to determine the thrust and torque coefficients. A lifting-line approach which includes the effect of propeller ventilation was developed by Furuya [4,5]. He used linearized boundary conditions and applied the image method to account for free surface effects. An unsteady lifting surface method was employed by Wang et al. for the analysis of 3-D fully ventilated thin foils entering into initially calm water [6]. The method was later extended by Wang et al. to predict the performance of fully ventilated partially submerged propellers with its shaft above the water surface [7,8]. Rose and Kruppa [9] conducted experiments on four-bladed SPP referred to as Rolla propeller series. The model propeller was tested in the free-surface cavitation tunnel K27 at Berlin's Lab. Three combinations of shaft inclination and immersion ratio were investigated. According to their results, vertical force reaches their highest values when the shaft inclination is large. Side forces, on the other hand, are largest when the immersion ratio is small. Kudo and Ukon [10] and also Kudo and Kinnas [11] used a 3D vortex-lattice method to analyze the super cavitating propellers. They assumed the propeller to be fully submerged and for the calculations regarding the partially submerged mode, i.e. the thrust and torque coefficients, they multiplied the results by the immersion ratio. Kamen has introduced and reviewed SPP and comprised a few samples of surface drive systems with each other [12].

Olafsson conducted an experimental study on hydrodynamic performance of four-blade SPP model B-841. The purpose of the experiments was to examine the influence of shaft yaw and inclination angles on the propeller characteristics at different Froude and cavitation numbers. He investigated the effect of shaft yaw angle on the performance of propeller and stated that the efficiency of propeller is changed with change in shaft yaw angle [13]. Dyson performed a series of experimental tests on SPPs and measured mean and transient values i.e. thrust and torque [14]. He found the mean side and vertical forces of a SPP to be about 20% and 40% of the thrust, respectively. Ferrando et al. performed experimental tests on a systematic series of SPPs with various numbers of blades and pitch ratios and investigated the influences of immersion ratio and shaft inclination on their performances [15]. Young presented a three dimensional low-order potential based boundary element method for the nonlinear analysis of unsteady sheet cavitation on fully submerged and partially sub-merged propellers subjected to a time-depended inflow [16]. In the past, the BEM was only able to predict the performance of unsteady partial back cavitation on conventional fully submerged propellers and Young extended that to a three dimensional boundary element method to predict the performance of super cavitating and SPP. Caponetto used the RANSE solver Comet, and investigated the pressure and forces exerted on a SPP and compared his results with those of the references [17]. Peterson used a full scale SPP and showed that the efficiency of propeller can be increased up to 3% to 5% by changing the angle of the propeller shaft, relative to the movement of the craft [18]. A thorough analysis of full scale sea trial tests showed that during turning circle maneuvers, propeller power/torque demand increase up to 100% and 50% of the value in the approach phase(straight path) for the external (relatively to the center of the turn) and internal propellers, respectively [19]. Quantification of the loads is essential in order to develop suitable control system strategies for preventing excessive structural loads, while not reducing the operational capabilities of the vessel [20]. Broglia et al. used URANS method to analyze different propellers effects on maneuvering and turning circle [21]. Himei performed a RANS simulation and applied the VOF method and compared his results with experiments [22]. Yari and Ghassemi calculated hydrodynamic performance and ventilation flow around 3D SPP by using CFD and compared with experimental data [23]. During two last decades, Ghassemi et al worked on the design of the planing craft and design of the SPP [24,25,26].

2. HSPC and Selection of Drive System

Those craft in which a part of their body out of the water and craft gets to water skiing status with speed increasing is known as planing craft. Required lift to be skiing in these craft is created due to the hydrodynamic forces which supplied through drive systems and body form. Velocity-to-length ratio of the craft is used in most of the maritime standards to introduce HSPC. According to the ABS standard, velocity-to-length ratio of the HSPC must follow bellow equation [27].

$$\frac{V}{\sqrt{L}} \geq 2.36 \tag{1}$$

where V is velocity in knots and L is craft's length in waterline which is in m in the equation. In the other side according to Savitsky equation, a HSPC can reach to planing status when it can reach to Froude number greater than 1.2, in addition to following previous equation.

$$Fn \geq 1.2. \tag{2}$$

One of the main factors of velocity increasing in HSPC is to select proper drive system, as well as lower body resistance of these craft and designers try to increase the maneuverability of planing craft by utilizing from a high efficiency drive system and optimum designing of the body and decrease the time needed for their getting to skiing status. Considering the advantages and disadvantages of different drive systems designed around the world, authors of present study have tried to conduct an applied and effective comparison among some common designed drive systems using experiences and obtained technical knowledge in the field of design and selection of marine engines. In present study, an election priority number (EPN) has been allocated to each of the introduced drive systems based on the effective parameters of designing. This number has been obtained by multiplying a few other parameters.

