Qualification of Propeller by Experimental and Analytical Methods

K. Siva Prasad*
Department of Mechanical Engineering,
Anil Neerukonda Institute of Technology & Sciences, India
E-mail: kspanits@gmail.com
*Corresponding author

S. Murthy Bellala
Department of Mechanical Engineering,
Anil Neerukonda Institute of Technology & Sciences, India
E-mail: murthy.bellala@gmail.com

Received: 19 January 2018, Revised: 26 March 2018, Accepted: 10 June 2018

Abstract: The paper focuses on static and dynamic analysis of propeller blade made of Aluminium-24345 material. The solid model of propeller blade and propeller are developed in CATIA V5 R20. By using this model, propeller blade was manufactured using 3-Axis CNC milling machine by adopting MASTERCAM software. Qualification tests were carried out on the propeller blade of an underwater vehicle for their strength and vibration. Impact Hammer Method is employed to measure the vibration-damping properties of Propeller blade. Computational Fluid Dynamics (CFD) analysis is carried out to analyze the contours of static pressure on the 5-Blade propeller and the forces, moments acting on the propeller. Finite element analysis (FEA) of the blade was carried in ANSYS 15.0. Static, modal, harmonic analysis was carried out on analysis software for the modeled propeller blade and factor of safety was determined to qualify the propeller. Deformation of the propeller blade is measured using Coordinate Measuring Machine (CMM).

Keywords: ANSYS, Cantilever Bend Test, Impact Hammer Test, Propeller

Reference: Siva Prasad, K. and Murthy Bellala. S, "Qualification of Propeller by Experimental and Analytical Methods", Int J of Advanced Design and Manufacturing Technology, Vol. 12/No. 1, 2019, pp. 31-39.

Biographical notes: K. Siva Prasad obtained PhD from Andhra University, India in 2014. He is currently working as Professor in Department of Mechanical Engineering, Anil Neerukonda Institute of Technology & Sciences, India. His current research interest includes Manufacturing and product design. He received research funds from UGC, DST, AICTE of Government of India. He had published around 84 papers in various journals and has supervised three PhD students and six MTech thesis. He has served as Editorial Board member and reviewer for various international journals. **S. Murthy Bellala** is PG student of Department of Mechanical Engineering, Anil Neerukonda Institute of Technology & Sciences, India.

1 INTRODUCTION

The techniques of propeller stressing remained in essence unchanged throughout the development of screw propulsion until the early 1970s [1-3]. Traditionally the cantilever beam method has been the instrument of stress calculation and formed the cornerstone of commercial propeller stressing practice. However, this method has, in many instances, been superseded by finite element methods which lend themselves to a more detailed stress analysis of the propeller blade. The cantilever beam method was originally proposed by Admiral Taylor in the early years of the last century and since that time a steady development of the method can be traced [4-5].
Propeller damages caused by insufficient general strength of blades are particularly dangerous and may create a breakdown situation. Fracture (breaking off) of blades occurs as a rule in the root area where the stresses in the cross-sectional areas are highest. Since the consequences of such damages are very serious, the problems of providing for sufficient strength of blades deserve maximum attention of researchers and designers [6-8]. At the same time, it is possible to name purely technical and operational economy factors which necessitate general strength calculations of propellers being designed**.** From the technical point of view, the calculation of maximal permissible stresses for a given material under specific conditions of operation makes it possible to assume the minimum thicknesses of propeller blades and in this way to improve the hydrodynamic efficiency of the propeller and at the same time to decrease the probability of cavitation [9-12].
In the present work; Thstatic, modal, harmonic analysis was carried on propeller blade made of Aluminium-24345 using ANSYS software. Experimental analysis was also carried out and factor of safety is computed.

2 FORCES CONSIDERED FOR ANALYSIS

The propeller is a vital component for the safe operation of ship at sea. It is therefore important to ensure that ship propeller have adequate strength to withstand the forces that act upon them. The forces that act on a propeller blade arise from thrust and torque of the propeller and the centrifugal force on each blade caused by its revolution around the axis. Owing to somewhat complex shape of propeller blades, the accurate calculation of the stresses resulting from these forces is extremely difficult. The stress analysis of propeller blade with Aluminium-24345 was carried out in the present work. The calculation of the stresses in a propeller is complicated due to:

1. The loading fluctuations
2. Its distribution over the propeller blade surface
3. The complex geometry of the propeller.

