Performance evaluation of composite marine propeller using L_8 orthogonal array

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Abstract

This work aims at understanding the effect of various parameters on the performance of a marine propeller using L_8 orthogonal array. The parameters chosen are advance velocity V_a, rotational speed N and the stacking sequence S. A four bladed composite propeller made of glass-epoxy is modelled using dynamic hydro-elastic scaling laws for marine propulsors and analyzed using the hydro-elastic model. An L_8 orthogonal array is used for understanding the effect of various parameters and their interaction effect on the performance of a marine propeller in terms of open water characteristics.

1. Introduction

Marine propeller is a component which forms the principal part of ships since it gives the required propulsion. Fiber reinforced plastics are extensively used in the manufacturing of various structures including the marine propeller. The hydrodynamic aspects of the design of composite marine propellers have attracted attention because they are important in predicting the deflection and performance of the propeller blade. A procedure for calculating the blade performance must involve numerical methods accounting for the nonlinear deflection and loading. A geometrically non-linear calculation is needed to calculate the quasi-static deflection of the blade that results from the centrifugal force and the distribution of pressure in the fluid. For designing an optimized marine propeller one has to understand the parameters that influence the hydro-dynamic behavior. Since propeller is a complex geometry, the analysis could be done only with the help of numerical tools. Most marine propellers are made of metal material such as bronze or steel. The advantages of replacing metal with an FRP composite are that the latter is lighter and corrosion-resistant. Another important advantage is that the deformation of the composite propeller can be controlled to improve its performance. Propellers always rotate at a constant velocity that maximizes the efficiency of the engine. When the ship sails at the designed speed, the inflow angle is close to its pitch angle. When the ship sails at a lower speed, the inflow angle is smaller. Hence, the pressure on the propeller increases as the ship speed decreases. The propulsion efficiency is also low when the inflow angle is far from the pitch angle. If the pitch angle can be reduced when the inflow angle is low, then the efficiency of the propeller can be improved. Traditionally marine propellers are made of manganese-nickel-aluminum-bronze (MAB) or nickel-aluminum-bronze (NAB) for superior corrosion resistance, high-yield strength, reliability, and affordability. More over metallic propellers are subjected to corrosion, cavitation damage; fatigue induced cracking and has relatively poor acoustic damping properties that can lead to noise due to structural vibration. Moreover, composites can offer the potential benefits of reduced corrosion and cavitation damage, improved fatigue performance, lower noise, improved material damping properties, and reduced lifetime maintenance cost. In addition the load-bearing fibers can be aligned and stacked to reduce fluttering and to improve the hydrodynamic efficiency by automatically adjusting the shape of the blade [*young 2001*]. Lin (1991a, 1991b) analyzes by the finite element method a moderately skewed partial composite blade from a 0.21m diameter seven-blade propeller, and compares the results with an all-alloy blade of the same geometry. The stress computations are performed using three-dimensional solid finite elements, and strength checks are made based on the finite element results. The computed tip deflection of the composite blade is an order of magnitude larger than that of the isotropic alloy blade. The maximum in-plane bending and shearing stresses for the composite blade are approximately 50 percent greater than the all-alloy blade. Lin and Lin (1997) examine the effects of stacking sequences on the performance of a composite propeller using a coupled fluid-structure interaction method. A geometrically non-linear finite element procedure for the structural analysis is coupled with non-cavitating lifting surface theory for the fluid analysis. The finite element analysis uses a degenerate shell element with five degrees of freedom per node. The effects of stacking sequence on the thrust, torque, efficiency and deflections are examined for a 1.40m diameter three-blade carbon fibre and epoxy propeller. Model scale analysis remains the standard means of evaluating the performance of the prototype because of the cost and the configuration considerations. In this work, the prototype is scaled down using the dynamic hydro-elastic scaling laws for the flexible rotors. Then the model is analyzed using the fluid and structural analysis. The fluid analysis is carried out using the general purpose CFD software Fluent 6.3.26 and structural analysis is carried out using ANSYS11. With the increased use of fiber-reinforced composites in structural components, studies involving the behavior of such structures and their members are receiving considerable attention. This study is directed toward one such engineering application, i.e., the composite propeller. The objective of this research is to study numerically the behavior of a conventional propeller, made from composite material, under hydro-dynamic loading. Emphasis is placed on understanding the effects of various parameters on propeller performance.

