Use of Hydro Generator on a Tanker Ship: A Computer-Generated Simulation Study

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Abstract. Considering ways of utilizing renewable energy sources in the marine environment, the possibility of fitting a ducted hydro generator on the hull of an existing 157 209 gross tonnage tanker ship was investigated. A three-dimensional (3D) model of the hydro generator was created and, using computational fluid dynamics (CFD) analysis, flow simulations were conducted to determine the additional hull resistance when a hydro generator is virtually fitted on the ship's hull. The additional hull resistance converted to resistance power was necessary to find out the net power of the hydro generator and determine its effectiveness and impact on the ship's fuel consumption. Using the characteristics of the tanker ship in study, an estimated 3.46% in fuel savings was obtained with the use of the hydro generator.

This study showed the design concept and computer-generated simulation carried out to analyze the performance of the hydro generator when integrated to the tanker ship running at full-speed sea condition of 15.5 knots with a head and tail water current velocity range of up to 2.5 m/s.

Keywords: computational fluid dynamics, hydro generator, renewable energy.

1 Introduction

The marine environment, mainly composed of vast oceans, can be considered as one of the largest unexploited renewable energy sources on our planet. Finding means of harvesting the available energy from these oceans can greatly contribute in addressing the current environmental issues on global warming and sustainability [1].

For navigating ships, considering the kinetic energy around the hull as it moves, predictable amount of wave energy can be extracted from the water. This can be made possible by a hydro generator, which is also termed "tidal generator". It operates under the principle of capturing and converting the kinetic energy and flow-pressure energy (if ducted) of the moving water into electrical energy. This energy, converted

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into power, can be directed to the ship's main bus bar to support power generation onboard.

This paper investigated the possibility of installing a hydro generator on an existing tanker ship, in a manner as shown in Fig. 1, having the following characteristics:

Length, Overall	329.99 m
Length, Between Perpendiculars	316.00 m
Breadth, Moulded	60.00 m
Depth, Moulded	29.70 m
Draft Loaded, Moulded	19.20 m
Deadweight	259 994 ton
Gross Tonnage	157 209
Net Tonnage	99 808
Speed	15.50 knots
Main Engine (ME) Output at Maximum Continuous Rating (MCR)	25 090 kW
ME Speed	78.60 rpm
ME Specific Fuel Consumption (SFC) at MCR	168.50 g/kW-h
Diesel Generator (DG) Rated Output	1 020 kW x 3
DG SFC	195.00 g/kW-h

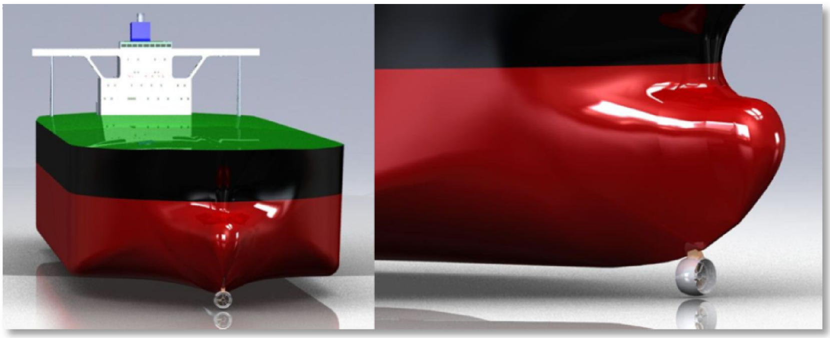


Fig. 1. Graphic conceptualization of the hydro generator fitted on the bow of the tanker ship in study

It is intended to provide the ship's electrical power requirement when the ship is running at full speed. This will reduce fuel consumption required to generate electrical power onboard, aside from the advantages brought about by the use of renewable energy.

Using a computer-aided design (CAD) software and the best dimension and scale available for a ducted hydro generator, a 3D model was created. Thereafter, CFD analysis was used to determine the increase in ship's hull resistance due to the fitting of the hydro generator. The additional hull resistance, converted to resistance power was necessary to examine the generator's estimated net power and its effect on the ship's fuel consumption.

2 Theory

Conversion of the linear movement of a flowing fluid into a useful rotational movement is usually done using a turbine. The power, P_T, in W harnessed by the turbine, is decided by its sweep area, A, in m^2, according to

$$P_T = \tfrac{1}{2} C_p A \rho_{fluid} V^3 \tag{1}$$

where C_p is the power coefficient, ρ_{fluid} is the fluid density, in kg/m^3, and V is the fluid velocity, in m/s.

