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Propeller Efficiency Enhancement by the Blade's Tip Reformation

Meysam Maghareh, Hassan Ghassemi*

Department of Maritime Engineering, Amirkabir University of Technology, Tehran, Iran
*Corresponding author: gasemi@aut.ac.ir

Abstract Many devices are designed to augment thrust and efficiency. Propeller's blade plays a fundamental role in order to enhance efficiency. In this paper, DTMB4382 is selected as reference propeller in which blade reformation has been applied on the tip toward suction and pressure side and hydrodynamic performance have been discussed by using numerical investigation. Numerical results of the hydrodynamic characteristics of the propeller at the different blade tip angles are presented and discussed.

Keywords: *DRMB4382 propeller, blade tip rake angle, hydrodynamic characteristics*

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1. Introduction

Nowadays in regard to increasing marine fuel price, considerable efforts have been made to manage and enhance its consumption. These efforts could be optimization of ship travel route, installation of additional accessories to the body or propulsion system and use of high efficiency components in ship building process. One of the main effective components on fuel consumption is the ship propulsion system. Ship propeller performance is impressed by propeller type, geometrical and performance parameters like radial velocity, thrust coefficient and so on. Many marine propulsor types have been employed to the marine vessel. As an example, three types which worked by Ghaseemi and his colleagues are Voith Schneider [1], ducted propeller [2] and waterjet propulsion system [3]. Those propuslors may be employed to the different ships.

The idea of tip rake comes from 1962 where Cone et al. [4] applied it on the airplane wing. Figure 1 shows the rake angle at the wing tip with two negative and positive angles. Both of them may effect on the aerodynamic performance of the wing. Based on the report which published by NASA, they examined lift and minimum induced drag on nonplanar lifting surfaces. In this theoretical work the effect of induced drag was determined for families of wings with lifting surfaces configured as circular and semi elliptic arcs and more complex forms including fins and end plates. It was found that such a wing could reduce the induced drag and thereby increase the lift/drag ratio compared to a flat elliptical planform wing with equal span. The reduction of induced drag was independent whether the nonplanar lifting surface was pointing toward the suction side or the pressure side of the wing. However, the nonplanar elements also induced additional lift, positive when curved to the suction side and negative when curved to the pressure side; that is, wings with elements pointing toward the suction side were found to be the most efficient by having the best lift/drag ratio.

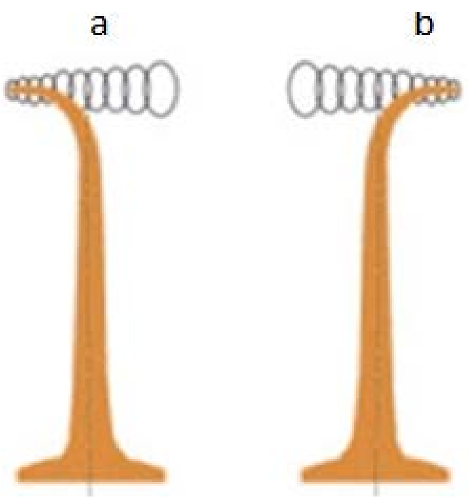


Figure 1. (a) Negative tip rake (b) Positive tip rake

Figure 2. Kappel propeller

Regarding to this idea, marine propeller designers have been applied this idea on ship propeller blade and they invented Kappel propeller which has rake angle to the suction side [5]. Figure 2 shows the Kappel propeller employed to the ship in order to enhance the performance of the propulsion system [6].

Up to date, many researchers have been investigated on this type of the propeller. Cheng et al. [7] performed numerical analysis between Kappel and conventional propellers which proved that Kappel propellers have a larger scale effects for both the thrust and the torque, also they have much more aspect ratio than the conventional ones as well as the more stress on the blade's tip.