2.1. Introducing EPN of Drive System

- Grade Number: grade number is a measurement from under study drive system potential in each under evaluation parameter. It is ranged from 0 to 10. Importance number: importance number is an index for the level of importance and effectiveness of under evaluation parameter in designing drive system with commercial approach. It is ranged from 0 to 10.
- EPN: It is a measurement from usability and selection of an appropriate drive system with optimized efficiency to manifest election priority of designers for craft and hull form. It is ranged from 0 to 100.

$$EPN = \frac{10 \times \sum_{i=1}^{n} (GN * IN)}{\sum_{i=1}^{n} (IN)} \tag{3}$$

where n is the number of selection criteria to investigate advantages and disadvantages of system.

2.2. Types of Surface Drive Systems

Nowadays, most of the engines of HSPC are from surface drive system type. However, other types of drive systems of planing craft have been also designed and made which among most successful of them one can refer to design and innovation of Howard Arneson from United States who used Boeing aircraft turbines as engine in drive system of his planing craft and moved speed record in the world. Surface drive system are divided in two main sub-groups of fixed surface drive systems and articulated surface drive systems. The only difference criterion between mentioned two groups is being fixed or articulated of shafts. Currently, it is recommended to use articulated surface drive systems in craft with a length of over 12 meters. Both groups of the mentioned drive system must use SPP to ski down the craft, because this type of propellers has higher hydrodynamic efficiency in high speeds compare to the submersible propellers.

The performance of semi-submersible propeller is shown with some parameters including Advance coefficient J, thrust coefficient K_T, torque coefficient K_Q and efficiency coefficient [26].

$$K_T = \frac{T}{\rho.n^2.D^2.A_O}, \quad K_Q = \frac{Q}{\rho.n^2.D^3.A_O}$$
$$\eta_O = \frac{K_T}{K_Q}.\frac{J}{2\pi}, \qquad J = \frac{V_A}{n.D} \tag{4}$$

where V_A is the velocity of propeller leading, n is rotational speed of propeller per second, D indicates propeller's diameter, T is thrust generated by the propeller, ρ indicates the density of water, Q is the torque required to drive the propeller and A_O is the area of immersed segment of the propeller disc. An important feature of surface drive systems is that whole of the system is installed on the transom wall and the propeller is placed on back of the craft's body (hull) instead of placing under it. Therefore, these systems are the best choice for shallow waters and the matter has caused to their popularity.

2.3. Introducing Fixed Surface Drive Systems

These systems are the first generation of surface drive systems which some of them have been comprised in present study. In these systems there is no possibility to change the angle of the moving shaft and the propeller is fixed on a certain position which depends on hull form, draft and weight of the craft. The systems utilize a separate and independence rudder and among their advantages one can refer to simply elements and appurtenance, low-cost maintenance, high reliability and ease of use. Among their disadvantages, it can be refer to no possibility of changing the amount of propeller immersion, risk off move in the shallow water, high sensitivity during installation, and limitation in propeller diameter and occasionally need to an especial transom to install drive system.

2.3.1. Q-Surface Piercing Dependability System

The successful company of Q-marine international in New Zealand is the designer of this drive system. Q-Surface Piercing Dependability System (Q-SPD) is in fact a designing innovation in the terms of system integration, components form as well as the use of resistant composite material [28]. Among the advantages of this system are High corrosion resistance, light weight, low noise while working and proper maneuverability. Lower fuel consumption of craft is another advantage of this system. The SD1 model of this system is from fixed shaft type. The system utilizes from a water line for cooling of bearing and also a line for supplying cooling water to rubber-bush and bearing lubrication is done by grease. A sample of this fixed shaft system has been shown in Figure 1 which designed to use in craft with engine power from 200 to 900 hp.

