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Design and Analysis of Marine Propeller with Leading-Edge Protuberances

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Abstract: The humpback whale is extremely manoeuvrable despite its size. This study investigates the effects of biologically inspired leading-edge protuberances (tubercles) of humpback whale flipper on INSEAN E779a marine propeller. The study of humpback whales and their flipper performance was the impetus to modify the leading edge of a marine propeller in order to gain a hydrodynamic advantage. This study examines the preliminary design and analysis for the effect of the leading-edge modification on propeller performance at various advance co-efficient. Simulations were executed on propeller with leading-edge sinusoidal protuberances, in order to compare the performance characteristics with that of a propeller with a smooth leading edge. The propeller is designed using CREO Parametric 3.0 and the open water test is simulated using Moving Reference Frame (MRF) approach for complete propeller geometry using ANSYS Fluent 16.2.
Keywords: Humpback whale, Protuberances, Flipper, Propeller, Computational Fluid Dynamics, Moving Reference Frame

I. INTRODUCTION

The humpback whale relies on its superior manoeuvrability when catching prey. This makes the humpback whale truly unique among the members of the Rorqual family. The reason for the humpback whales high manoeuvrability is the shape and size of the flippers. The most unique feature of the humpback whale flipper is the tubercles on the leading edge. These tubercles are thought to be the main reasons for the humpback whales manoeuvrability. This is because the tubercles help to delay the separation from the boundary layer. The tubercles are the humps on the leading edge of the flipper as shown in Figure 1.

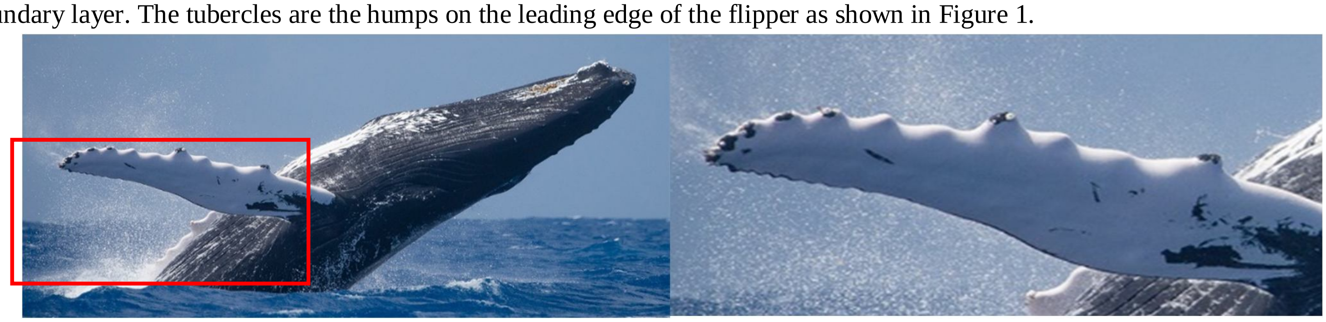

Figure 1: Left – The Humpback Whale. Right – Close-up of the Pectoral Fin with Tubercles.

A marine propeller is a device used for propulsion of the vessel by transmitting the power generated from the main engine. The rotational motion of propeller is converted into thrust by imparting momentum to the fluid, which results in a force that acts on the vessel and pushes it forward through a transmission system. The fluid is accelerated behind the blade due to a pressure difference between face and back surfaces of the aerofoil shaped blade. A marine propeller works on the basis of Newton's third law and Bernoulli's principle.

II. LITERATURE REVIEW

Frank E. Fish was the first to investigate tubercles on the leading edge of an aerofoil in 1995 (Fish and Battle, 1995) [1]. Since then he has conducted several studies on the tubercles including the effects of the tubercles on lift and drag and the geometry itself. According to Fish et al. (Fish and Murray, 2011) [2], wind tunnel tests showed that an aerofoil with leading-edge tubercles improved maximum lift by 6%, increased the ultimate stall angle by 40%, and decreased drag by 32%. They were also able to see a decrease in noise emitted from the foil.

Fish et al. (Fish, Weber, et al., 2011) [3] observed that implementing leading-edge tubercles improved the lift significantly up to the post-stall regime at 11° while reducing drag. At the same time, the tubercles delayed stall for a flat foil from angle of attacks 11° to

17° for a foil with tubercles. When stall occurred for a foil with tubercles it happened slow and graduate compared to a flat foil where the stall occurs sudden. It also showed that it had some increase in lift in the pre-stall regime, below 11°, but most importantly, no increase in drag. This resulted in a higher lift-to-drag ratio, both for mean and peak value. However, the most important improvement occurs in the post-stall regime.