It is therefore usual to use simplified methods to calculate the stresses in the propeller blades and to adopt a large factor of safety based on experience. The simple method described here is based on the following principal assumptions:

a) The propeller blade is assumed to be a cantilever fixed to the boss at the root. The critical radius is just outside the root fillets.
b) The propeller thrust and torque, which arise from the hydrodynamic pressure distribution over the propeller blade surface, are replaced by single force acting at a $1/3^{rd}$ point on the propeller blade from root section.
c) The centrifugal force on the propeller blade is assumed to act through the centroid of the blade, and the moment of the centrifugal force on the critical section can be obtained by multiplying the centrifugal force by the distance of the centroid of the critical section from the line of action of the centrifugal force.
d) The geometrical properties of the radial section (expanded) at the critical radius may be used instead of a plane section of the propeller blade at that radius, and the neutral axes may be taken parallel and perpendicular to the base line of the expended section.

3 MODELING AND FABRICATION OF SINGLE BLADE FOR EXPERIMENTAL AND ANALYTICAL TESTING

The single blade model created in CATIA V5R20 as shown in Fig. 1 is fabricated and tested experimentally and analytically.

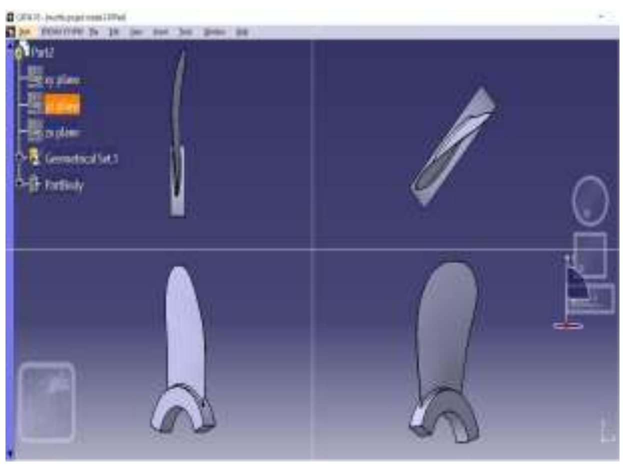

Fig. 1 3D Model of single blade propeller created in CATIA

3.1. Dimensions of Propeller blade

Length of propeller blade: 149.69 mm
Width of propeller blade at Root section: 94.0 mm
Outer diameter of Hub: 140 mm
Inner diameter of Hub: 90 mm
Thickness of blade at Root section: 11 mm
The modeled propeller is converted to IGES format and uploaded to MASTERCAM software and the manufacturing of the Propeller Blade was done using 3-axis CNC machine as shown in Figs. 2 & 3.

Fig. 2 3-Axis CNC machine used for machining of the Blade

Fig. 3 Finished top surface of blade

Fig. 4 Manufactured blade model

4 QUALIFICATION OF PROPELLOR BLADE BY CANTILEVER METHOD

The propeller thrust, which arise from the hydrodynamic pressure distribution over the propeller blade surface, are replaced by single force acting at a $1/3^{rd}$ point on the propeller blade from root section [13]. The working load and stress on the propeller blade is found analytically using Computational Fluid Dynamics (CFD) in FLUENT. In order to find the factor of safety and qualify the propeller blade, the yield stress of the propeller blade was found using the cantilever beam method [14].
The propeller blade is assumed to be a cantilever fixed at hub and free at other end. The manufactured propeller blade is fixed to the universal testing machine with the help of fixture and the load is applied in incremental steps on the propeller blade at 0.33R from root section i.e., at a distance of 50 mm with the help of plunger.

4.1. Experimental Setup

Figure 5 describes the experimental setup for the present work to perform load test on the propeller blade. The equipment specifications are given in “Table 1”.

Fig. 5 Experimental Setup of cantilever load test of propeller blade

Table 1 Specifications of UTM

Model No	UNITEK 95100
Make	FIE
Capacity	10 Tons
Test standard	ASTM E290
Test speed	0.25 mm/min
Pre-load	0.01 KN
Safe load	10 KN

The assembly of propeller blade, fixture, plunger and dial gauge to the UTM is shown in Fig. 6.

