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RESEARCH ARTICLE

**An ethical committee approval and/or legal/special permission has not been required within the scope of this study.*

NUMERICAL INVESTIGATION OF THE HYDRODYNAMIC PERFORMANCE OF A PROPELLER CONVERTED FROM FPP TO CPP*

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ABSTRACT

Present paper investigates the hydrodynamics of a Controllable Pitch Propeller (CPP) which is generated by geometrical modifications applied on a benchmark propeller designed as a fixed pitch propeller (FPP). The aim of the study is to examine the practical feasibility of converting a propeller model designed as a FPP to a new one operating with CPP principles. The flow around propeller models is solved via computational fluid dynamics and the results of the new generated model are presented in comparison with its parent geometry. The well-known KP505 propeller model is chosen as test case. The primary results show that the effect of the geometrical modifications on the propeller efficiency mainly depends on the propeller load and the blade pitch angle. The optimum efficiency point is determined as J=0.8, for the new design model. For the J values below this point, negative pitch angle changes improve the efficiency compared to FPP model. If the J exceeds the above mentioned value, positive pitch angle changes are needed to gain efficiency increase. The results led us to conclude that, it's possible to convert a FPP to a CPP, but the blade pitch angle should be carefully controlled, for efficient operation.

Keywords: *FPP to CPP, Fix-Pitch Propeller, Controllable Pitch Propeller, CFD, RANS*

FPP'DEN CPP'YE DÖNÜŞTÜRÜLEN BİR PERVANENİN HİDRODİNAMİK PERFORMANSININ SAYISAL İNCELENMESİ

ÖZ

Bu makale, sabit hatveli pervane (FPP) olarak tasarlanmış bir pervane üzerinde uygulanan geometrik modifikasyonlarla oluşturulan Kontrol Edilebilir Hatveli Pervanenin (CPP) hidrodinamiğini incelemektedir. Çalışmanın amacı, FPP olarak tasarlanmış bir pervane modelinin CPP prensipleriyle çalışan yeni bir pervaneye dönüştürülmesinin pratikte uygulanabilirliğini incelemektir. Pervane modelleri etrafındaki akış hesaplamalı akışkanlar dinamiği ile çözülmüş ve yeni oluşturulan modelin sonuçları ana geometrisi ile karşılaştırmalı olarak sunulmuştur. İyi bilinen KP505 pervane modeli test vakası olarak seçilmiştir. İlk sonuçlar, geometrik değişikliklerin pervane verimliliği üzerindeki etkisinin esas olarak pervane yüküne ve kanat hatve açısına bağlı olduğunu göstermektedir. Yeni tasarım modeli için optimum verimlilik noktası J=0.8 olarak belirlenmiştir. Bu noktanın altındaki J değerleri için, negatif hatve açısı değişiklikleri FPP modeline kıyasla verimliliği artırmaktadır. J değerinin yukarıda belirtilen değeri aşması durumunda, verimlilik artışı elde etmek için pozitif hatve açısı değişikliklerine ihtiyaç duyulmaktadır. Sonuçlar, bir FPP'yi CPP'ye dönüştürmenin mümkün olduğu, ancak verimli çalışma için kanat hatve açısının dikkatlice kontrol edilmesi gerektiği sonucuna varmamızı sağladı.

Anahtar Kelimeler: *FPP’den CPP’ye, Sabit hatveli Pervane, Kontrol edilebilir hatveli Pervane, HAD, RANS*