A physical change of the geometry of the foil is a passive method of enhancing the performance of a foil. The tubercles create vortices which travel down the chord length of the foil. The vortices are either co-rotating or counter rotating. Introducing these vortices to the boundary layer increases the velocity in the layers and thus increase the turbulent flow velocity. This means that the generated vortices improve the momentum exchange in the boundary layer, and thus helps to delay the flow separation and stall. (Hansen, 2012) [4], (Bakker, 2006) [5].

A study of the load characteristics of a humpback whale flipper model in a wind tunnel was done by Miklosovic et al. [6].The models tested were similar in shape (tapering from root to tip) and aspect ratio to the actual humpback whale flipper. In general, the shape of the flipper models was the same for both baseline as well as a modified model, except that the modified model has protuberances along its leading edge. Miklosovic et al. reported a 6% increase in maximum lift over the baseline wing and a 40% increase in stall angle by the flipper model with protuberances.

Salvatore et al. [7] performed computational analysis by using the INSEAN-PFC propeller flow code developed by CNR-INSEAN. Experiments are carried to know the open water performance, evaluation of velocity field in the propeller wake and prediction of cavitation in uniform flow conditions.

A study on the propeller flow and cavitation is carried out by S. Subhas et al. [8] with a complete computational solution using Fluent 6.3 software to solve advanced phenomenon like cavitation of the propeller. The simulation results of cavitation and open water characteristics of the propeller are compared with experimental predictions. The results show that the open water characteristics and cavitation can be predicted using fluent software with the use of Standard k–ε turbulence model and the simulated estimations are very close to the experimental results. Mohammed Bennaya et al. [9] simulated the hydrodynamic performance of DTRC P4119 marine propeller using different turbulence models and adopted Multiple Rotating Reference Frame (MRF) approach in ANSYS Fluent for the simulation and compared the results. The results show that the RNG k–ε turbulence model yields the most accurate results with a minimal error when compared to remaining turbulence models. The results also show that all turbulence models have high accuracy at low advanced coefficient and this error is increased with increase in advance coefficient with an acceptable range.

III. GEOMETRIC MODELLING

The 3D CAD modelling of propeller was done using Creo Parametric 3.0. The non-dimensional geometry data of the propeller is presented in Tables 1 & 2. This data was converted into natural co-ordinate data to generate the expanded sections, these sections were rotated according to pitch angle and wrapped around respective cylindrical diameters according to their radial distance as shown in Figure 2. Finally these sections were connected smoothly by blended surface as shown in Figure 3. The final propeller INSEAN E779a is as shown in Figure 4. The leading edge of the blade is selected and is modified with a parametric relation of a sine wave with amplitude as 5% of total length of the leading edge as shown in Figure 5. Table 1 shows dimensions of the INSEAN E779a model propeller used in present flow simulations using ANSYS Fluent 16.2. Table 2 shows the blade characteristics of the INSEAN E779a model propeller used to generate the surface model of propeller.

TABLE I Dimensions of the INSEAN E779a model propeller

Diameter, D [mm]	227.2727274
Number of blades, Z	4
Nominal pitch, P [mm]	250.0
Nominal pitch ratio, P/D	1.1
Nominal rake, positive forward [deg]	4.5833
Expanded area ratio, A_E/A_O	0.689
Hub diameter at prop. reference line [mm]	45.53
Blade-hub fillet radius (back) [mm]	6
Blade-hub fillet radius (face) [mm]	6
Number of radial sections	11

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TABLE II
Blade Characteristics of the INSEAN E779a model propeller

r / R	P / D	C / D	X_{LE} / D	T_{MAX} / D	X_{TMAX} / D	Rake / D
0.2640	1.1118	0.2784	0.1604	0.0404	0.1763	-0.0060
0.3520	1.1204	0.3080	0.1708	0.0312	0.1047	-0.0107
0.4400	1.1202	0.3357	0.1802	0.0257	0.0867	-0.0144
0.5280	1.1167	0.3600	0.1872	0.0213	0.0699	-0.0179
0.6160	1.1147	0.3767	0.1897	0.0167	0.1035	-0.0216
0.7040	1.1173	0.3784	0.1849	0.0130	0.0386	-0.0250
0.7920	1.1174	0.3634	0.1695	0.0097	0.0166	-0.0288
0.8800	1.1102	0.3170	0.1345	0.0063	-0.0757	-0.0327
0.9680	1.1179	0.1917	0.0597	0.0039	-0.1884	-0.0364
0.9900	1.1261	0.1157	0.0162	0.0033	-0.4599	-0.0376
0.9988	1.1261	0.0491	-0.0207	0.0018	-0.9726	-0.0384

