Theoretical and Numerical Analyses on Propulsive Efficiency of Unmanned Aquatic Vehicle’s Propeller

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Abstract. Hydrodynamic effects are severely affecting the performance of a Marine Propeller. Basically, maneuvering of an Unmanned Aquatic Vehicle’s is controlled by its propeller, which is drastically depends on the fluid. Therefore the study about fluid behaviour and its effects are mandatory to enhance the efficiency of the marine propeller. In this work deals, the hydrodynamic force estimations on the marine propeller by using both theoretical formulae and numerical analysis. The aim of this work is to obtain the fine tuned hydrodynamic forces of marine propeller for its performance enhancement. Fundamentally, complexities involved in the force estimation approaches are represent the fluid behaviour and environmental conditions. Standard formulae are used for estimations of hydrodynamic forces. CATIA is used for the generation of conceptual design on the marine propeller. ANSYS Fluent 16.2 is used for numerical simulation, in which fluid is provided the ocean water properties. Finally, the hydrodynamic forces are compared for future work.

1. Unmanned Aquatic Vehicle’s Propeller

In general, a smart way of handling the hydrodynamic forces can able to provide the safe and secure mission to marine vehicles [1]. Rotor components such as marine propeller, hydro rotor, etc., are playing the predominant role in the dealing of hydrodynamics forces in an efficient manner [2]. To increase the efficiency of the marine propeller, design study about propeller and its hydrodynamic outputs are mandatory fields to do the modifications [3]. Generally, two or more number of blades are twisted and equipped in the marine rotor for successful dealing of hydrodynamic fluids [4]. The design parameters such as individual blade twist, diameter of the rotor are precise, which needs to be accessed in a right manner for continuous mission execution [5]. Stainless steel and Aluminium alloys are familiar materials, which are implemented in the construction of marine propeller [6]. And currently, the advanced structural load withstanding capable composites are also implementing in the construction of marine propeller, in which Carbon Fiber Reinforced Polymer (CFRP), Glass Fiber Reinforced Polymer (GFRP) and Kevlar. Comparatively Kevlar and GFRP have good impact resistance than other materials, and thereby its implementations are executed everywhere.
2. Problems and Solution to Unmanned Aquatic Vehicle’s Propeller

Generally, utilization of energy of working fluid is lack in the fluid based applications such as marine and air [7]. Primarily, research on the rotor profiles will provide the path to energy extraction in an efficient manner [8]. Also, perfect execution of maneuvering of a marine vehicle and its components high life time are more user needed factors [9]. Hence before the practical implementation, there must be an engineering research to analysis the hydrodynamic forces and their side effects on components for successful execution [10]. Especially fundamental studies about of impact forces on components, fatigue life estimation, material selection are mandatory for efficient execution of mission [11]. Instead of experimental study, theoretical and numerical analyses are used everywhere due to their flexibility [12]. In this work, hydrodynamic forces on propeller are estimated and compared each other with the help of theoretical and numerical methods for the purpose of tackling of forces [13]. In the evaluation, standard fluid formulae are used for the estimation of all hydrodynamic forces on the propeller [14]. Also, numerical analysis on propeller is executed for verification purpose, in which fluid density and their operating pressures are predominately contributes towards the representation of ocean water environments in the simulation. Finally the efficiency and minimum power requirement of the rotor are obtained for the further process [15]. From these outputs, the working speed range of UAVs and mass range of the UAVs are obtained.

3. Numerical Simulation

Numerical simulation is one of the advanced methodologies involved in the engineering problems, which can be able to solve complicated environmental issues [16].

Figure 1. Conceptual design of marine propellers
In this work static and steady conditional based solver used for the prediction of hydrodynamic forces on the marine propeller [17]. Based on this prediction, the performance and specifications of marine propeller are needs to be evaluated [18]. Generally, generation of physical model, construction of finite volume model and solver are the primary steps involved in the numerical simulation, in which first phase output is shown in the figure 1. The advanced modelling tool CATIA is used to design the model of this 10 inch diameter marine propeller [19]. The fine finite volume model is shown in the figure 2, in which the wireframe mode enabled in order to generate clear view of the tool body. There are variety number of forces are acting on the marine propellers that are analyzed using Ansys Workbench 16.2. In which, drag and lift forces are contributed a lot in the optimization process. Pressure distributions on the marine propeller are predicted, which are revealed in different perspective in the figures 3 and 4. The maximum pressures are acting in the frontal part of the marine propeller, in which the energy transfers take places drastically. At frontal part of the marine propeller, the stagnation point may chance to occur, in which the velocity of the fluid is presence at very low velocity and therefore the kinetic energy is transferred to potential energy of the fluid [20, 21]. Figure 5 and 6 revealed the velocity variations on the marine propeller in different views for the given boundary conditions. In velocity contours, initially the velocity of the fluid is in the low speed condition and later on it reached reasonable speed rang at exit area because of the profile of marine propeller.