Not all of the extracted energy from the fluid is converted to other energy forms. In this case, wherein electrical energy is desired, the non-conversion is due to the losses in the system, as shown in Fig. 2.

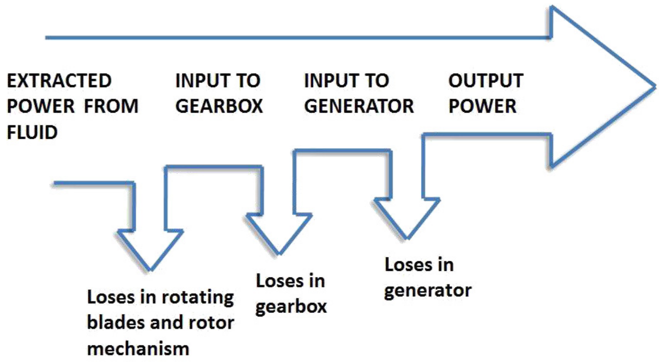


Fig. 2. Power flow of a turbine energy extractor

To find the turbine's generated electrical power output, P_{out} in W, the power, P_T, is multiplied by the blade efficiency, η_{blade}, gearbox efficiency, η_{gear}, and generator efficiency, η_{genr}, which can be written as

$$P_{out} = P_T (\eta_{blade} \eta_{gear} \eta_{genr}) . \tag{2}$$

For output power estimation, blade efficiency of 90%, gearbox efficiency of 95% and generator efficiency of 70% can be assumed [2].

There are different turbine types and designs that can be used to extract energy from a moving fluid [3]. In view of the benefits of putting a duct or shroud around a turbine, a ducted water turbine was considered in this investigation.

A duct surrounding a turbine serves as a convergent-divergent diffuser which creates a drop in fluid pressure behind (downstream) the rotor blades, allowing increased fluid flow through the turbine, thereby increasing the power. In addition, a ducted or "diffuser-augmented" turbine eliminates tip losses on axial flow turbine blades and improves efficiency. It is not subject to the Betz limit which defines an upper limit of 59.3% of the incident kinetic energy that can be converted to shaft power by a single actuator disk turbine in open flow [4]. Increase in theoretical maximum power coefficient for a diffuser-augmented turbine of up to 3.3 times higher than the Betz limit of 59.3% has been claimed [5]. Experimentation with wind tunnel models even reported a power augmentation factor of 4.25 for a turbine with a diffuser, producing 4.25 times as much power than the same turbine in open flow [6]. Actual test data have also shown increase in performance by a factor of about 3 when a duct was added to a water turbine [4].

The seeming violation of the Betz law by ducted turbines in extracting more energy from the fluid than what is available arises from the C_p formula, which can only calculate the percentage of kinetic energy extracted from the fluid. Ducted turbines capture not only the kinetic energy but also certain percentage of the flow-pressure energy. In this study, an augmentation factor of 3 or a power coefficient, C_p, of 1.77 was used.

To calculate the hydro generator's generated power, relative water current velocities with respect to the ship were considered. While the ship is running in the open sea, the water current may flow from different directions with different magnitudes. This can greatly influence the power produced by an open flow hydro generator. However, this might not hold true for a ducted hydro generator. Due to the duct surrounding the turbine, only the head and tail water current will have considerable effect on energy extraction and power conversion. Also, the ship's cruising speed of 15.5 knots or 7.97 m/s is expected to ensure positive power in most conditions. In this investigation, a head and tail water current velocity range of up to 2.5 m/s was considered [7-8].

3 Method

The results and findings of this computer-generated simulation study were based on the calculation of (1) generated power, (2) resistance power, (3) net power, (4) fuel consumption – taking into consideration the additional resistance power and (5) fuel savings – obtained by comparing the consumption when using the diesel generator with the hydro generator.

3.1 Generated Power

The hydro generator's generated power was calculated using Equations (1) and (2). A 2.5-m turbine diameter was initially selected for the hydro generator with a hub of

20% or 0.5 m. The effect of water velocity from two directions (head and tail current flow) on the generated power was examined with the ship running on full speed sea condition. The generated output power is shown in Table 1.