1. INTRODUCTION

Propulsion of commercial and military marine vessels often relies on various types of propellers, typically positioned at the stern of the ship. The key factors influencing the performance of propellers are referred to as propeller speed, propeller diameter, and ship speed. The effectiveness of propellers is determined by the thrust they generate, the torque they demand, and their efficiency, which is influenced by these two variables. In recent times, extensive research has been conducted to investigate the impacts of these parameters on propeller performance (Wang et al., 2022). It is known that the propeller speed, which is the most important performance-impacting parameter, is limited by the main propulsion system that produces the mechanical shaft work. This results in very different performance of the propellers at different ship speeds. Controllable pitch propellers (CPP) have emerged with the idea of changing the propeller pitch to improve hydrodynamic performance while keeping the main propulsion system output speed constant. The propeller pitch is determined by the speed of the vehicle and the propeller speed to achieve maximum efficiency. In order to improve the performance, it is aimed to change the propeller pitch at the request of the vehicle user during the cruise (Turnbull,1931). The propeller speed, which is a crucial factor influencing performance, is limited by the primary propulsion system responsible for generating mechanical shaft work. Consequently, propellers exhibit varying performance levels at different ship speeds. Controllable pitch propellers (CPP) have emerged as a solution, allowing for adjustments to the propeller pitch in order to enhance performance while maintaining a constant output speed from the main propulsion system. The propeller pitch is determined based on the vehicle's speed and the propeller speed required to achieve maximum efficiency. The objective is to enable changes in propeller pitch during the cruise, as desired by the vessel operator, with the aim of improving performance (Turnbull, 1931). The challenges associated with Controllable Pitch Propellers (CPP) have led to limited information regarding the performance of various pitch propellers in the Wageningen-B series propellers (FPP) databases. While there have been a few experimental investigations, research on CPP propellers has predominantly focused on the application of Computational Fluid Dynamics (CFD) techniques. In a recent study by Ozturk et al. (2022), a systematic examination was conducted to analyze the impact of propeller pitch on the self-propulsion point in ships, utilizing the Wageningen-B series propeller database. Funeno et al. (2013) conducted a comprehensive investigation into the pitch and performance of Controllable Pitch Propellers (CPP) utilized in commercial ships. Their study encompassed both experimental and numerical analyses, covering a broad range of conditions. Notably, they observed disparities between the numerical and experimental datas, particularly at low advance coefficients and near the neutral pitch points. As a result, they recommended further research into the flow characteristics around the propeller, with specific emphasis on examining the neutral pitch points. Rhee H.S. and Joshi S. (2003) conducted a validation study where they compared experimental results of the DTMB P5168 model CPP test propeller with Computational Fluid Dynamics (CFD) methods. However, it's worth noting that while the study utilized a CPP propeller geometry, it did not account for the motion of the blades around their shaft axis. In a separate numerical investigation by Kolakoti et al. (2013), the interaction between the propeller body and CPP propellers was studied. Additionally, Xiong Y. et al. (2013) examined the impact of fin geometries added to the CPP propeller hub on propeller characteristics and pressure distributions on the blades under open water test conditions. Controllable Pitch Propellers (CPP) necessitate the implementation of specialized blade root designs that facilitate proper interaction with the propeller hub, enabling blade movement. However, compared to Fixed Pitch Propellers (FPP), CPPs require significantly more intricate designs. In a recent study conducted by Yurtseven A. and Aktay K. (2023), the researchers converted a three-blade FPP propeller into a CPP configuration and examined the torques exerted on the blade shafts during blade pitch movements.

In this study, a test propeller designed with a fixed pitch, which is not common in the literature, has been geometrically updated and made usable for CPP purposes. The hydrodynamic performance of this mutant propeller is analyzed and compared with its FPP parent.

2. METHOD

2.1. Governing Equations

The study was solved in a computer environment using computational fluid dynamics (CFD) methods. The flow around the propeller is modeled as a 3-dimensional, time-dependent, incompressible and turbulent flow.

The governing equations used to model this flow are the continuity equation and the Reynolds-Averaged Navier Stokes (RANS) equations for three-dimensional, incompressible flow. The time-dependent continuity equation is given in equation 1.

$$\frac{\partial U_i}{\partial x_i} = 0 \tag{1}$$

The momentum conservation equation is given in equations 2 and 3.

$$\rho\left(\frac{\partial U_i}{\partial t} + U_j \frac{\partial U_i}{\partial x_i}\right) = -\frac{\partial P}{\partial x_i} + \frac{\partial \tau}{\partial x_j} - \frac{\partial\left(\overline{\rho u_i' u_j'}\right)}{\partial x_j} \tag{2}$$

where U_i is the mean velocity vector, u' is the turbulent velocity vector, $\left(\overline{\rho u_i' u_j'}\right)$ is the turbulence stress tensor, P is the mean pressure, ρ is the density and μ is the dynamic viscosity.

$$\tau = \tau_{ij} = \mu\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right) \tag{3}$$

where τ_{ij} is the average molecular stress tensor.

In addition, the realizable $k-\varepsilon$ turbulence model was chosen to express the turbulence in the flow.

A commercial computational fluid dynamics code "Siemens Simcenter Star-CCM+" package program was used in the study. The governing equations are discretized using the finite volume method.

2.2. Geometry and Simulation Conditions

The test propeller geometry of KCS/KP 505, which was used as a fixed pitch propeller in the study, was converted from FPP propeller form to CPP propeller form by computer-aided design improvements. The FPP versions of this propeller have been used in a number of studies in the literature, especially recently in the field of hydrodynamics and cavitation (Lungo, A., 2018; Farkas et al.,2020). The propeller properties for the base propellers are given in Table 1.

Table 1. *KCS/KP 505 Propeller specifications*

D (m)	0.250
Z	5
Blade Section	NACA66 a=0.8
Rotation direction	Right

The converted CPP version of the FPP KCS/KP 505 propeller chosen as the test propeller is shown in Figure 1.

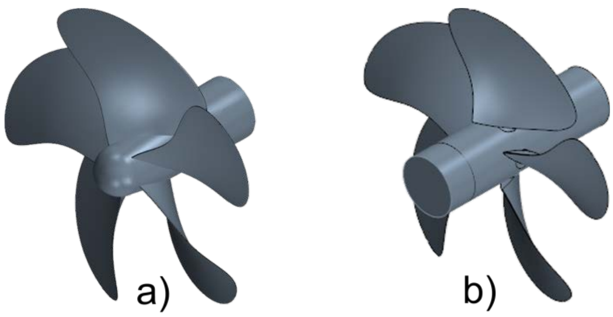

Figure 1. *a) FPP-KCS/KP 505, b) CPP-KCS/KP 505 CAD Geometries*

When the figure is examined, the development was applied by cutting the blades of the FPP propeller from the root region where they are connected to the main drive shaft and reassembling them with the help of shafts that will allow them to rotate around their own axis perpendicular to the main drive shaft. Thus, the blades are able to move around their own axis.