![Figure 2. Finite Volume model of the marine propeller](image_url)
Figure 3. Pressure variations on the front side of the marine propeller

Figure 4. Pressure variations on the back side of the marine propeller
Figure 5. Representation of Velocity streamlines on the back view of marine propellers

Figure 6. Representation of Velocity streamlines on the front view of marine propellers
3.1. Comparative analysis

The drag force, rotational force, pressure distributions and velocity variations are predicted for all the velocities, which are noted and listed in table 1.

**Table 1. Comparative analysis**

| Sl. No | Velocity (m/s) | Pressure (Pa) | Velocity Variations (m/s) | C_D | C_L | Drag Force (N) | Torque (N-m) |
|--------|----------------|---------------|---------------------------|-----|-----|----------------|--------------|
| 1.     | 5              | 0.1305×10⁵    | 7.039                     | 2.2468×10⁻³ | 1.2343×10⁻⁷ | 460.585       | 8.7665       |
| 2.     | 10             | 0.5166 ×10⁵   | 14.38                     | 8.9468×10⁻³ | 6.1279×10⁻⁷ | 1834.1        | 34.898       |
| 3.     | 15             | 1.159 ×10⁵    | 21.78                     | 2.0090×10⁻² | 4.1730×10⁻⁷ | 4118.63       | 78.334       |
| 4.     | 20             | 2.050×10⁵     | 29.13                     | 3.5665×10⁻² | 3.5990×10⁻⁶ | 7311.39       | 138.99       |
| 5.     | 25             | 3.217 ×10⁵    | 36.64                     | 5.5662×10⁻² | 2.1056×10⁻⁶ | 11410.7       | 216.84       |
| 6.     | 30             | 4.633 ×10⁵    | 44.10                     | 8.0096×10⁻² | 4.9888×10⁻⁶ | 16419.7       | 311.94       |

4. Theoretical Estimation Forces acting on the Unmanned Aquatic Vehicle’s Propeller

4.1. Force calculations

Naturally, three forces are acting on Unmanned Aquatic Vehicle (UAV), which are thrust, drag and weight. Thrust force is a forward force, which is primarily depends on the fluid properties of a medium and the profile of the marine rotor. The primary requirement of the forward force is must tackle the weight and drag. Drag force is an opposing force, which relays on the nature of fluid and outer boundary of the UAV. Finally, weight is downward force, which because of own UAV’s weight and depended gravity of an earth. Nowadays, weight reduction plays an important role in every perspective in order to get high efficiency [22].

4.1.1. Weight

Weight of the Marine Aluminium Alloy Propeller

Density = 2710 kg / m³
Volume of the marine propeller = 7.0007 X 10⁻⁵ m³
Mass of the propeller = 2710 X 7.0007 X 10⁻⁵ m³
Weight = mass x acceleration = 0.18971897 x 9.81 = 1.8611430957 N

Weight of the Marine Stainless steel Propeller

Density = 7700 kg / m³
Volume of the marine propeller = 7.0007 X 10⁻⁵ m³
Mass of the propeller = 7700 X 7.0007 X 10⁻⁵ m³
Weight = mass x acceleration = 0.5390539 x 9.81 = 5.288118759 N

Weight of the Marine Kevlar Propeller

Density = 1470 kg / m³
Volume of the marine propeller = 7.0007 X 10⁻⁵ m³
Mass of the propeller = 1470 X 7.0007 X 10⁻⁵ m³
Weight = mass x acceleration = 0.10291029 x 9.81 = 1.0095499449 N

Weight of the Marine GFRP Propeller

Density = 1800 kg / m³
Volume of the marine propeller = 7.0007 X 10⁻⁵ m³
Mass of the propeller = 1800 X 7.0007 X 10⁻⁵ m³
Weight = mass x acceleration = 0.1260126 x 9.81 = 1.236183606 N

Weight of the Marine CFRP Propeller

Density = 1600 kg / m³
Volume of the marine propeller = 7.0007 X 10⁻⁵ m³
Mass of the propeller = 1600 X 7.0007 X 10⁻⁵ m³
Weight = mass x acceleration = 0.1120112 x 9.81 = 1.098829872 N

4.1.2. Drag Force

Drag force is given by: 
\[ F_D = 0.5 \times C_D \times \rho \times v^2 \times A \]  
(1)
Coefficient of drag \( C_D \) is
Hence, drag force comes out to be:
\[ F_D = 0.5 \times 1025 \times 100 \times 0.071966 \times C_D \]
\[ F_D = 368.2575 \times C_D \]
Coefficient of drag \( C_D \) is 0.035665 (From the numerical simulation)
Hence, drag force comes out to be:
\[ F_D = 0.5 \times 1025 \times 400 \times 0.071966 \times C_D \]
\[ F_D = 14753.03 \times 0.035665 = 526.1668 \text{ N} \]