Inukai carried out on this propeller type during 2011~2013 and published his work in the SMP [8,9]. He worked the effect of the rake angle on the single propeller and coaxial two propeller series with vice-versa rotation means contra-rotating propeller (CRP). Effect of the rake and skew of the propeller was investigated on the propeller performance and calculated noise pressure level (SPL) carried out by Gorji et al [10]. Gaggero et al. [11] designed and analyzed a new generation of contracted and loaded tip (CLT) propellers.

Ghassemi et al. [12] investigated on composite marine propeller hydro-structure statues while pressure hydrodynamic loading applied. The blade deformation of a propeller analyzed using FVM-FEM coupled method through iterative process. They obtained possible stress locations on propeller blade working in optimized condition. Hydrodynamic characteristics of the Kort-Nozzle simulated by using different turbulence models and in order to evaluate the propulsive performance of the Kort-nozzle propeller, a Reynolds-Averaged Navier-Stokes (RANS) solver is employed [13].

In this article, we consider DTMB4382 propeller as our reference and apply rake in two different ways and angles at the blade's tip; furthermore the effects of tip rake on hydrodynamic performance and the efficiency are investigated and the form in which maximum efficiency and thrust is produced will be determined.

2. Governing Equations

In this paper, the conservation form of unsteady Navier-Stokes equation along with momentum equations has been numerically solved to obtain the velocity and pressure fields.

In this regard, first, the conservation of mass principle has been considered, which leads to the following differential equation in terms of the velocity filed and the mass density, and is known as the continuity equation:

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x_i}\left(\rho u_i\right)=0 \quad (1)$$

where ρ is the density of the fluid while u_i shows the fluid velocity-vector components. Furthermore, the principal of the conservation of linear momentum was also satisfied by solving the following well-known global Navier-Stokes equation:

$$\frac{\partial}{\partial t}\left(\rho u_i\right)+\frac{\partial}{\partial x_j}\left(\rho u_j u_i\right)=-\frac{\partial p}{\partial x_i}+\frac{\partial \tau_{ij}}{\partial x_j}+\rho g_i \quad (2)$$

where p denotes pressure and g is the gravitational acceleration. In fact, as equations (1) and (2) are coupled, these equations should be solved simultaneously and in an iterative manner. It should be noted that in case of incompressible flow, the density is constant and the propeller flow is considered to be steady.

It is well accepted that the hydrodynamic propeller operation can be modeled by the following non-dimensional equations:

$$J=\frac{V_A}{nD},\ K_t=\frac{T}{\rho n^2 D^4},\ K_q=\frac{Q}{\rho n^2 D^5}. \quad (3)$$

And the propeller efficiency may be obtained as follow:

$$\eta=\frac{K_t}{K_q}\frac{J}{2\pi} \quad (4)$$

where J denotes advanced coefficient, n refers to rotational speed in RPS (revolution per second), D is propeller diameter and V_A represents for propeller advanced velocity related to the ship's speed, T is thrust power, Q is Torque, ρ denotes the density of water.

3. Modeling and Solving

The equations are solved by the finite volume method while the SST turbulence model was utilized to compute the transport of the turbulent shear stresses. The SST model was selected since it has been widely used by different researchers in the past and its proficiency and reliability in predicting the flow separation has been well demonstrated. Moreover, the multiple reference frame (MRF) method is used for propellers numerical investigations.