The idea behind the operation of CPP propellers is to change the pitch angles depending on the change in ship speed while keeping the propeller constant rotation. It is important to obtain the advance coefficient at which the propellers are most efficient. The advance coefficient depends on the ship speed and propeller revolution. Keeping the propeller rotation constant also ensures that the efficiency of the power generation and power transmission systems that drive it is kept high. Therefore, while keeping the propeller efficiency constant, it is necessary to change the propeller pitch to ensure that the efficiency is kept at the highest possible point with the change in ship speed. In this context, the direction of the pitch angle changed in the analysis is given as + (Pos) and **-** (Neg) as shown in Figure 2.

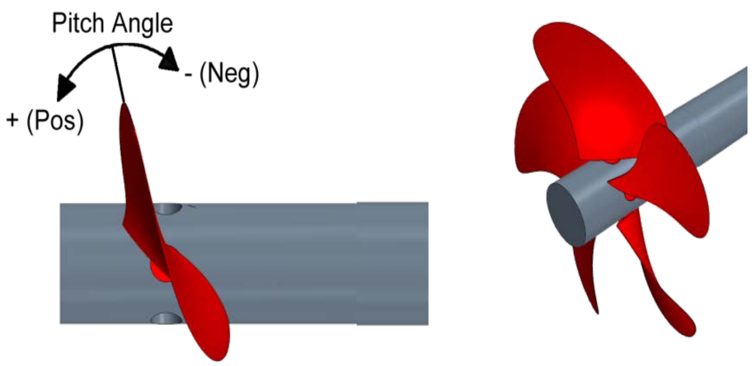

Figure 2. *Pitch angle directions for propeller blades*

2.3. Computational Domain and Boundary Condition

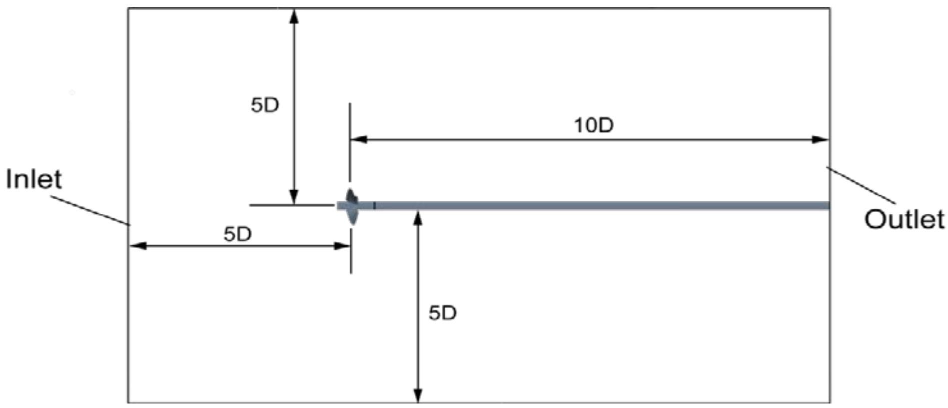

Figure 3. *Solution domain visualization*

In order to perform the flow analysis of the propellers, the flow domain shown in Figure 3 was created. The variable given as "D" in the figure refers to the propeller diameter. According to the direction of rotation of the propellers, the "Inlet" and "Outlet" boundary conditions in the solution domain are switched. Except for the propeller and shaft surfaces, all other external surfaces in the domain are used with the symmetry boundary condition.

Propeller open water test conditions were used in the study. In this context, the advance coefficient for the KCS/KP505-CPP propeller was taken as 0.2, 0.4, 0.6, 0.7, 0.8 and 0.9. The speed of the test propeller used in the study was taken as constant and 32 rps. Thus, different current speeds were used for each advance coefficient. These conditions are also considered suitable for the use of CPP propellers. Because the main purpose of using CPP propeller is to increase the propeller efficiency as much as possible at different ship speeds without changing the shaft speed at the highest point of the speed corrector transmission efficiencies by keeping the main engine speed constant. In the study, current input is used with uniform current input and current output is used with pressure output boundary condition.

It is known that two different rotational motions occur in controllable pitch propellers. The first of these motions is the basic rotational motion of the propeller around the main shaft axis. Apart from this basic rotational motion to which the propeller speed is applied, there is also the pitch motion of the blades around their own rotational shaft axes. In the analysis, the motion model called "Rigid Body Motion" combined with interfacial connections in the static domain was preferred for the basic rotational motion. For the blade pitch motion that will occur together with this motion, the motion called "Overset Motion" is used under superposition conditions. In the study, the time step was chosen to satisfy CFL<1 condition.