Figure 1. Q-SD1 Surface Drive

2.3.2. Levi Drive Unit

Levi drive unit (LDU) is another type of fixed surface drive systems which has been designed and constructed by German company of Levi Drives International. The products of this company have been designed to power range of 800 to 4000 hp. This system is distinctive for this inverted U-shaped rudder that encloses the propeller. Emissions from diesel exhaust are discharged as a spray at the top of the propeller disk to reduce load on the blades of the propeller and increase the speed and power of engine. Among the advantages of this system one can refer to simplicity and easy installation, high hydrodynamic efficiency, lower fuel consumption and low price [29]. A sample of this system has been installed on a 30 feet HSPC with a maximum speed of 40 knots with shaft angle of 8 degrees which shown in Figure 2.

Figure 2. Levi Drive Unit

2.4. Introducing Articulated Surface Drive Systems

Articulated surface drive systems are themselves divided into two main types; both of them are used in new HSPC. The first type of these systems are considered as the first generation of them in which the shaft can move only in vertical direction and known as Trimble propulsion system and one sample of them with appropriate hydrodynamic performance has been mentioned in present study. The second type of these systems are considered as the next generation of them in which propeller can move toward horizontal plate in addition to the Trimble and vertical movement and known as Trimble & Steerable drive systems. And two successful samples of them have been introduced in present study. This type of systems has no need to separate rudder due to the horizontal movement of its SPP and propeller beside the skeg blade mounted on the moving shaft work as a rudder. Among general advantages of articulated surface drive systems is reduced drag force of drive system during movement which reduces the forces of drag force up to 50% in high speeds, because resistance force has a direct relationship with second-order of craft's velocity ($R \propto V^2$). Another advantage increased acceleration and reduce time to ski. In contrast, it can be refer to lower reliability due to more articulated parts and higher maintenance costs (periodic maintenance and repair) compare to the fixed surface drive systems as their disadvantages.

2.4.1. Arneson Surface Drive System

Arneson Surface drive (ASD) system is one of the best-selling articulated surface drive systems in United States. This brand has been designed and made by American company of twin disc. The company has 95 years of experience since 1920 [30]. One of the advantages of this system is hydrodynamic efficiency. All models of this drive system have maximum Trimble ability up to 15 degrees and the maximum steering angle of them is 40 degrees (20° toward left and 20° toward right). An example of this system has been presented in Figure 3 which a power equal to 350 hp and utilizes from Rolla six-blade SPP. Rolla propeller is one of the brands of Twin disc Company [32].

Figure 3. Arneson Surface Drive

2.4.2. Q-SPD Surface Drive System

A sample of Q-SPD-TA model with Trimble capability has been presented in Figure 4 [28]. Trimble drive systems can reach to optimum efficiency in all speeds through adjusting the thrust of the propeller in the water and considering sea condition and the amount of craft's loads. One of the advantages of Trimble model of Q-SPD is that all of the jacks and hydraulic appurtenant of this system have been designed inside the hull and there is no moving parts outside the body. Therefore, it utilizes from a high reliability.

2.4.3. Top System Surface Drive

Italian company of Top system is articulated in the field of designing and constructing marine drive system and manufacturing variety of propellers. The products of this company in different models have been designed for power range from 350 to 4700 hp [31]. One of the advantages of this system is the capability of installing different types of diesel engines and propellers. An example of TS-55 of the system installed on a craft with two 1800 hp engines is shown in Figure 5. Each line drive in this model weighs about 500 kg and a maximum input torque of the motor is stopped about 2,600 meters. All models of the system have Trimble ability equal to 20 degrees (13° downwards and 7° upwards).

Figure 4. Q-SPD Surface Drive

Figure 5. Top system Surface Drive

2.5. Introducing Selection Criteria

It is clear that no drive system can lonely having optimum efficiency in different areas of usage. Therefore, the most proper drive system must be selected based on the type and sizes of the craft and its mission. But it is possible to evaluate general selection designing criteria of an optimum drive system. The criteria are constant and effective in most of the craft with any type of missions. Various factors and criteria are effective in selecting drive system of HSPC which listed in Table 1. In present study, these parameters have been used to select desired drive system and comprising three mentioned systems.