Table 1. Generated power of the hydro generator on up to 2.5 m/s water current

Turbine Diameter (m)	Water Current (m/s)	Relative Velocity, V_R (m/s)		Generated Power (kW)		Average Generated Power (kW)
		Against the Current	With the Current	Against the Current	With the Current	
2.50	0.00	7.97	7.97	1294.57	1294.57	1294.57
	0.50	8.47	7.47	1553.83	1065.89	1309.86
	1.00	8.97	6.97	1845.57	865.87	1355.72
	1.25	9.22	6.72	2004.22	776.00	1390.11
	1.50	9.47	6.47	2171.71	692.57	1432.14
	2.00	9.97	5.97	2534.18	544.10	1539.14
	2.50	10.47	5.47	2934.89	418.52	1676.71

3.2 Resistance Power

Drag resistance plays a vital role in considering the net power benefitted from the hydro generator. The main engine needs to burn more fuel and produce more power to overcome this resistance in order to propel the ship and maintain its speed.

To determine the resistance power, a 3D model of the hydro generator was created using a CAD software, as seen in Fig.3, with the best dimension and scale available for ducted tidal turbines.

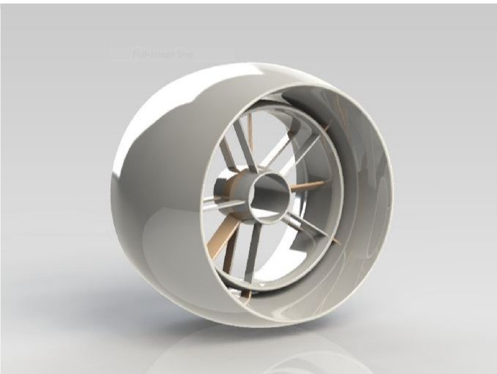


Fig. 3. Hydro generator 3D model

CFD analysis (Fig.4) was then used to estimate the drag brought about by the integration of the hydro generator to the ship. “Flow Simulation”, a CFD analysis program embedded in SolidWorks® was used. It solves the Navier-Stokes equations, which are formulations of mass, momentum and energy conservation laws for fluid flows. It employs one system of equations to describe both laminar and turbulent flows.

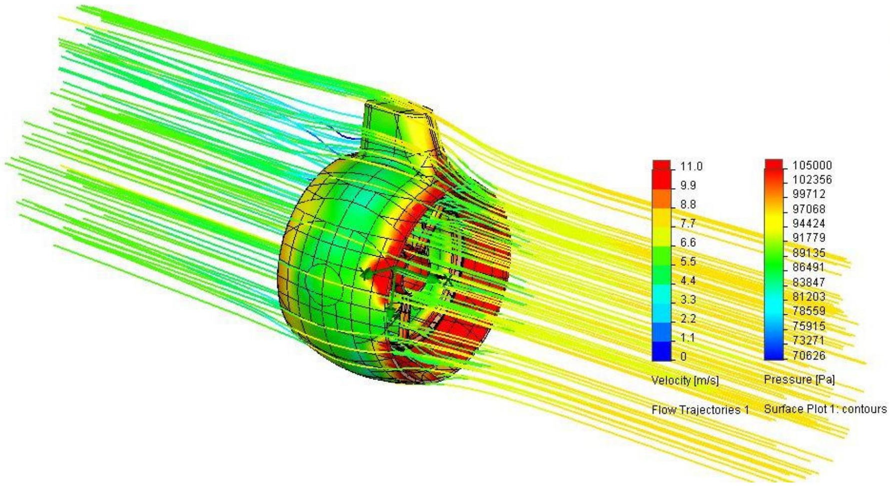


Fig. 4. CFD analysis on the hydro generator with bracket to estimate drag

In fluid dynamics, drag, sometimes called fluid resistance, refers to forces that oppose the relative motion of an object through a fluid, which is, in this case, water. Drag forces act in a direction opposite the oncoming flow velocity. Unlike other resistive forces such as dry friction, which is nearly independent of velocity, drag forces depend on velocity. For a solid object moving through a fluid, the drag is the component of the net aerodynamic or hydrodynamic force acting opposite to the direction of the movement [9]. Therefore, drag brought about by the integration of the aero and hydro generators to the ship opposes its motion and has to be overcome by additional propeller thrust. The power, P_R, in W to overcome fluid resistance or drag is equivalent to

$$P_R = F_D V \tag{3}$$

where F_D is the drag force, in N, and V is the fluid velocity, in m/s.

From the CFD analysis conducted, drag results were converted to equivalent resistance power using Equation (3) and are shown in Table 2.