2.4. Solution Mesh Structure

In order to perform CFD analyses, solution domain decomposition was performed in accordance with the finite volume method. Thus, the solution mesh was obtained.

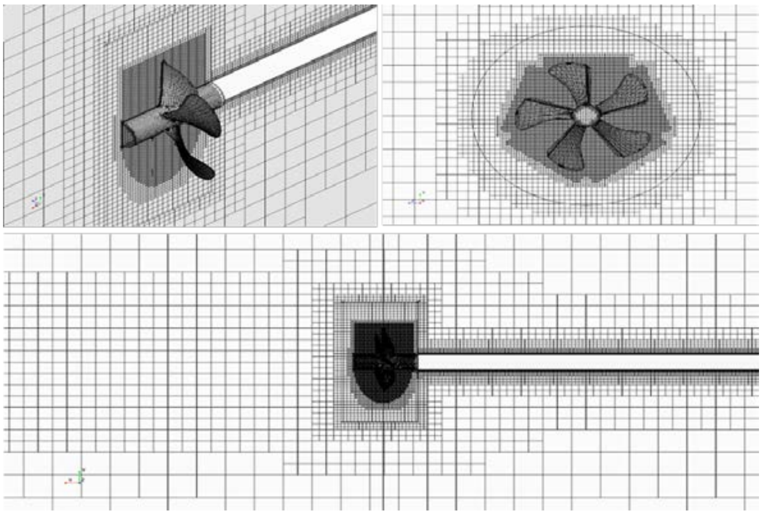

Figure 4. *Solution Mesh Image*

In the solution mesh, boundary layer mesh elements of the expanding type suitable for the boundary layer were preferred in order to estimate the wall velocities accurately, especially in the parts approaching the propeller surfaces. Hexahedral solution elements were used in the solution mesh. The solution mesh structure used is shown in Figure 4.

The solution mesh was developed to keep the value of y+ (y+ = u*y/μ where u* is the reference velocity, y is the normal distance of the center of gravity of the cell nearest to the wall from the wall and μ is the kinematic viscosity) calculated with the first-row solution mesh width over the propeller between 30 and 150. The distribution of the wall y+ value in the numerical analysis for the controllable pitch version of the KCS/KP-505 propeller is shown in Figure 5.

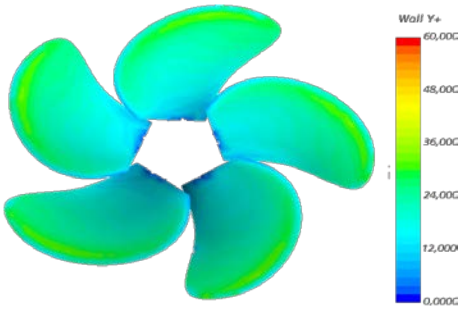

Figure 5. *KCS/KP 505-CPP (J=0.8) Wall Y+ Image*

The solution mesh independence and time step independence results for the analyses are given in Table 2.

Table 2. *Mesh dependency and Time step dependency Values (J=0.8)*

	Cell Count	Trust [N]
Finer	2618798	468,85
Fine	1302017	468,08
Medium	642223	466,35
Coarse	320829	464,24
Coarser	159309	461,60

	Timestep[s]	Trust [N]
Fine	0,0005	468,08
Medium	0,001	468,08
Coarse	0,002	465,34

When these results are examined, the "Fine" configuration was preferred as the solution mesh resolution and 0.001 s as the time step to be used in the analysis.

2.5. The Validation

In order to investigate the compatibility of the numerical model with the experimental data, six different advance coefficients (0.2, 0.4, 0.6, 0.7, 0.8, 0.9) were analyzed. The flow conditions and fluid properties used in the analysis are given in table 3.

Table 3. *Flow conditions and fluid properties*

J	0.2	0.4	0.6	0.7	0.8	0.9
V_A (m/s)	1.6	3.2	4.8	5.6	6.4	7.2
ρ (kg/m^3)	997.56	**μ (Pa.s)**	8.887E-4			

Figure 6 shows the experimental data (EFD) and numerical data (CFD) together.

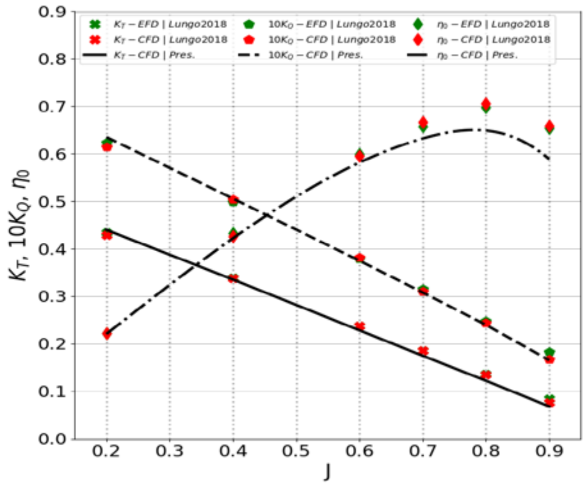

Figure 6. *Comparison of experimental and numerical data for the KCS/KP505 propeller (Lungu, A., 2018)*

When the figure is examined, it is seen that experimental studies and numerical studies give close results on an acceptable scale.