Table 1. Selection criteria of drive system

1	Ease of use system	6	Reliability
2	The ability of maneuver	7	Power to weight ratio
3	shaft trimming	8	Simply of equipment
4	Corrosion resistance	9	No need for special hull
5	Ease of installing to hull	10	Maintenance costs

2.6. Calculation of EPN Number and Comparing Introduced Systems

Table 2 and Figure 4 represent a comparison between fixed surface drive systems according to the selection criteria of drive system introduced in previous table and through allocating grade number and importance number to each parameter and final calculation of EPN. Numbering and final result must be investigated and confirmed by a designing analysis team with high knowledge and experiences. In present study, the calculated EPN for each system has been obtained based on the commercial approach and fieldwork and users' opinions have been also taken into account in calculations in addition to the numerical analyzes were carried out on some parameters. The importance number of each comparison must be considered the same for all of the under evaluation drive systems to obtain a valid final EPN. There is the possibility of change in importance and grade numbers, if the approach of systems' evaluation is explained with any purposes other than commercial approach. Hence, evaluation with other approaches can lead to different results and finally another product has priority.

2.6.1. Comparing Introduced Fixed Surface Drives

The direct comparison of articulated and fixed surface drive systems is not desirable due to the difference between their overall design of the shaft and rudder mechanisms and the nature of their use. Therefore, a separate comparison between introduced fixed surface drive systems has been conducted in Table 2 and Figure 6 based on the selection criteria of fixed surface drive systems.

Table 2. EPN of fixed surface drives

Row	Selection Criteria	(IN)	LDU	Q-SPDSD1
			(GN)	
1	Ease of use system	6	8	8
2	The ability of maneuver	7	8	10
3	shaft trimming	6	0	0
4	Corrosion resistance	6	6	8
5	Ease of installing to hull	6	8	9
6	Reliability	10	7	8
7	Power to weight ratio	7	7	9
8	Simply of equipment	5	9	7
9	No need for special hull	6	8	9
10	Maintenance costs	10	7	8
EPN			68.12	77.10

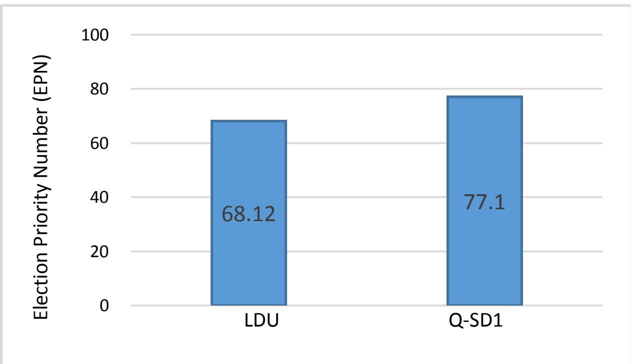

Figure 6. Comparison of the EPN of introduced fixed surface drives

Ease to installing and very good maneuverability of Q-SPD mode SD l, has been distinguished this system. However, its composite platform is vulnerable to shock because it is hollow. Also in some cases, excessive heat of coupling set has been reported in long maneuvers. New models of LDU system have proper reliability and have been designed in an integrated form as like Q-SPD system. In both of the systems, it is better that the coupling is designed with the capability of angle changing to facilitate assembly operations. Figure 7 represents model MY which is another sample of Q-SPD fixed surface drive system.

Figure 7. Q-SPD Surface Drive, model MY

2.6.2. Comparing Introduced Articulated Surface Drives

Table 3 also Figure 8 and Figure 9 are represented the comparison between articulated surface drive systems according to the selection criteria of drive system introduced in previous table and through allocating grade number and importance number to each parameter and final calculation of EPN.

Table 3. Calculating of the EPN of introduced systems

Row	**Selection Criteria**	**(IN)**	**ASD**	**TS**	**Q-SPD**
				(GN)	
1	Ease of use system	6	7	7	8
2	The ability of maneuver	7	9	9	5
3	shaft trimming	6	9	10	6
4	Corrosion resistance	6	7	7	9
5	Ease of installing to hull	6	7	7	8
6	Reliability	10	8	7	9
7	Power to weight ratio	7	7	7	8
8	Simply of equipment	5	9	8	6
9	No need for special hull	6	7	7	9
10	Maintenance costs	10	8	8	9
EPN			77.8	76.3	76.5