Fig. 6 Assembly of propeller blade and dial gauge to the fixture

4.2. Application of Load on Propeller Blade

Load is applied on the propeller blade with the help of plunger provided, incremental loads of 0.5 KN was applied on the blade. When the load is removed it was observed that there is no permanent deformation in the blade until the application of load of 3.5 KN. 4.0 KN of Load is applied on the propeller blade by movement of plunger with a control displacement of 0.25 mm/min. The result of the test is shown in the Figs. 7 and 8.

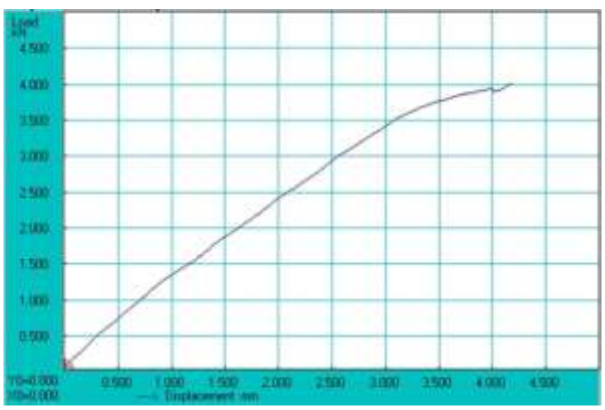

Fig. 7 Load vs Displacement plot at 4.0 KN Load

When the load is removed it is observed that the propeller blade does not retains to its original position which indicates there is permanent deformation occurred in the blade due to application of 4.0 KN load. The stress on blade at this load is 466 N/mm^2.

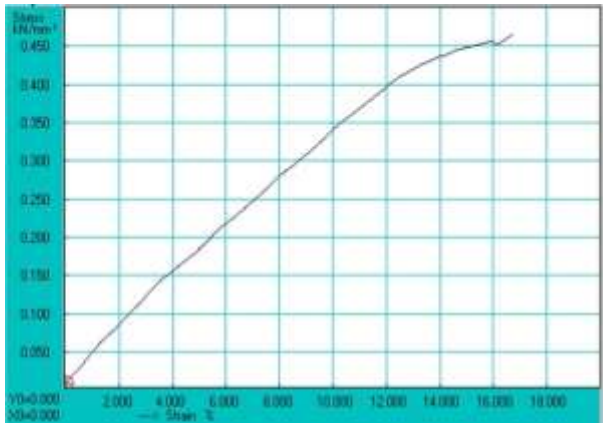

Fig. 8 Stress vs Strain plot at 4.0 KN Load

4.3. Static Analysis of Propeller Blade using ANSYS for Determination of Stress and Deformation

Static analysis is concerned with the behavior of elastic continuum under prescribed boundary conditions and statically applied loads. The propeller blade was considered as a cantilever beam fixed at one end and free at other end. The given loads of 0.5 KN to 4.0 KN were applied normal to the surface of blade and then static stresses and deformation of the blade are determined. The analysis of blade at 4.0 KN is as shown in the Figs. 9 and 10. Comparison of experimental & analytical data for stress and deformation is shown in “Table 2”.

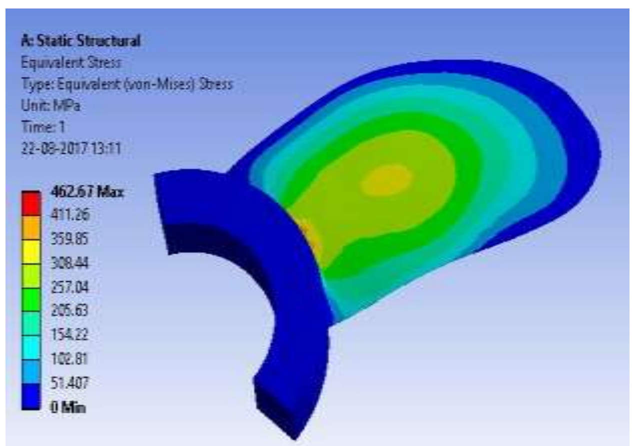

Fig. 9 Stress Analysis at 4.0 KN

Overall % error is found and the very reason for having an error with the experimental and ANSYS results is due to the series of assumptions that are followed in the experimental analysis owing to the high degree complexity of the geometry of the propeller blade for which exact analytical solution is very tedious and cumbersome process.