3. RESULTS

This section presents the results of the converted KCS/KP505-CPP propeller under open water test conditions. The performance of the fixed pitch version at different advance coefficients is compared with the performance of the controllable pitch version. Different pitch angles were applied to the blades to adapt to changes in the advance coefficient.

The advance coefficient is given in equation 4, thrust coefficient is given in equation 5, torque coefficient is given in equation 6 and propeller efficiency is given in equation 7, which are frequently used to examine propeller performance under open water propeller test conditions.

$$J = \frac{V_a}{nD} \tag{4}$$

$$K_T = \frac{T}{\rho n^2 D^4} \tag{5}$$

$$K_Q = \frac{Q}{\rho n^2 D^5} \tag{6}$$

$$\eta_0 = \frac{K_T}{K_Q}\frac{J}{2\pi} \tag{7}$$

When the open water test results of the KCS/KP505 propeller used in the study are analyzed in Figure 6, it is seen that the highest efficiency point is realized at 0.8 advance coefficient at the design pitch of the propeller. It is seen that the efficiency decreases at lower advance coefficients before this point and at larger advance coefficients after this point. In this case, it is seen that as long as the pitch of the propeller remains constant, the propeller efficiency decreases significantly at low and high speeds and causes energy loss if the marine vessels using the propeller keep the shaft speed constant. Due to this situation, some geometrical modifications were made on the propeller, whose design conditions are FPP, and the propeller was transformed into a form that can be used as CPP. Thus, even if the propeller speed is kept constant at low and high speeds, the efficiency obtained in the FPP version can be exceeded by changing the pitch.

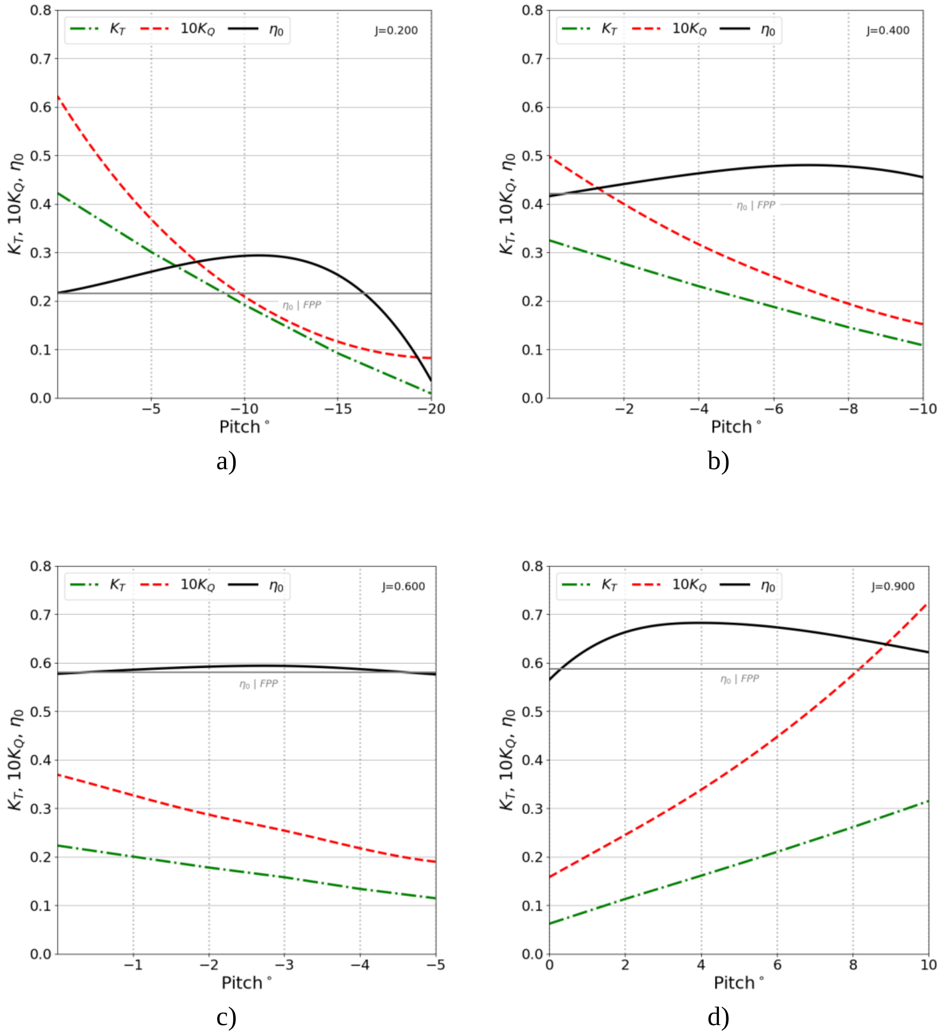

Figure 7. *Propeller performances for different pitch angles at a) J=0.2, b) J=0.4, c) J=0.6 and d) J=0.9 advance coefficients*