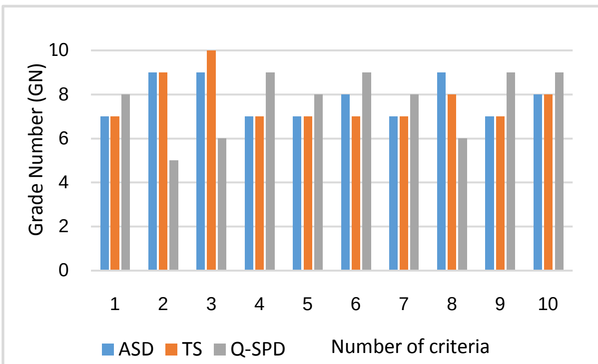

Figure 8. Comparison of the GN of introduced articulated systems

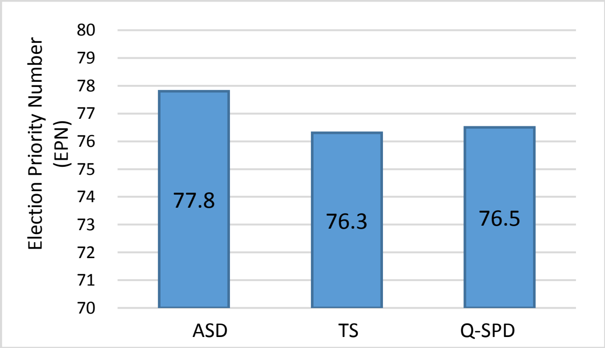

Figure 9. Comparison of the EPN of introduced articulated systems

All three comprised drive systems utilize from advantages which put them among most popular and best-selling engines in the world, but they differ in designing. Although Trimble surface drive of Q-SPD don't have steering ability but has a unique design and utilizes from proper hydrodynamic forces by using two rudder blades which optimally cover the propeller. However in cannot compete with articulated surface drive systems in which shafts have steering capability and have no separate rudder blades, because drag forces resulted by rudder angle during turning toward steering, reduces hydrodynamic efficiency leads to a decrease in craft speed. Designing composite structures of this system has led to corrosion resistance increasing and lightweight and in addition provides the capability for propeller to modify the influx and the speed of craft reach to its maximum amount in moving forward with zero steering angles. In addition, the exhaust ventilation of propeller has been properly used in integrated design of system and led that lower forces applied on the engine the moments before ski down the craft. Therefore, the craft is more accelerated and fuel consumption decreases.

The design of Top system surface drive has many similarities with the design of Arneson system engine and the matter has led these two systems have similar technical capabilities. But the most important difference in designing these to system is how to transfer the thrust force from fixed shaft to articulated shaft. The action is carried out by thrust ring in Top system which four brass balls have been used in its designing. In contrast, the action is carried out by thrust ball in Arneson system which has higher reliability. In addition, Top system has used conventional base-pin hydraulic jacks to connect jacks to transom. But Arneson system has used spherical base flanges in most of its models which improve the performance of system during the maneuver and mobility shafts. The drive designing is also unique in the Arneson drive system and its integrated and H-joint cardan reduces the total length of drive system and has higher reliability. In designing of new Arneson drive system (Figure 9) the mechanism connecting the two thrust line is done by tie-bar is changed and joint place of tie-bar has been replaced to upward. By this way, the drive system has more safety at sea and has higher reliability.

3. Conclusions

The importance and role of articulated surface drive systems in HSPC were described and three examples of successful articulated surface drive systems produced by three different countries were investigated and comprised. It is difficult to make detailed comparisons between introduced drive systems, because it is practically impossible to provide simultaneous test conditions for them with same type of engine and power transmission mechanism and a similar planing body. Therefore, the EPN is used in present study to comprise the systems. The results showed that Arneson drive system has allocated the highest EPN to itself and it can be said that high reliability and proper maneuverability is the turning point of this system. It seems that Twin Disc-old company, which is outstanding in manufacturing of power transmission parts in the world, has had better performance in designing Arneson drive system in the term of reliability and has allocated the highest score to itself. In addition, the company has allocated a larger share of the market accounted for the sale and installation to itself in the terms of credibility and its history. In an overall conclusion, it can be said that all of these three systems utilize from special and desirable capabilities and have their unique designing and innovation. In the term of comprising fixed surface drive systems, model SD1 of Q-SPD has allocated higher EPN value to itself compare to LDU system and it can be said that high reliability is the main advantage of this New Zealand system because all accessories including jacks and hydraulic hoses are installed inside the craft's hull. In further designing optimizations of this system, it is expected that two tapered roller bearings are used instead of a wing angular contact bearing, because the thrust force is imposed from two directions in forward and backward movement. As an overall conclusion, it can be said that the ratio of annual maintenance of Q-SPD fixed surface drive system to its initial cost is appropriate for users and owners of small size craft and is a user-friendly propulsion system in the term of technical features. In the near future, it will be possible to observe designs of integrated surface drive systems with very high reliability, even in multi-hull craft.

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