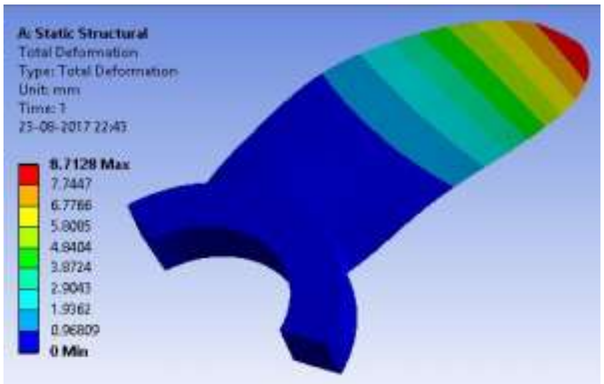

Fig. 10 Deformation at 4.0 KN

Table 2 Comparison of experimental & analytical data for stress and deformation

Load KN	Stress (MPa)			Deformation (mm)		
	Experimental	Analytical	% Error	Experimental	Analytical	% Error
0.5	59	57.83	1.98 %	0.81	0.970	16.49 %
1.0	118	115.67	1.97 %	1.65	1.964	15.98 %
1.5	176	173.50	1.42 %	2.62	2.950	11.18 %
2.0	233	231.33	0.71 %	3.68	3.920	6.12 %
2.5	292	289.17	0.96 %	4.79	4.910	2.44 %
3.0	352	347.00	1.42 %	5.93	5.900	0.50 %
3.5	408	404.83	0.77 %	7.05	6.891	2.25 %
4.0	466	462.67	0.71 %	9.10	8.712	3.69 %

Fig. 11 CMM Global to check deformation

4.4. Co-ordinate Measuring Machine to Check Deformation

The Co-ordinate measuring machine is used to check deformation at equal intervals of 10 mm on the center line of the propeller blade before and after the cantilever load test. The probe used to measure the co-ordinates is the finest probe produced by TESASTAR. The specification of the CMM is given in "Table 3". The GLOBAL CMM measuring the deformation of propeller blade is shown in Fig. 11.

Table 3 Specifications of Co-ordinate Measuring Machine

Model	Global performance
Make	DEA
High accuracy	Sensor accuracy of ± 20 μm
Probe	TESASTAR

The CMM data for propeller blade is taken at 10 mm interval on the center line of the blade and the report data is given below in "Table 4".

Table 4 CMM result for propeller blade before and after load test

S.No	Y-Axis (mm)	Before Load test Z-Axis (mm)	After Load test Z-Axis (mm)
1	80	11.255	11.263
2	90	11.896	11.90
3	100	12.718	12.734
4	110	13.322	13.344
5	120	13.805	13.831
6	130	14.201	14.231
7	140	14.610	14.650
8	150	14.961	15.014
9	160	15.360	15.429
10	170	15.915	16.002
11	180	16.455	16.563
12	190	16.784	16.900
13	200	17.073	17.228
14	213	17.671	17.860

5 CFD ANALYSIS OF PROPELLER

Figure 12 shows the contours of static pressure on the 5-Blade propeller and the forces, moments acting on the propeller. The forces acting on 5 Blade propeller are shown in "Table 5".