When the figure is examined, the efficiency value of the FPP version propeller is indicated as the threshold for the current advance coefficient in each graph. It is seen that the change in propeller pitch angle affects the propeller efficiency more as we move away from the optimum efficiency point under design conditions. In Figure 7.a, at the lowest vessel speed conditions, when the propeller pitch is moved in the negative direction by 12° compared to the design pitch, higher efficiency values are obtained according to the advance coefficient. In Figure 7.b, when the vessel speed increases a little more, it is understood that the optimum pitch angle should be moved in the negative direction of 7° compared to the design pitch. In Figure 7.c, it is seen that the optimum pitch angle is 2.5° in the negative direction for the case where the advance coefficient is very close to the advance coefficient where the highest efficiency is obtained. In Figure 7.d, it is seen that the optimum pitch changes direction and becomes 4° positive at the forward speed where the vessel speed exceeds the optimum efficiency point.

It is also understood from the figure that the increase in the propeller efficiency to be obtained by changing the pitch when approaching the advance coefficient where the highest efficiency is obtained under design conditions gives more limited values.

The pressure and wall shear stress distributions on the propeller blades at different pitch angles are given in Figure 8 for J=0.2, Figure 9 for J=0.4 and Figure 10 for J=0.9. Considering that the highest efficiency point in the design conditions is around J=0.8, it is understood that a negative pitch angle change is made in Figure 8 and Figure 9 and a positive pitch angle change is made in Figure 10. In Figure 8, it is noteworthy that in the application where the pitch angle is -10°, there is a near-uniform pressure distribution in front of the blade (Downstream face) and behind the blade (Upstream face) compared to the FPP propeller model. In the wall shear stress distributions, it is predicted that the wall shear stress decreases at the blade tips, especially at the blade rear face, and therefore the propeller torque requirement is also reduced.