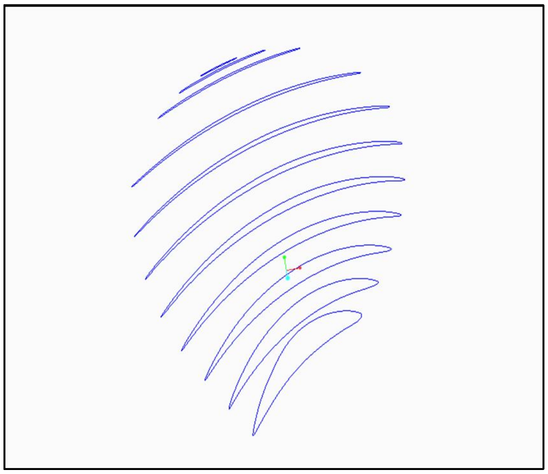
Figure 2: Wrapped Sections

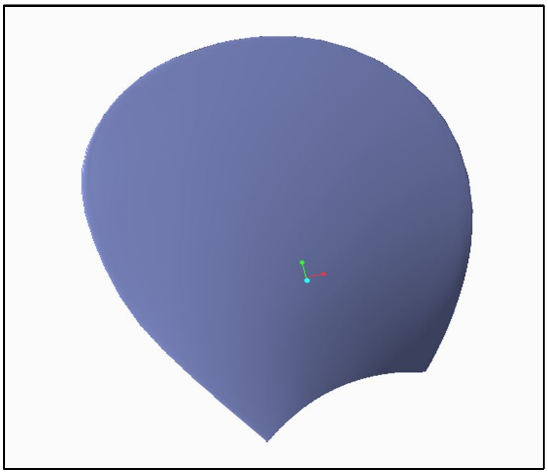
Figure 3: Blended Surface

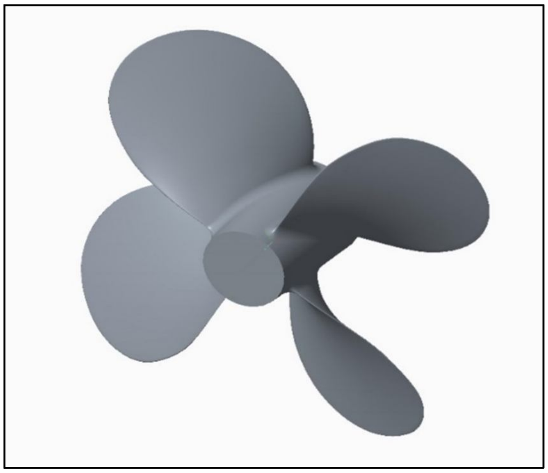
Figure 4: Wrapped Sections

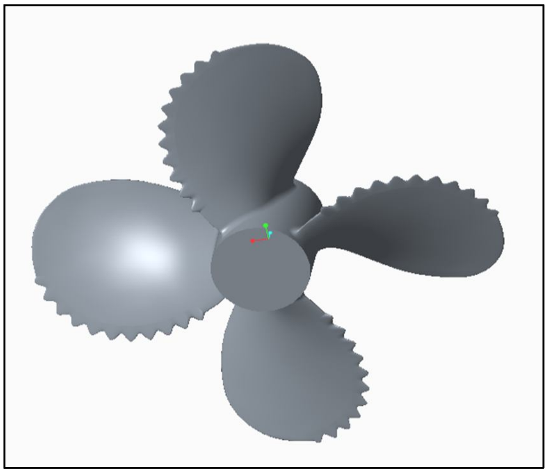
Figure 5: Blended Surface

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IV. ANALYTICAL METHODOLOGY

A. Grid Generation

The flow domain is required to be discretised to convert the partial differential equations into series of algebraic equations. This process is called grid generation. A solid model of the propeller was created in Creo Parametric 3.0 as an initial step of grid generation. The complexity of the blade and complete domain is shown in Figure 6. The whole computational domain was divided into two main parts, rotating and fixed computational domain according to the following dimensions:

1) For Inner Enclosure (Rotating Domain)

a) Diameter = 1.2D = 0.27272 m

b) Depth = 0.7D = 0.15908 m

2) For Outer Enclosure (Stationary Domain)

a) Diameter = 2.942D = 0.66863 m

b) Inlet = 1.25D = 0.28408 m

c) Outlet = 4D = 0.90908 m

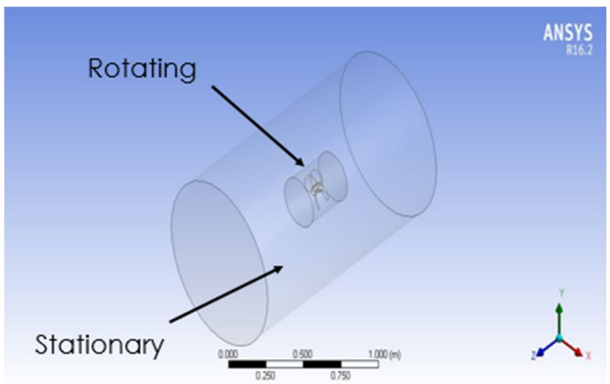

Figure 6: Computational Domain of the Propeller

The unstructured meshing for the computational domain is generated by using ANSYS Meshing tool with tetrahedral element as shown in Figure 7. The total number of cells generated for the entire grid was 3,596,951 with average orthogonal quality 0.90015 and average skewness 0.16112.

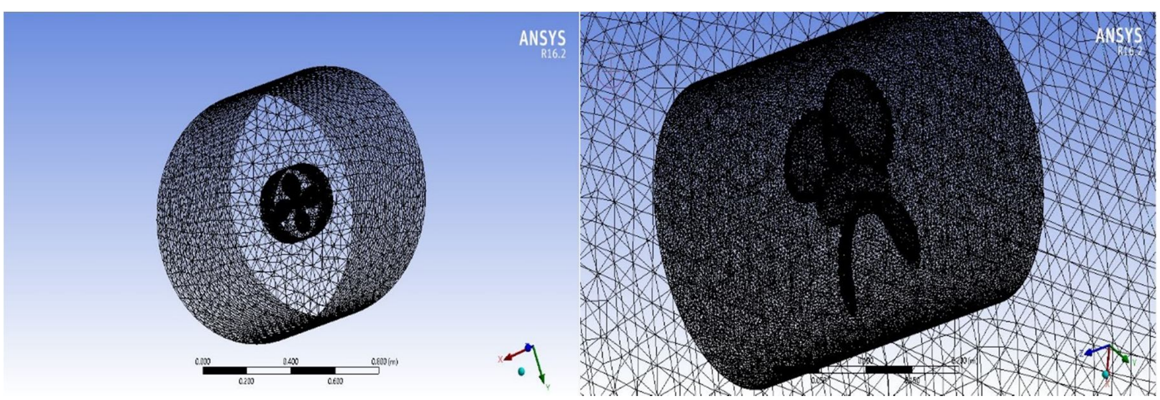

Figure 7: Grid over the entire Domain

B. Boundary Conditions

The continuum was chosen as fluid and the properties of water were assigned to it. A moving reference frame is assigned to the rotating domain with a rotational velocity (1500 rpm, 1800 rpm, 2400 rpm and 3000 rpm). A uniform velocity of 6.22 m/sec was prescribed at inlet. At outlet, outflow boundary condition was set. The far-field was assigned an absolute rotational velocity of zero as shown in Figure 8.