Table 1. Rake distribution on blade tip

r/R	Rake type 1	Rake type 2
0.8~0.2	0	0
0.9	3	2
0.95	5	3
1.0	10	6

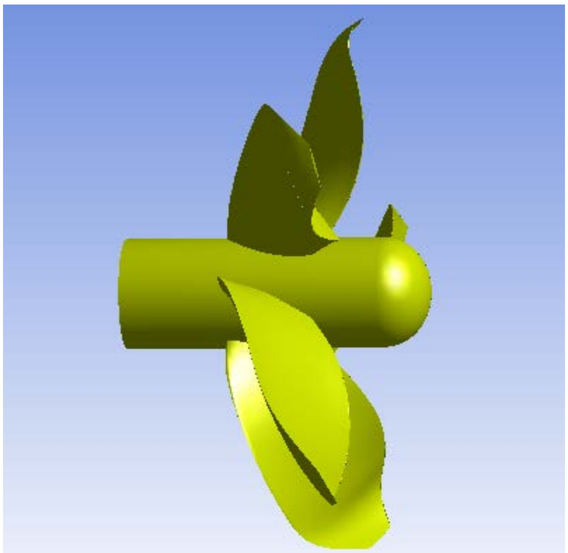


Figure 3. Three-dimensional propeller with blade tip rake angle

The Geometrical specification of DTMB4382 could be extracted from Carlton's [14]. With the use of this information we can design 3-dimensional model of the propeller in CAD Software and we will apply positive and negative rake distribution as presented in Table 1. Three-dimensional propeller with blade tip rake angle is show in Figure 3.

The computational domain is required to be discretized to convert the partial differential equations into series of algebraic equations. The propeller is placed in two cylindrical-flow-field containing proper dimensions in the range of the other research's flow-field dimensions. For the propeller, the first domain cylinder diameter is almost 0.1D and second one radius is 5D. Upstream and downstream dimension have been presented in Table 2. Computational domain is shown in Figure 4.

Generating mesh on the domain is needed for further investigation. Inflation and unstructured method of mesh generation were used in this investigation with the specification as given in Table 3.

Table 2. Main geometry of the DTMB4382 propeller

Geometrical Parameter	Value
Propeller Diameter	0.3 m
first domain diameter around propeller	0.34 m
second domain radius around propeller	1.5 m
Propeller upstream	1 m
Propeller downstream	4 m

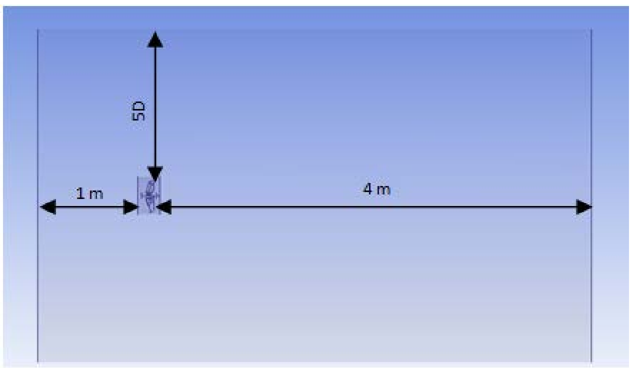


Figure 4. Computational domain

Table 3. Mesh generation specification

Parameter	Value/description
Type	Inflation and unstructured
Number of elements	1483315
Number of nodes	356759

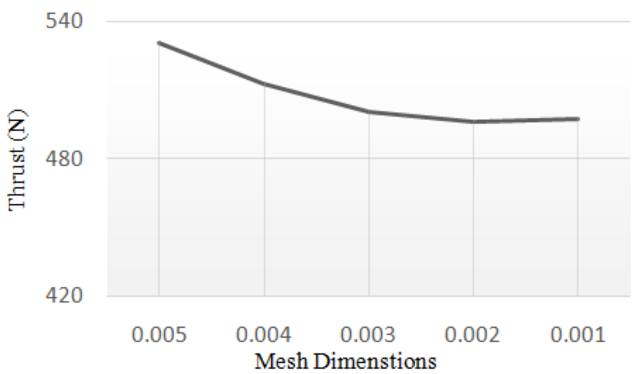


Figure 5. Mesh independency

As it mentioned k-ω SST has been used as turbulent model, MRF was applied to first domain. The radial velocity of the zone around propeller was assigned 1100 RPM and constant. The inflow and out flow were set to velocity inlet and pressure outlet respectively. The far field boundary was taken as wall. According to employed numerical procedure (turbulence modeling, computation domain, boundary conditions), thrust is converged by mesh size bigger than around 0.002 (Figure 5).