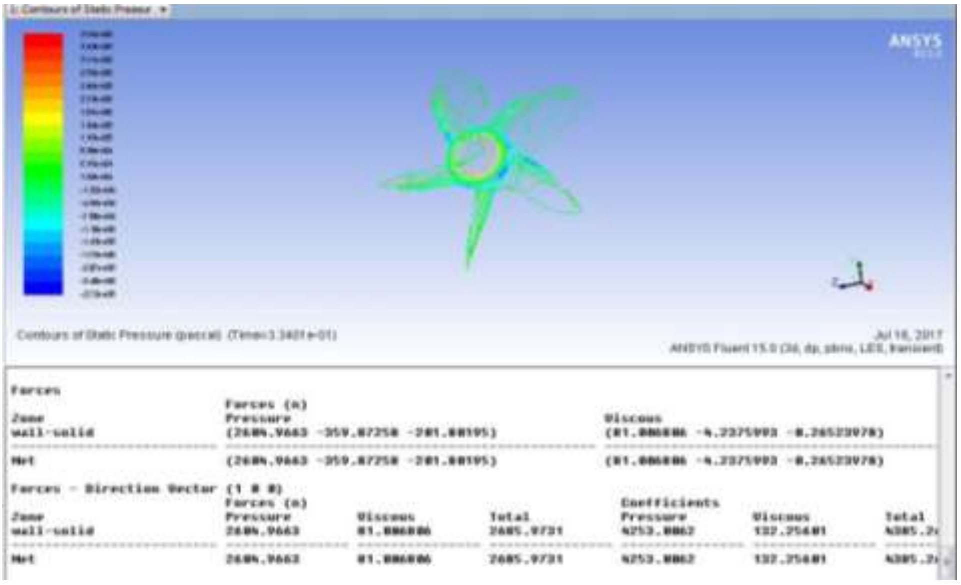

Fig. 12 CFD-LES analysis of 5 blade propeller in FLUENT

Table 5 Forces acting on 5 Blade propeller

Force vector (1 0 0) Zone name	Pressure force (N)	Viscous force (N)	Total force (N)	Pressure coefficient	Viscous coefficient	Total coefficient
Wall	2604.96	81.00	2685.97	4253.00	132.25	4385.25
Net	2604.96	81.00	2685.97	4253.00	132.25	4385.25

5.1. Calculation of Factor of Safety

F.S = Yield Load/Working Load = 4000/2604.96 = 1.53

It is found from the cantilever load test that the propeller is within safer limits and having a factor of safety of 1.53.

6 QULIFICATION OF PROPELLER BY VIBRATION ANALYSIS

6.1. Vibration Analysis on Propeller Blade using Impact Hammer Test Method

This test method measures the vibration-damping properties of Propeller blade. Accurate over a frequency range of 50 to 5000 Hz and over the useful temperature range of the material, this method is useful in testing materials that have application in structural vibration, building acoustics, and the control of audible noise.

Table 6 Instruments used for the test

Accelerometer	Type 4519-003 (Make: B&K)
Impact hammer	Type 086D05 (Make: PCB)
Software	LANXI Pulse Analyser, Version 16.1 (Make:B& K)

Such materials include metals, enamels, ceramics, rubbers, plastics, reinforced epoxy matrices, and woods that can be formed to cantilever beam test specimen configurations [15]. Instruments used for the test are shown in “Table 6”.

Fig. 13 Experimental setup for impact hammer test method

6.2. Test Methodology

Impact hammer test was carried out to determine the Frequency Response Function and damping ratios of Propeller Blade. The blade was fixed like cantilever and impact test was carried out to determine the damping ratio. One end of the blade was fixed in bench vice and the other end was free. The blade was excited by impact hammer having inbuilt force sensor to measure the force and response was measured on the sample by using accelerometer. The frequency range of measurement is DC - 2 kHz.

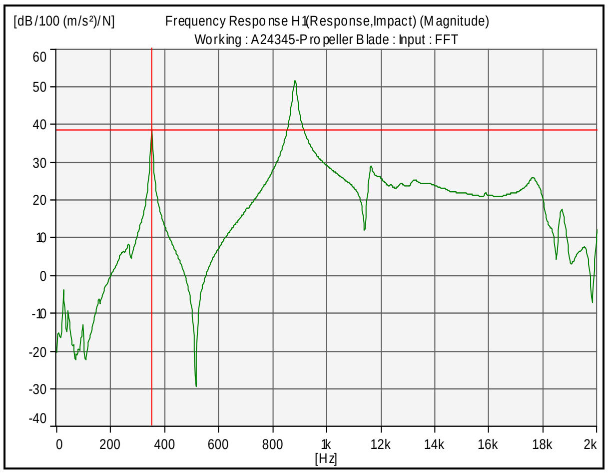

Fig. 14 FRF of AL-24345 Propeller Blade

The Natural frequencies and Damping ratios of Propeller blade is evaluated from FRFs and comparative statement is made and shown in "Table 7".

Table 7 Natural frequency and damping ratios of AL-24345 Propeller blade

SL. No	Name of Sample	Modal Frequency(Hz)	Damping Ratio (%)
1	AL-24345 Propeller Blade	350	0.771
2	AL-24345 Propeller Blade	880	0.802

6.3. Vibration Analysis on Propeller Blade using ANSYS

Modal and harmonic analysis is used to determine the natural frequencies and mode shapes of a structure. The natural frequencies and mode shapes are important parameters in the design of a structure for dynamic loading conditions. They are also required to do a spectrum analysis or a mode superposition harmonic or transient analysis. The natural frequencies for the corresponding mode shapes of the propeller blade obtained from modal analysis are shown in "Table 8". So, the fundamental frequency of propeller is 368.63 Hz.