Table 2. Drag and resistance power of the hydro generator on up to 2.5 m/s water current.

Water Current (m/s)	Relative Velocity V_R (m/s)		Drag (kN)		Resistance Power (kW)		Average Resistance Power (kW)
	Head Water Current	Tail Water Current	Head Water Current	Tail Water Current	Head Water Current	Tail Water Current	
0.00	7.97	7.97	33.02	33.02	263.17	263.17	263.17
0.50	8.47	7.47	37.23	28.99	296.72	231.05	263.89
1.00	8.97	6.97	41.82	25.15	333.31	200.45	266.88
1.25	9.22	6.72	44.17	23.42	352.03	186.66	269.35
1.50	9.47	6.47	46.51	21.70	370.68	172.95	271.82
2.00	9.97	5.97	51.54	18.62	410.77	148.40	279.59
2.50	10.47	5.47	56.87	15.66	453.25	124.81	289.03

3.3 Net Power

In this study, the net power is the ultimate beneficial power obtained from the hydro generator, measured as the generated power less the resistance power. A summary of the powers obtained, including the net power for the hydro generator is shown in Table 3.

Table 3. Power summary

Water Current (m/s)	Generated Power (kW)		Resistance Power (kW)		Net Power (kW)		Average Net Power (kW)
	Head Water Current	Tail Water Current	Head Water Current	Tail Water Current	Head Water Current	Tail Water Current	
0.00	1294.57	1294.57	263.17	263.17	1031.41	1031.41	1031.41
0.50	1553.83	1065.89	296.72	231.05	1257.10	834.84	1045.97
1.00	1845.57	865.87	333.31	200.45	1512.26	665.42	1088.84
1.25	2004.22	776.00	352.03	186.66	1652.18	589.34	1120.76
1.50	2171.71	692.57	370.68	172.95	1801.03	519.62	1160.32
2.00	2534.18	544.10	410.77	148.40	2123.41	395.69	1259.55
2.50	2934.89	418.52	453.25	124.81	2481.64	293.71	1387.67

3.4 Fuel Consumption

The tanker ship considered in this study was equipped with 3 diesel generator engines to generate electrical power supply. While running on full-speed sea condition, a 960 kW diesel generator engine supplied all the necessary electrical power requirement.

To maintain the ship's speed, the main engine needed to overcome the resistance brought about by the hydro generator's integration. This meant that the main engine had to produce more thrust and thus, would require additional fuel consumption. Considering the main engine's SFC at maximum continuous output of 168.5 g/kW-h, the additional main engine fuel consumption to develop more thrust to overcome the resistance of the hydro generator is shown in Table 4. This will also give an average additional fuel oil consumption of 45.8 kg/h.

Table 4. Additional fuel oil consumption to overcome hydro generator average resistance

Water Current (m/s)	Drag (kN)		Resistance Power (kW)		Average Resistance Power (kW)	Additional Fuel Consumption to Overcome Average Resistance (kg/h)
	Head Water Current	Tail Water Current	Head Water Current	Tail Water Current		
0.00	33.02	33.02	263.17	263.17	263.17	44.34
0.50	37.23	28.99	296.72	231.05	263.89	44.46
1.00	41.82	25.15	333.31	200.45	266.88	44.97
1.25	44.17	23.42	352.03	186.66	269.35	45.38
1.50	46.51	21.70	370.68	172.95	271.82	45.80
2.00	51.54	18.62	410.77	148.40	279.59	47.11
2.50	56.87	15.66	453.25	124.81	289.03	48.70

To sustain the ship's electrical power requirement at full speed sea conditions, the hydro generator considered in this study has to generate 960 kW of electrical power, equivalent to one diesel generator engine which supplied all the electrical power requirement when the ship was running at full speed.

In the condition wherein the diesel generator engine was running to supply the ship's electrical power requirement on full-speed sea condition, the fuel consumption was obtained, taking the maximum rated output of both main and diesel generator engines. Table 5 reflects the data.

Table 5. Main and diesel generator engine fuel consumption at full speed sea condition

	Specific F.O. Cons. (g/kW-h)	Max. Continuous Output (kW)	Fuel Cons. (kg/h)
Main Engine	168.50	25,090	4,227.70
Diesel Generator Engine	195.00	1,020	198.90
(AC Generator)		(960)	
Total			4,426.60

4 Results

The 2.5-m turbine diameter hydro generator had a calculated average generated power which met the 960 kW power requirement of the ship under study, regardless of water current direction, as shown in Fig.5.