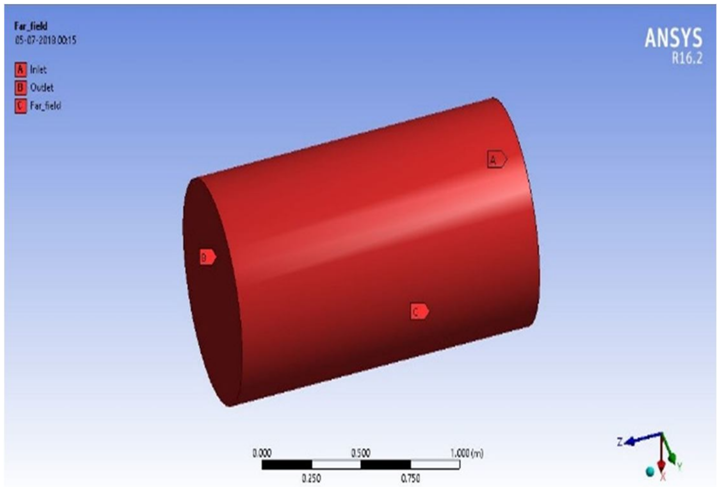

Figure 8: Boundary Conditions on Propeller Domain
(A) Inlet, (B) Outlet, (C) Far-Field

C. Flow Solution and Solver Settings

The CFD code ANSYS Fluent 16.2 was used to solve the three dimensional viscous incompressible flow. The solver settings of the flow is as shown in Table III.

TABLE III
Solver Settings

Pressure Link	SIMPLE
Gradient	Least Square Cell Based
Pressure	Second Order
Momentum	Second Order Upwind
Turbulence Model	Realizable k-ε
Near Wall Treatment	Enhanced Wall Function
Solver	Steady

V. RESULT AND DISCUSSION

After modifying the leading-edge of a marine propeller with protuberances, there is a small increase in thrust generated by the propeller and a substantial decrease in torque required for different rotational speeds of the propeller have been observed computationally and these results are compared to the propeller with smooth leading edge.

The performance of the propeller is conventionally represented in terms of non-dimensional coefficients, i.e., thrust coefficient (K_T), torque coefficient (K_Q) and efficiency and their variation with advance coefficients (J). A complete computational solution for the flow around a propeller was obtained using ANSYS Fluent 16.2 software. The estimated thrust and torques for the modified propeller are shown in Table IV whereas the comparison of the computational solution with smooth leading edge is shown in Table V.

TABLE IV
Computational Estimation of Thrust and Torque with Leading-edge Protuberances

Rotational Speed (n) rps	Velocity of Advance (Va) m/sec	Advance Coefficient (J)	Thrust (T) N	Torque (Q) N-m
25	6.22	1.0947	85.1408	5.0852
30	6.22	0.9123	342.5885	14.6377
40	6.22	0.6842	1084.432	41.2032
50	6.22	0.5474	2125.7388	79.4447

TABLE V
Comparison of Performance Characteristics with and without Tubercles

Advance Coefficient (J)	Thrust Coefficient		Torque Coefficient		Efficiency	
	K_T (with tubercles)	K_T (without tubercles)	10 K_Q (with tubercles)	10 K_Q (without tubercles)	η (with tubercles)	η (without tubercles)
1.0947	0.0512	0.0448	0.1345	0.1316	0.6627	0.5936
0.9123	0.1430	0.1404	0.2688	0.2809	0.7720	0.7258
0.6842	0.2546	0.2512	0.4256	0.4460	0.6511	0.6131
0.5474	0.3194	0.3159	0.5252	0.5398	0.5296	0.5097