Table 8 Details of Mode shape and frequency for propeller blade

Mode	Frequency [Hz]
1.	368.63
2.	1019.5
3.	1291.3
4.	2034.8
5.	2480.3
6.	3242.3

Frequency Response Graph

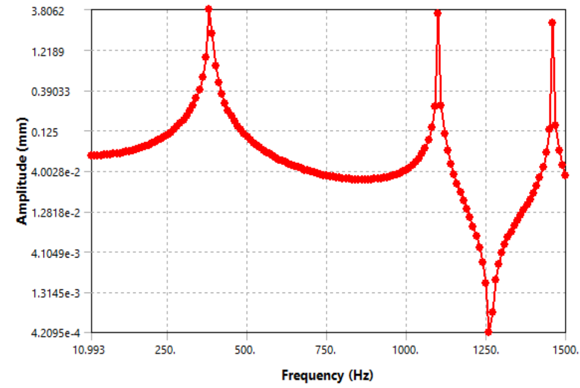

Fig. 15 Variation of amplitude with different exciting frequencies

6.4. Comparison of Analytical and Experimental Result

A finite element propeller model was developed and applied to the analysis of propeller vibrations. Experimental verification of the predicted natural modes was undertaken using accelerometers. The experimental results are used to verify the numerical results obtained in a FE analysis. There is a good correspondence between the measured and calculated natural frequencies and the mode shapes, even though the measured frequencies are lower than the predicted values. The predicted mode shapes and natural frequencies agree remarkably well with experimental observations for the lower modes. Comparison of analytical and experimental result is shown in "Table 9".

Table 9 Comparison of Analytical and Experimental result

Frequency value in Hz		% Error
Experimental	By ANSYS	5.053 %
350	368.63	

From the vibration testing of the blade experimentally and analytically, it is observed that the natural frequency of the propeller blade is almost same with an error of 5%. From the cantilever load test experimentally and analytically, the factor of safety of the propeller is determined based on the working loads on the propeller.

7 CONCLUSIONS

➢ A finite element propeller model was developed and applied to the analysis of propeller vibrations. Experimental verification of the predicted natural modes was undertaken using accelerometers. Comparison of analytical and experimental results was based on correspondence of mode shapes recorded with contour plots of modes determined computationally. The predicted mode shapes and natural frequencies agree remarkably well with experimental observations for the lower modes.

- From the cantilever load test experimentally and analytically, the factor of safety of the propeller is determined based on the working loads on the propeller. From the CMM result, it is observed that there is a deformation of 0.19 mm at the tip of the blade due to application of 4 KN of load on the propeller blade. It is found from the static analysis that the propeller blade is within safer limits and having a factor of safety of 1.53.

REFERENCES

[1] Pavan Kishore, M. L., Behera, R. K., Pradhan, S. K., Parida and P. K., Effect of Material Behavior on Dynamic Characteristics Determination of Marine Propeller Blade using Finite Element Analysis, Procedia Engineering, Vol. 144, 2016, pp. 767 – 774.

[2] Dubbioso, G., Muscari, R. and Di Mascio, A., Analysis of a Marine Propeller Operating in Oblique Flow, Elsevier- Computers & Fluids, Vol. 92, No.1, 2014, pp. 56–81.

[3] Haimov, H., Gallego, V., Enrique Molinelli and Borja, T., Propeller Acoustic Measurements in Atmospheric Towing Tank, Ocean Engineering, Vol. 120, 2015, pp. 190-201.

[4] Fang wen, H., Shi tang, D., Numerical Analysis for Circulation Distribution of Propeller Blade, Journal of Hydrodynamics Vol. 22, No. 4, 2010, pp. 488-493.

[5] Sebastian Kowalczyk, A., JudytaFelicjancik, N., Numerical and Experimental Propeller Noise Investigations, Ocean Engineering., Vol.120, 2016, pp.108-115.

[6] Kaidi, S., Smaoui1, H. and Sergent, P., Numerical Estimation of Bank-Propeller-Hull Interaction Effect on Ship Manoeu- Vring using CFD Method, Journal of Hydrodynamics, Vol. 29, No.1, 2017, pp.154-167.

[7] Yao, J., Investigation on Hydrodynamic Performance of a Marine Propeller in Oblique Flow by RANS Computations, Ocean Engineering., Vol. 7, 2015, pp. 56-69.