1.1. Propeller performance

In general, the performance of a marine propeller is measured in-terms of open-water characteristics. The parameters used for this purpose are

$$advance\ coefficient = J = \frac{V_a}{nD}$$

$$torque\ coeffcient = K_Q = \frac{Q}{\rho n^2 D^5}$$

$$thrust\ coefficient = K_T = \frac{T}{\rho n^2 D^4}$$

$$efficiency = \eta = \frac{TV_a}{2\pi nQ} = \frac{K_T * J}{2\pi K_Q}$$

$where\ D = daimeter\ of\ the\ propeller;$

$V_a = axial\ velocity;$

$n = rotational\ velocity(rps);$

$\rho = fluid\ density;$

$T = thrust\ and$

$Q = torque.$

2. Methodology

In this work, three parameters are considered for analysis. They are advance velocity Va, rotational speed N and the stacking sequence. For this purpose a four bladed prototype propeller having diameter 410mm is scaled down using hydro-dynamic scaling laws for shape-adoptive marine propulsors as shown in table 1. The scaling factor adopted here is $\lambda_D = 1/2$. accordingly the parameters are evaluated for prototype and the model for Reynolds similarity. The fluid analysis is carried out using the general purpose CFD software Fluent 6.3.26 fairing caps and shaft are added to the propeller. The inlet was considered at a distance of 3D (where D is diameter of the propeller) from mid of the chord of the root section. Outlet is considered at a distance of 4D from same point at downstream. In radial direction domain was considered up to a distance of 4D from the axis of the hub. This peripheral plane is called far-field boundary. The mesh was generated in such a way that cell sizes near the blade wall were small and increased towards outer boundary. The pressure obtained from the above analysis is used as an input to the structural model using general purpose finite element software ANSYS 11.0 to get the deformed configuration. Fluid analysis is carried out again on the deformed configuration to obtain the new pressure distribution on the blades. This process is repeated till the convergence is achieved, i.e the difference is K_Q between two consecutive iterations is less than 5%. The methodology adopted is as shown in fig1.

Table 1: scaling factors of different variables

Variable	**symbol**	**expression**	$\lambda_{R_n} = 1$
Reynolds number	R_n	$\frac{\lambda_n \lambda_D^2}{\lambda_v}$	1
Axial velocity	V_a	λ_V	$^1/_{\lambda_D}$
Angular velocity	n	λ_n	$^1/_{\lambda_D^2}$
Angular velocity	n	λ_n	$^1/_{\lambda_D^2}$
Elastic modulus	E_i	$\lambda_{E_i} = \lambda_n^2 \lambda_D^2$	$^1/_{\lambda_D^2}$
Shear modulus	G_{ij}	$\lambda_{G_{ij}} = \lambda_n^2 \lambda_D^2$	$^1/_{\lambda_D^2}$
Poisons ratio	ν_{ij}	$\lambda_{\nu_{ij}}$	1

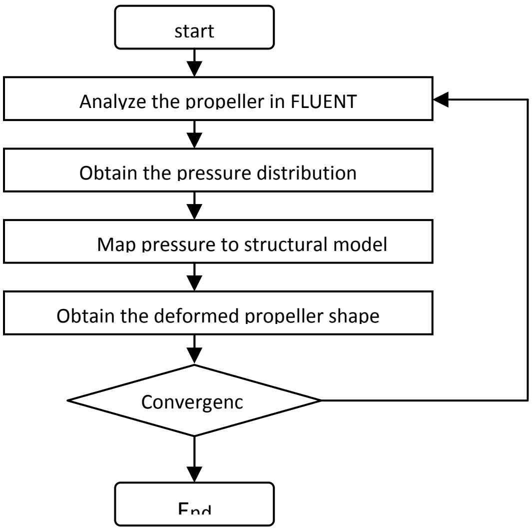

Fig 1: Hydro-elastic model

3. Results and discussion

The analysis is carried out for three parameters at two levels using an L_8 orthogonal array. The material properties of glass-epoxy are shown in table 2 and the parameters and the values used are presented in table 3.