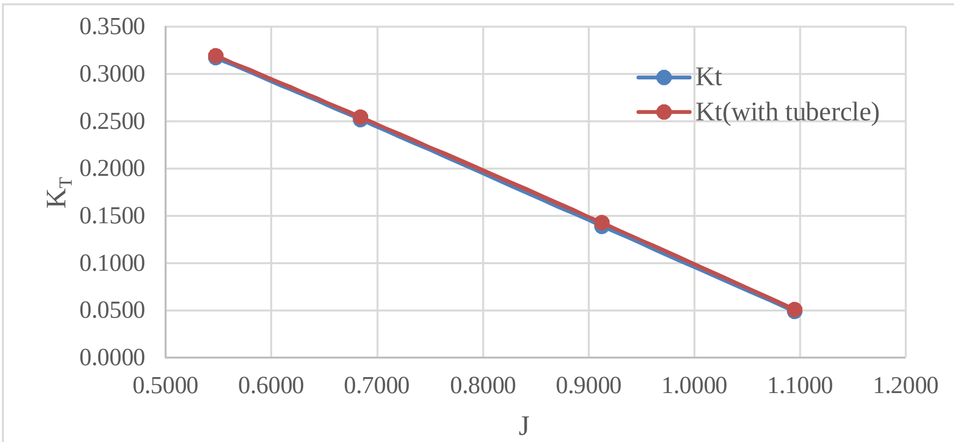

Figure 9: Comparison of K_T with and without Tubercles

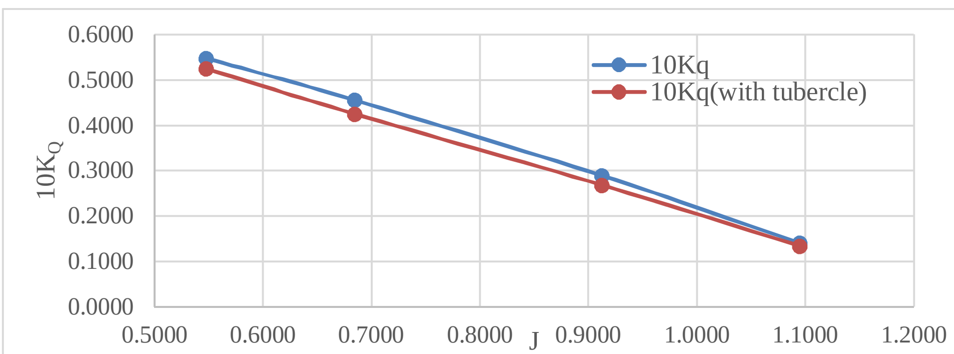

Figure 10: Comparison of K_Q with and without Tubercles

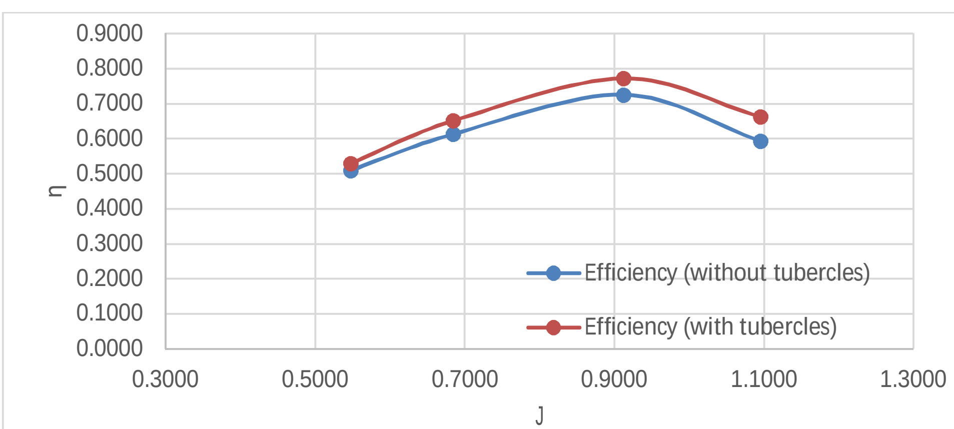

Figure 11: Comparison of η with and without Tubercles

Figure 9, Figure 10 & Figure 11 shows the comparison of predicted K_T, K_Q and η with leading-edge tubercles and without tubercles. It shows that K_T and K_Q coefficients are decreasing with increasing of advance coefficients (J). It can also be observed from Figure 9 and Figure10 that there is a small increase in thrust generated from the propeller and a substantial decrease in the torque demand with leading-edge tubercles. From Figure11 it can be seen that there is a small increment in the efficiency of the propeller with leading-edge tubercles. Maximum efficiency is observed at J = 0.9.

VI. CONCLUSION

A numerical simulation was investigated on the marine propeller INSEAN E779a with Leading-edge protuberances. The performance characteristics of the propeller with leading-edge protuberances were obtained using commercial software package ANSYS FLUENT 16.2 and compared to a propeller without tubercles.

A. The accuracy of the CFD based on RANS equation is dependent on the used turbulence model. According to the steady flow simulation, the RNG K-ε turbulence model yields to provide the most accurate results, so it is recommended to do such kind of simulation.

B. The thrust generated from the propeller is increased and torque demand is decreased and hence the efficiency of the propeller is increased by using leading-edge tubercles to the propeller.

VII. FUTURE SCOPE

The design that is considered in this work is just an example of preliminary model keeping in mind time and computational costs incurred. There is huge scope for further improvement. These can be listed as below;

A. The amplitude and wave-length of the protuberances can be varied.
B. Cavitation analysis can be performed.
C. Fluid structure interaction analysis and harmonic analysis can be performed.
D. Modal analysis can be performed by using various kinds of materials.

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