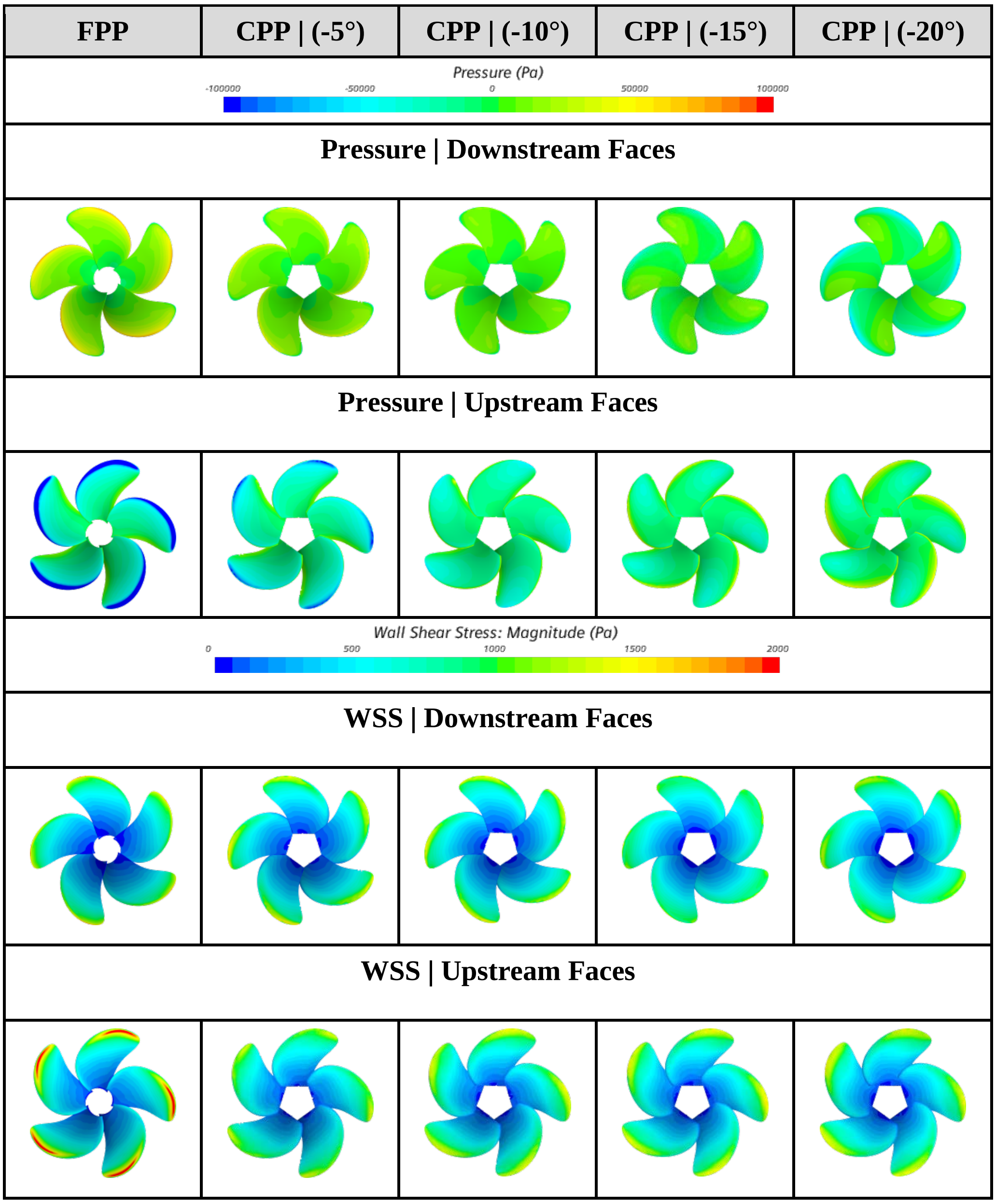

Figure 8. *Pressure and wall shear stress distributions on FPP version blades and CPP version blades at different pitch angles for J=0.2*

In Figure 9, it is seen that the optimal pitch angle change is around -6° and the surface distributions at this point are the same as in Figure 8 with homogeneity in pressure distribution and reduction in wall shear stress.

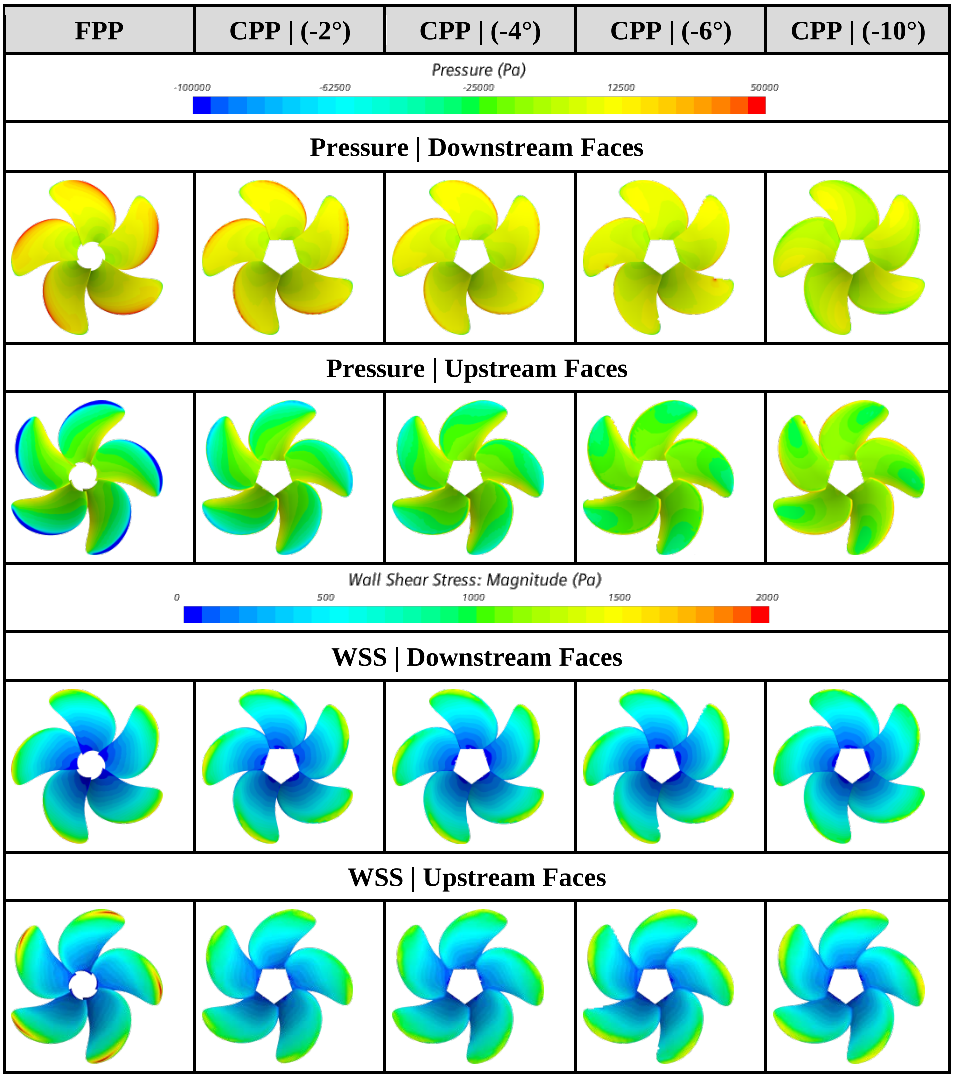

Figure 9. *Pressure and wall shear stress distributions on FPP version blades and CPP version blades at different pitch angles for J=0.4*

Figure 10 shows that in the model where the propeller pitch angle is in the positive direction and the optimal angle change is +4°, it is understood that there are increasing values in the end regions of the front face for the pressure distribution and decreasing values in the end regions of the back face for the wall shear stress distributions.