Table 2: Properties of glass-epoxy

Material properties	**Full model**
E1	153 GPa
E2	10.9 GPa
G12	5.9 GPa
G13	5.9 GPa
ν 12	0.3

Table 3: L_8 Array and the parameters

Run	*Va(m/sec)*	*N(RPM)*	*Stacking sequence*
1	6.2	1100	S 1
2	6.2	1100	S 2
3	6.2	1500	S 1
4	6.2	1500	S 2
5	9.25	1100	S 1
6	9.25	1100	S 2
7	9.25	1500	S 1
8	9.25	1500	S 2

Where S 1 and S 2 consist of all glass-epoxy layers of 0.3mm thick and the stacking sequence is as shown. $S1 = [0/\pm 22.5/90/\pm 45/0/\pm 67.5/\overline{90}]s$, $S2 = [90/\pm 22.5/0/\pm 45/90/\pm 67.5/\bar{0}]s$. The table 4 presents the effect of various parameters on the thrust coefficient Kt.

Table 4: effect of various parameters on K_T

Run	Va (m/sec)	N(RPM)	Va*N	S	Va*S	N*S	Va*N*S	K_T
1	1	1	1	1	1	1	1	0.094
2	1	1	1	2	2	2	2	0.22
3	1	2	2	1	1	2	2	0.222
4	1	2	2	2	2	1	1	0.243
5	2	1	2	1	2	1	2	0.11
6	2	1	2	2	1	2	1	0.226
7	2	2	1	1	2	2	1	0.27
8	2	2	1	2	1	1	2	0.245
S1	0.779	0.65	0.829	0.696	0.787	0.692	0.833	
S2	0.851	0.98	0.801	0.934	0.843	0.938	0.797	
S2-S1	0.072	**0.33**	-0.028	0.238	0.056	**0.246**	**-0.036**	

The advance velocity, rotational speed, stacking sequence, combination of advance velocity and stacking sequence, rotational speed and stacking sequence are having positive correlation. In that rotational speed is highly influencing then followed by combination of rotational speed and stacking- sequence. The combination of advance velocity, rotational speed and advance velocity, rotational speed and stacking sequence are having negative correlation. In that interaction of all the three parameters is influencing more. Similarly the effect of various parameters on the torque coefficient Kq is obtained as shown in table 5.

Table 5: effect of various parameters on K_Q

Run	Va (m/sec)	N(RPM)	Va*N	S	Va*S	N*S	Va*N*S	K_Q
1	1	1	1	1	1	1	1	0.0245
2	1	1	1	2	2	2	2	0.0622
3	1	2	2	1	1	2	2	0.062
4	1	2	2	2	2	1	1	0.069
5	2	1	2	1	2	1	2	0.031
6	2	1	2	2	1	2	1	0.051
7	2	2	1	1	2	2	1	0.077
8	2	2	1	2	1	1	2	0.055
S1	0.2177	0.1687	0.2187	0.1945	0.1925	0.1795	0.2215	
S2	0.214	0.263	0.213	0.2372	0.2392	0.2522	0.2102	
S2-S1	**-0.0037**	**0.0943**	-0.0057	0.0427	0.0467	0.0727	-0.0113	

As seen from table 5, the rotational speed, stacking sequence, combination of advance velocity and stacking sequence, and combination of rotational speed and stacking sequence are having positive effect as far as torque coefficient is concerned, i.e increasing the values will increase the Kq. In that the rotational speed has more effect on Kq. And the other parameters are having negative correlation. Similarly the effect on the efficiency is evaluated as presented in table 6.

Table 6: effect of various parameters on η

Run	Va (m/sec)	N(RPM)	Va*N	S	Va*S	N*S	Va*N*S	η
1	1	1	1	1	1	1	1	0.673
2	1	1	1	2	2	2	2	0.68
3	1	2	2	1	1	2	2	0.678
4	1	2	2	2	2	1	1	0.698
5	2	1	2	1	2	1	2	0.72
6	2	1	2	2	1	2	1	0.75
7	2	2	1	1	2	2	1	0.73
8	2	2	1	2	1	1	2	0.791
S1	2.729	2.823	2.874	2.801	2.892	2.882	2.851	
S2	2.991	2.897	2.846	2.919	2.828	2.838	2.869	
S2-S1	0.262	0.074	-0.028	0.118	-0.064	-0.044	0.018	

The advance velocity is playing a prominent role as far as efficiency is concerned.

4. Conclusions

1. The propeller which is a complex geometry can be analyzed numerically for performance evaluation.
2. The dynamic hydro-elastic scaling laws for shape adoptive composite materials along with hydro-elastic model prove to be an efficient tool for the analysis of marine propeller.
3. Taghchi's orthogonal arrays can be used effectively for understanding the effect of various parameters and their interaction effects on the performance of a marine propeller.
4. This analysis can be used for designing a marine propeller for specific requirement by controlling the affect of various parameters.

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