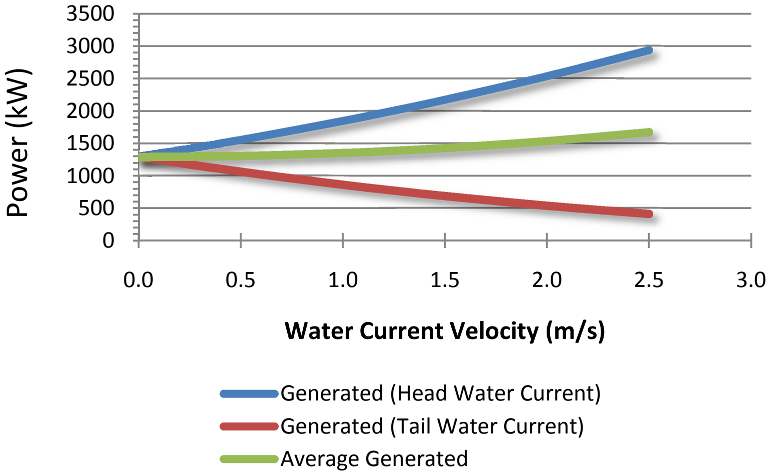
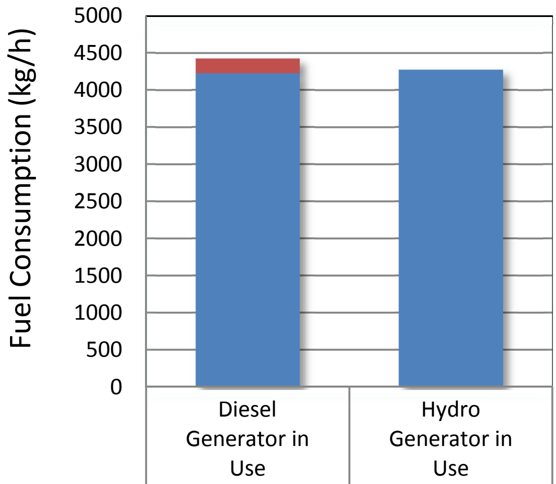


Fig. 5. Generated and average generated power of the hydro generator at different water current velocities (ship at 15.5 knots)



	Diesel Generator in Use	Hydro Generator in Use
DG Consumption	198.90	0.00
ME Consumption	4227.70	4273.50

Fig. 6. Comparison of the calculated fuel consumption using a diesel generator and hydro generator at full speed sea conditions

As the hydro generator supplies the electrical power requirement when the ship is running at full speed, no diesel generator engine is operated. This reduces the ship's total fuel oil consumption by eliminating the need to operate a diesel generator engine for generating electrical power.

A comparison of the calculated fuel consumption using a conventional diesel generator and a hydro generator - taking into account the additional main engine fuel consumption to overcome resistance due to its integration, is shown in Fig.6. A reduction in fuel consumption of 153.1 kg/h can be obtained. This was equivalent to 3.46% of the 4 426.6 kg/h combined rated main and diesel generator engine fuel consumption at full speed sea condition. This meant savings of 3.46%.

5 Discussion

The hydro generator arrangement can be integrated to the ship's electrical power plant similar to shaft generator systems, which are already in existence. It is connected in line when the ship is running at its rated rpm. For safety reasons, one stand-by diesel generator should be readily available whenever the hydro generator is in use. Since its operation is affected by the water current's direction and velocity, its variable frequency and voltage output have to be converted into fixed voltage and frequency to match with machinery requirement. The use of a rectifier/inverter module can help address this concern, which operates by rectifying the variable frequency into direct current (DC) which is later inverted into fixed frequency alternating current (AC). The power management system onboard ships may provide a central place to make efficient utilization of all the electrical power as shown in Fig. 7. It usually includes the mode controllers, power flow meters, transfer switches and protection circuit breakers, and battery charge and discharge regulators.