4.1.3. Thrust Force

The thrust force on a blade is given approximately by:
\[ F_T = 0.5 \times A \times \rho \times [v_e^2 - v_i^2] \]  
(2)
For the sample case, input velocity of 20 m/s is taken, and the exit velocity of 29.13 m/s is predicted with the help of static analysis of CFD numerical tool.
\[ F_T = 0.5 \times 0.071966 \times 1025 \times [(29.13)^2 - (20)^2] \]
\[ F_T = 0.5 \times 0.071966 \times 1025 \times 448.5569 \]
\[ F_T = 16543.934 \text{ N} \]

4.1.4. Lift Force

The lift force on a blade is given approximately by:
\[ F_L = 0.5 \times C_L \times \rho \times v^2 \times A \]  
(3)
Now, the area \( A \) is the area of the total rotor disk. So, area \( A \) is given by:
\[ A = \pi R^2 \]  
(4)
Here, Radius = 0.15132175 m so, area of the rotor disk is:
\[ A = 0.071966 \text{ m}^2 \]
Here \( C_L \) is 0.0000035990 (from the numerical simulation)
Density of ocean water is \( \rho = 1025 \text{ kg/m}^3 \).
Hence the lift force comes out to be:
\[ F_L = 0.5 \times C_L \times \rho \times v^2 \times A \]
\[ F_L = 0.5 \times 1025 \times 400 \times 0.071966 \times 0.0000035990 \text{ N} \]
\[ F_L = 14753.03 \times 0.0000035990 = 0.05309615497 \text{ N} \]

All the primary forces are obtained with the help of standard formulae and numerical simulation’s output. In which, thrust estimation must be greater than weight and drag, in order to provide the successful forward movement of the UAV. From the theoretical and numerical studies, the overall maximum opposing forces values are 531.454918759 N and 7316.678118759 N respectively, which includes the maximum weight of the marine propeller and its corresponding drag forces. The forward force is calculated, which is 2.26 times greater than maximum opposing forces and the difference between the force values is 940.6 kg. Finally, it is understood that, the remaining
940.6 kg used for the purpose of UAV’s adaptation and thereby the chosen marine propeller is suitable to handle the UAV’s weight range of 500 kg to 1000 kg.

4.2. Propulsive Efficiency of the Marine Propeller

The main application of this work is to find the fish in the ocean with the help of Unmanned Aquatic Vehicle, in which the maximum velocity of the eatable fishes are estimated, that is 30 m/s. So in this work executed the comparative analysis and efficiency, power requirement for the maximum speed case i.e., 30 m/s [1].

Thrust = 38535.2832 N
Unmanned Aquatic Vehicle’s speed $v_s = 30$ m/s
Density water = 1025 kg/m$^3$
Diameter = 0.3026434866308 m

\[
\eta_{\text{Propulsive}} = \frac{2}{1 + \left( \frac{T}{Av^2 \rho / 2} + 1 \right)}
\]

\[
\eta_{\text{Propulsive}} = \frac{38535.2832}{0.071966 * 30^2 * 1025 / 2 + 1}
\]

\[
\eta_{\text{Propulsive}} = 63.27 \%
\]

4.3. Ideal (minimum) Power

This is the ideal (minimum) power required to drive the propeller. In general, the actual power required would be about 15% greater than this [1].

\[
Power = \frac{1}{2} * T * v * \left[ \left( \frac{T}{A * v^2 * \rho / 2} + 1 \right)^{\frac{1}{2}} + 1 \right]
\]

\[
Power = \frac{1}{2} * 38535.2832 * 30 * \left[ \left( \frac{38535.2832}{0.071966 * 30^2 * 1025 / 2} + 1 \right)^{\frac{1}{2}} + 1 \right]
\]

\[
Power = 1427732.2426445 \text{ Watts}
\]

The minimum power requirement and efficiency of the 10 inch diameter of marine propeller are calculated for peak condition i.e., 30 m/s. From the results, it have been noted that, the selected marine propeller and its geometrical parameters are unfit to work at 30 m/s. But the safest zones are found out from this negative output, which is nothing but the working range of this 10 inch diameter marine propeller. From the calculation, it is noted that, the selected marine propeller is more fit work in between the 15 m/s to 20 m/s and also fit to work in between the velocity range of 20 m/s to 25 m/s.

5. Conclusion

The hydrodynamic forces on Unmanned Aquatic Vehicle’s propeller are determined and thereby propulsive efficiency of marine propeller is calculated with the help of standard theoretical formulae. After the theoretical estimation, computational simulations of hydrodynamic forces are carried out on marine propeller for verification purpose. In numerical simulation, conceptual design of marine propeller is modelled with the help of CATIA and hydrodynamic flow analyses are executed by using ANSYS Fluent 16.2. In flow analysis, primary evaluating parameters such as drag, lift, thrust and torque are calculated and listed for various velocities. The predicted and estimated hydrodynamic forces are compared with each other and there by the weight range to handle UAVs are estimated for
the short listed propulsive system. Finally, the minimum power requirement and propulsive efficiency are estimated for the peak loading conditions, in which the outputs are located in the below average level. Therefore the low level loading conditions are used and analysed, which are provided the working ranges of the short listed rotor.

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