4. Numerical results

Firstly, validation of the numerical results is needed to make its accuracy. Figure 6 shows the comparison of numerical results and experimental data and gives good agreement.

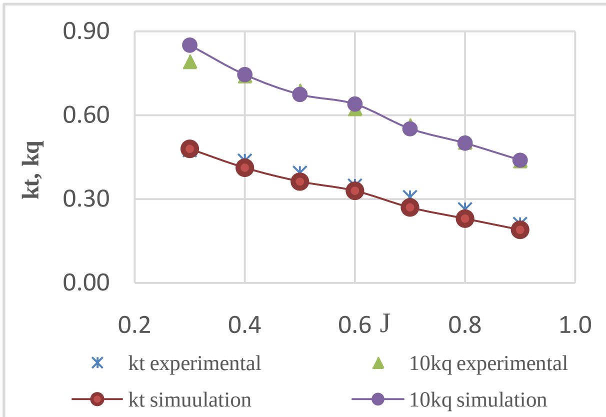


Figure 6. Comparison of numerical results and experimental data

Here, the tip rake is changed by different angles. Hydrodynamic performance of propellers with four blade tip rake angles (±10 and ±6 degree) were achieved by pre-mentioned method and equations. Torque coefficient of different raked propellers has been presented in Figure 7. As we can see positive 10 degree tip rake makes the propeller higher torque coefficient.

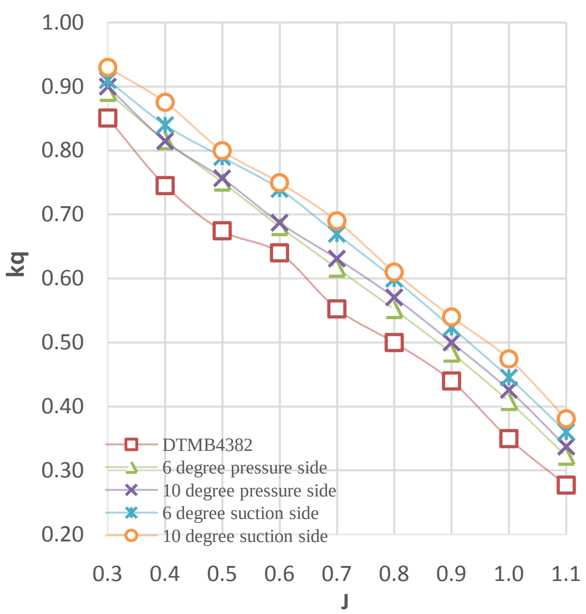


Figure 7. Torque coefficient at different blade tip rake angles

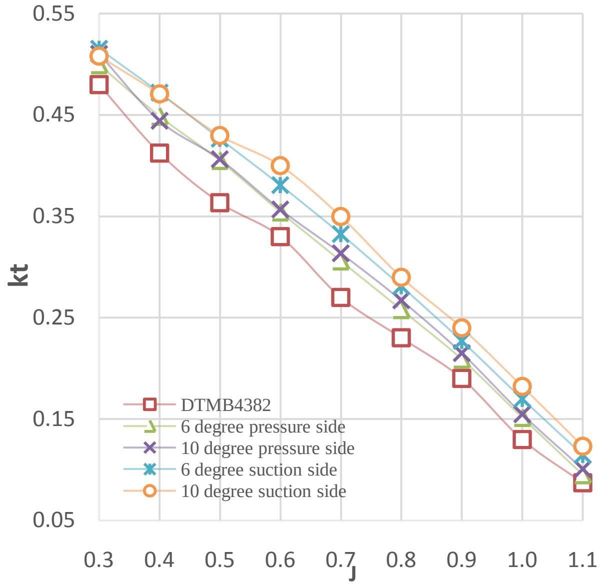


Figure 8. Thrust coefficient at different blade tip rake angles

Thrust coefficient at different blade tip rake angle is shown in Figure 8. It can be observed that positive rake is more effective on thrust coefficient than negative. Open-water efficiency of propellers has been compared in Figure 9 in which the higher degree positive rake is more efficient than conventional DTMB4382 at the operating circumstance of this type of propeller (J=0.7). Moreover, it can be observed that in bollard condition negative rake has lower efficiency while still exerting positive rake can perform more efficient operation.