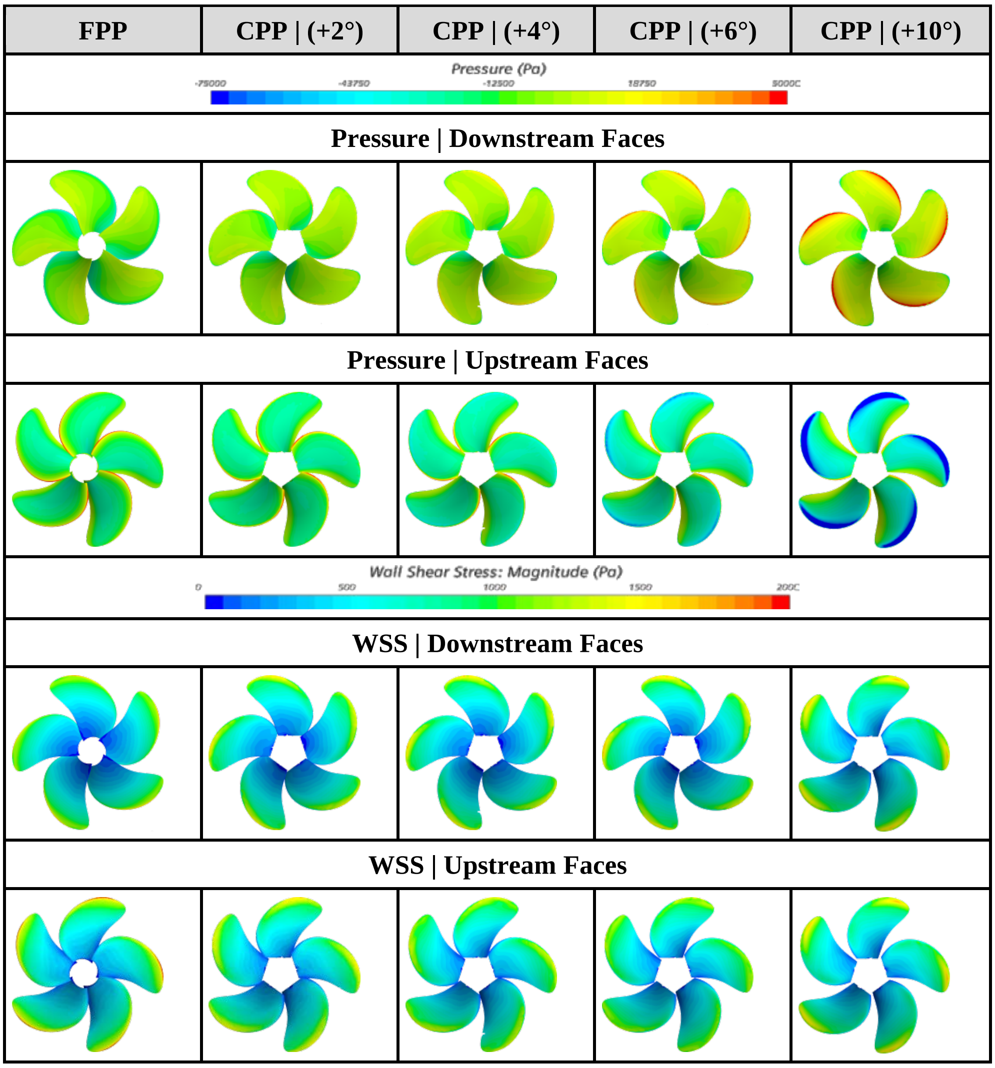

Figure 10. *Pressure and wall shear stress distributions on FPP version blades and CPP version blades at different pitch angles for J=0.9*

4. CONCLUSION

In this study, a test propeller designed as an FPP was made to operate with CPP principles by geometric modifications in the blade and hub geometry. The hydrodynamic performance of this modified propeller compared to its parent FPP propeller is investigated. It was observed that the efficiency of the FPP propeller decreased significantly, especially as the advance coefficient moved away from the optimum efficiency point in the design conditions. The modified CPP propeller has been developed with pitch changes and higher efficiency values have been obtained.

In modified CPP propellers, it is understood that the pitch of the propeller blades should be adjusted to a negative position at vessel speeds that give lower advance coefficients than the advance coefficient, which is the optimum efficiency point under design conditions, and to a positive position at vessel speeds that give higher advance coefficients.

It is understood that the farther away from the optimum efficiency point, the greater the contribution of the blade movements obtained with the modification to the efficiency.

In future studies, it is envisaged that researchers will make significant contributions to the literature by investigating both cavitation formation and hydro-acoustic investigations in such modified CPP propellers.

CONFLICT OF INTEREST STATEMENT

The author declares no conflict of interest.

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