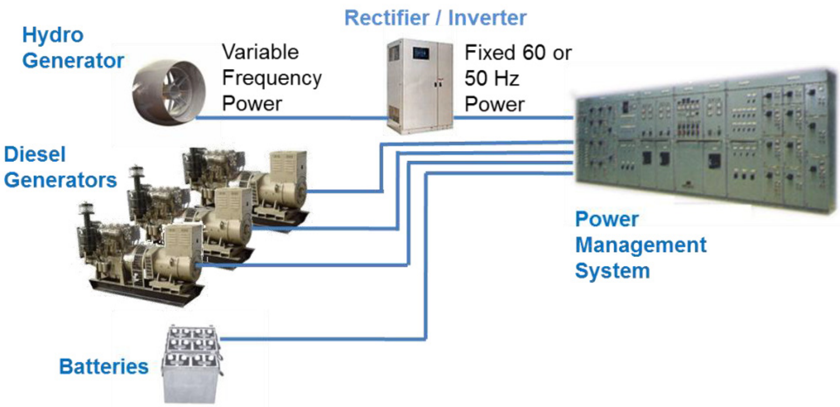


Fig. 7. Power management system layout

Then again, unlike tidal turbine generators which operate at lower water velocities, the hydro generator integrated in the ship's hull should be designed and constructed to operate at higher water velocities and withstand the sea forces and vibration experienced by the ship during adverse weather condition.

For the protection of marine life, a hollow turbine center with shrouded blade tips, non-usage of hydrocarbon-based lubricants and very low operating frequency sound are only some of the safety features available in some hydro generator designs [10-11].

On maintenance issues and concerns, there are hydro generators wherein maintenance schedule may be made to coincide with the ship's drydocking period. For instance, Clean Current's tidal turbine generators are constructed with a bearing system seal which is scheduled for replacement every 5 years and with the generator overhaul scheduled every 10 years. Moreover, these tidal turbine generators are designed for a service life of 25 to 30 years [10], which can be considered even longer than a ship's average service life.

In 2005, the unit capital cost of tidal turbine generators ranged from USD 1 700 to 2 000 per kW [12-13]. To date, it is estimated that the market is at USD 2 000 to 3 000 per kW [10]. Nonetheless, there are some makers who claim to achieve a target capital cost of less than USD 1 610 per kW [14]. Taking the average of these figures, which is equivalent to USD 2 055 per kW, a 960 kW hydro generator may be estimated to incur a capital cost of USD 2 million, with a total annual operation and maintenance cost estimated at USD 82 000 [12]. Taking this into consideration and with a zero salvage value, a payback period of 5 years can be expected.

With an average annual sea time of 264 days or 6 336 h for the ship in study [15] and with a bunker price of IFO 380 at USD 505 per ton (991 kg/m3 density) [16], an estimated annual savings of USD 489 871 can be projected with the use of a hydro generator.

6 Conclusion

Theoretical data obtained in this study approves the use of a hydro generator as another means to supply the tanker ship's electrical power requirement at full-speed sea conditions using renewable energy source. With the appropriate size of turbine diameter, it can theoretically generate the required power, regardless of water current velocity and direction. Also, taking into consideration the estimated savings in fuel consumption, capital and operational cost recoveries and amortization benefits can be realized within the first quarter of the equipment life cycle. Since the benefits in using hydro generators can be enjoyed during full-speed sea conditions, tanker ships, which spend most of their time at sea, can be expected to benefit more from such applications.

7 Recommendation

It is recommended that further studies be conducted on the validation of the simulation results presented in this paper. This is to determine the degree to which the model accurately represented the real world from the perspective of its intended use. Tests using scaled model on a towing tank may also be considered. Studies should include identification of the best efficient location on the hull where to affix the unit, including the design of the hydrodynamic mounting or means of attachment that will integrate it to the ship.

One issue that is of concern is the protection of marine life. Although there are tidal turbines designed with a hollow center, means of protection should still be installed to protect sea creatures from being caught by the rotating turbine blades.

In terms of design and construction, the hydro generator integrated in the ship's hull should be able to operate at higher water velocities. This is contrary to tidal turbine generators which are driven by tidal currents and operate at lower water velocities. The hydro generator's strength, durability and reliability, being located underwater, should also be taken into consideration to withstand pounding and slamming in harsh weather conditions. Vibration that could be brought about by its integration should also be looked into. Safety of Life at Sea (SOLAS) requirements and classification society rules on the use of hydro generators on ships are other important areas of further research.

As regard the ship's characteristics, the effects on hull center of buoyancy, trim, dynamic stability, seakeeping at all headings including the ease of maneuvering are some other things which should be further looked into. Drag effects to the ship running at a lower rpm and during maneuvering are other concerns.

Possibility of installing hydro generators on other ship types could also be explored.

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