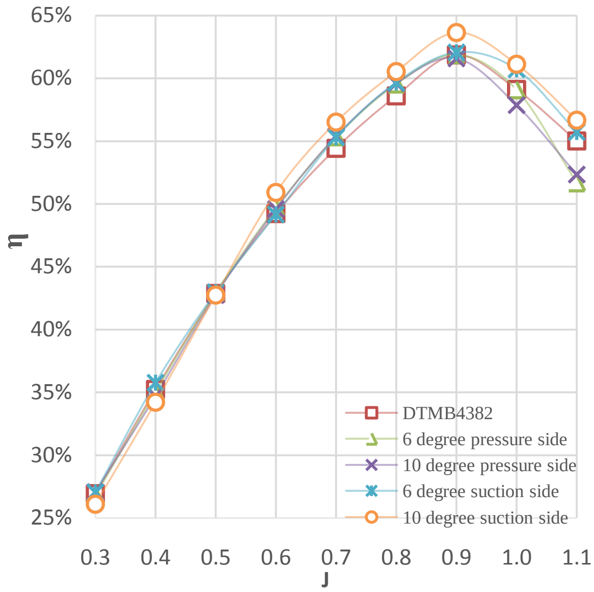


Figure 9. Efficiency at different blade tip rake angles

The results show up to 4 percent augmentation of propeller performance efficiency where tip rake and especially positive rake was used.

Pressure distribution on face and back of the conventional DTMB4382 and 10° positive raked propeller at 0.1D upstream is illustrated in Figure 10 and Figure 11, respectively.