[8] Cansın Özdena, M., Gürkana, A. Y., Arıkan Özdenb, Y., Canyurta, T. G. and Korkuta, E., Underwater Radiated Noise Prediction for a Submarine Propeller in Different Flow Conditions, Ocean Engineering., Vol.126, 2016, pp.488-500.

[9] Usha, Y., sateesh, B. and Murthy, B. S. R., Modelling and Analysis of Five Blade Ship Propeller, International Journal of Mechanical Engineering and Materials Sciences (IJMEMS), Vol.7, No.1, 2014, pp. 77-81.

[10] Jalali, H., Ahmadian, H., Model Identification and Dynamic Analysis of Ship Propulsion Shaft Lines, Journal of Theoretical and Applied Vibration and Acoustics, Vol. 1, No. 2, pp. 85-95.

[11] Uppalapati, S., Raghavulu K. V. and Kumar Singam, K., Design and Analysis of Propeller Blade Using CATIA & ANSYS Software, International Journal of Management, Information Technology and Engineering, Vol. 4, No. 4, 2016, pp. 83-96.

[12] Seetharama Rao, Y., Sridhar Reddy, B., Harmonic Analysis of Composite Propeller for Marine Applications, International Journal of Research in Engineering and Technology, Vol.1, No.3, 2012, pp. 257-260.

[13] Bhanu Priya, M., Mohan Krishna, K. and Giribabu, P., Design and Analysis of a Propeller Blade, IRJET, 2015, pp. 1198-1202.

[14] Burrill, L. C., Marine Propellers and Propulsion, Chapter 19.

[15] Burrill, L. C., Marine Propellers and Propulsion, Chapter 21.

[16] Pavan Kishore, M. L., Behera, R. K. and Harsha Vardhan, D., Free Vibration Analysis of Four Bladed Propeller using Different Materials, Proceedings of 4th SARC International Conference, 30th March-2014.

[17] Pavan Kishore, M. L., Behera, R. K., Sreenivasulu Bezawada, Structural Analysis of NAB Propeller Replaced with Composite Material, International Journal of Modern Engineering Research (IJMER), Vol. 3, No.1, 2013, pp. 401-405.

[18] Chittaranjan Kumar Reddy, T., Nagaraja Rao, K., Design and Simulation of a Marine Propeller, International Journal of Research in Advanced Engineering Technologies, Vol. 5, No. 1, 2015, pp. 111-128.

[19] Ristea, M., Popa, A. and Ionut Neagu, D., CFD Modelling of a 5 Bladed Propeller by Using the RANSE Approach, Naval Academy Scientific Bulletin, Vol. XVIII, No. 2, 2015.

[20] Colley, E., Analysis of Flow Around a Ship Propeller using OpenFOAM, Curtin University, October, 2012.

[21] Samad, Z., Abdullah, A. B., Khaleed, H. M. T., Abu-Bakar M. H. and Arshad, M. R., A Novel Manufacturing Method of Propeller for Autonomous Underwater Vehicle (auv) using Cold Forging Process, Indian Journal of Geo Marine Sciences, Vol. 41, No. 3, 2012, pp. 242-248.

[22] Chen, F., Liu, L., Lan, X., Li, Q., Leng, J. and Liu, Y., The Study on the Morphing Composite Propeller for Marine Vehicle. Part I: Design and Numerical Analysi, Composite Structures, Vol. 168, 2017, pp. 746-757.

[23] Aktas, B., Atlar, M., Turkmen, S., Shi, W., Sampson, R., Korkut, E. and Fitzsimmons, P., Propeller Cavitation Noise Investigations of a Research Vessel using Medium Size Cavitation Tunnel Tests and Full-Scale Trials, Ocean Engineering, Vol.120, 2016, pp.122-135.

[24] Abbas, N., Kornev, N., Shevchuk, I. and Anschau, P., CFD Prediction of Unsteady Forces on Marine

Propellers Caused by the Wake Non-Uniformity and Non-Stationarity, Ocean Engineering, Vol. 104, 2015, pp. 659–672.

[25] Majumder, P., Pandey, K. M. and Deshpand, N. V., Design and Analysis of a Propeller Blade for Underwater Vehicle, Journal of Material Science and Mechanical Engineering (JMSME), Vol. 3, No. 2, 2016, pp. 105-110.