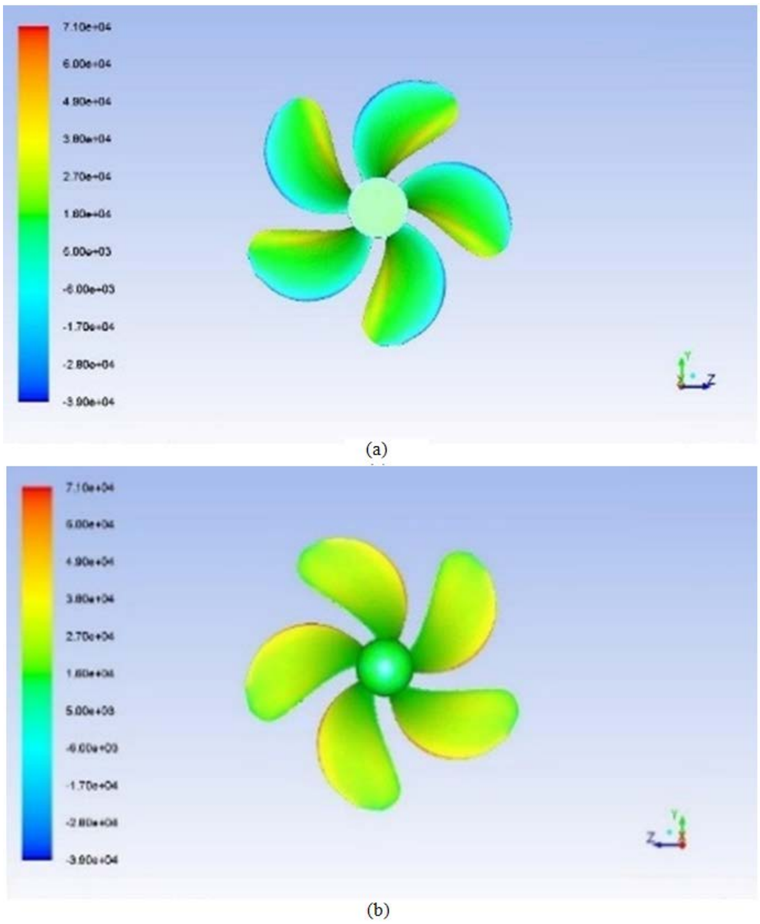
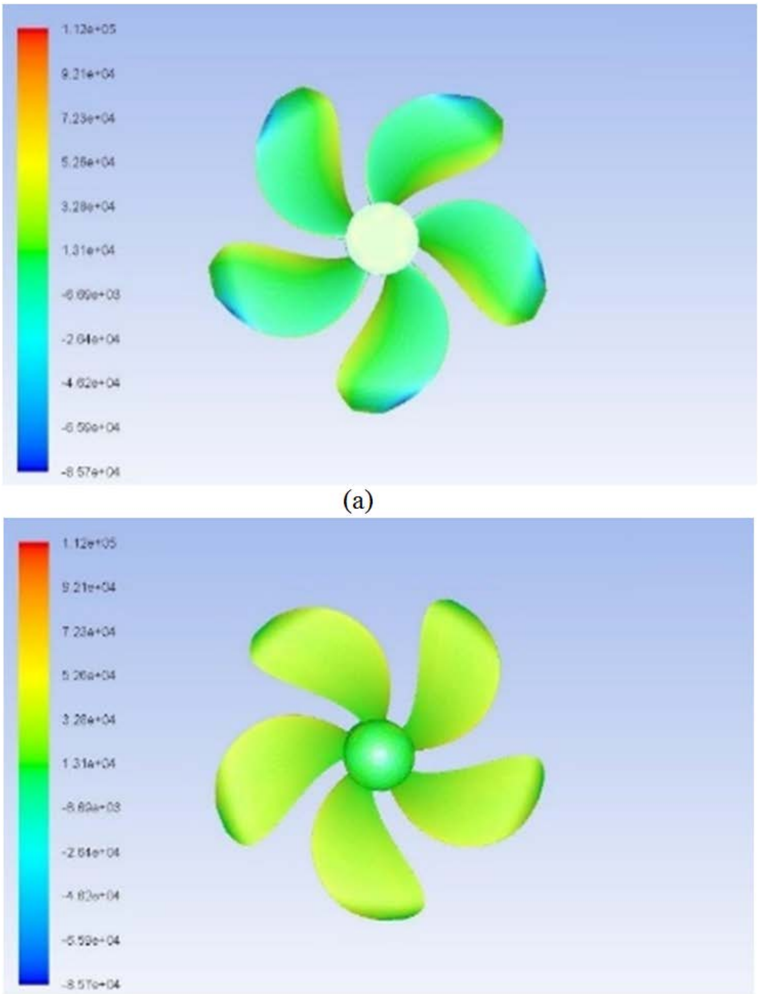


Figure 10. DTMB4382 pressure distribution on (a): back (b): face



(a) (b)

Figure 11. Pressure distribution at positive 10° rake on (a) back (b) face

5. Conclusions

In this study, a DTMB4382 propeller with different tip rake angle is numerically analyzed using RANS solver. According to the results, the main findings of this research can be summarized as follows:

- Positive and negative bade tip rake was exerted on DTMB4382 propeller in different angles. The numerical result showed enhancement of thrust coefficient compared to conventional DTMB4382.
- In operating condition (J=0.7) the presence of higher degree positive tip rake makes operating more efficient.
- In bollard condition (J=1.1), using negative tip rake is not recommended whereas the optimal performance of the positive raked propeller cannot be negligible.
- Pressure distribution on tip raked propeller is more moderate and considerable differences can be observed.

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