Prini F, Benson SD, Dow RS.

The Effect of Laminate, Stud Geometry and Advance Coefficient on the Deflection of a Composite Marine Propeller.

In: Proceedings of the 6th International Conference on Marine Structures (MARSTRUCT 2017). 2017, Lisbon, Portugal: Taylor and Francis.

Copyright:

This is the author's manuscript of a paper that was presented at *6th International Conference on Marine Structures (MARSTRUCT 2017)*, held 8-10 May 2017, Lisbon, Portugal

DOI link to article:

<https://www.routledge.com/Progress-in-the-Analysis-and-Design-of-Marine-Structures-Proceedings-of/Soares-Garbatov/p/book/9781138069077>

Date deposited:

04/05/2017

Embargo release date:

28 April 2018

This work is licensed under a

[Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International licence](https://creativecommons.org/licenses/by-nc-nd/4.0/)

The Effect of Laminate, Stud Geometry and Advance Coefficient on the Deflection of a Composite Marine Propeller

F. Prini, S.D. Benson & R.S. Dow

Newcastle University, Newcastle-upon-Tyne, UK

ABSTRACT: The effect of key design parameters including laminate lay-up, stud geometry and advance coefficient on the structural response of a large composite marine propeller is investigated. The deflection patterns are evaluated for three different propeller loading conditions, four different carbon/epoxy composite constructions and three different blade-hub attachment studs. The displacement patterns show how these factors affect the deflection experienced by composite blades. The twist of the blade sections for a given propeller loading condition, hence the rate of change of pitch, is shown to be related to the mechanical properties of the laminate and the stud geometry. Results suggest that, by taking into account the laminate lay-up and the whole propeller operational range, a desired blade deflection pattern can be achieved if the material design is embedded into the structural and hydrodynamic design. Hydroelastic effects can be positively exploited to dynamically vary the blade pitch with a potential increase of the propeller hydrodynamic performance.

1 INTRODUCTION

Materials usually employed in the construction of large marine propellers are nickel-aluminium bronze (NAB) and manganese-nickel-aluminium bronze alloys. These materials present high corrosion resistance, high-yield strength, reliability and cost convenience. Nevertheless, alloys used for the construction are subject to corrosion, cavitation damage and fatigue induced-cracking. Their poor damping properties induce relatively high structural vibration with consequent noise (Young, 2008). Moreover, the weight of bronze alloy propellers can considerably influence the ship displacement. The high concentrated load at the end of the shaft line can increase the wear of gearbox and shaft bearings.

The increasing use of composite materials in many different structural applications has promoted an increasing interest in employing them as an alternative for propeller construction. Composite propellers have potential advantages compared to their metal counterparts. Reduced corrosion and cavitation damage, improved fatigue performance, improved vibration damping properties with subsequent lower noise are some of the potential benefits of composite propellers. Moreover, their low magnetic, acoustic and electric signatures are of high interest to the naval sector.

Composite blades can be designed with the fibres aligned to support the major loading experienced in operating condition and achieve maximum performance in terms of mechanical properties and weight optimisation. However, the stiffness of composite

blades for a given geometry is still lower than that of metal blades. As a consequence, hydroelastic effects may be of greater importance. The lower stiffness of composites causes greater blade deflections. If not considered properly, this is likely to result in inferior hydrodynamic performance of composite blades. However, it gives the designer the possibility of exploiting the potential advantages of hydroelasticity.

As load is taken up by the propeller, blade deflection occurs in both the radial and chordal directions. Fundamentally this results in a variation of the blade pitch angle. The propeller pitch is defined to have maximum efficiency at specific design conditions; consequently, if the same blade geometry as for a metal propeller is used, then this variation results in a reduction of the propeller efficiency. However, the blade can be designed to account for the reduction of pitch when the hydrodynamic load increases on the blade. Precisely, the blade pitch in unloaded condition should be higher in order to account for the reduction of pitch under loaded condition, due to the effect of hydroelasticity. As a result, the efficiency of a composite propeller should equal that of a metal propeller at the design condition and could give higher performance at off-design conditions.

The rate of change of pitch with the propeller loading condition is strictly related to the elasticity of the blade, which depends on the mechanical properties of the composite. Different stacking sequences and laminate lay-ups will provide the blade with different deflection properties in each of the radial and chordal directions. Understanding the effect of these

parameters on the blade deflection patterns becomes therefore fundamental in order to improve the hydrodynamic performance of composite propellers.

2 BACKGROUND

2.1 Advantages of Composite Propellers

As reported by Young (2008), the use of composite materials can lead to substantial weight savings between 50 and 80%, since they are characterised by high strength-weight and stiffness-weight ratios. Reduced corrosion, cavitation damage and improved fatigue performance are other potential benefits of composite propellers that reduce their lifetime maintenance cost. The material damping properties guarantee good acoustic and structural performance in terms of noise attenuation and blade vibration reduction. The use of lighter composite materials allows the blades to be thicker without significantly adding to the weight of the propeller, and more flexible, so that the hydrodynamic performance can be enhanced by increasing the cavitation inception speed.

The better cavitation performance is also highlighted by Selvaraju and Ilaiyavel (2011). They show that theoretical models predict a cavitation inception speed for composite propeller 30% higher compared to that of an original NAB propeller.

Fibre-reinforced composites can be tailored to specific requirements of certain applications (Almeida and Awruch 2009) by exploiting their anisotropic properties. By considering different fibre orientations and stacking sequences of the laminate, the propeller mechanical properties and its performance can be significantly influenced.

2.2 Hydroelasticity of Composite Propellers

Composite marine propellers are subject to two mechanisms that deeply influence their performance: bending-twisting coupling effects of anisotropic composites and load-dependent self-adaptation behaviour of composites blades (Ahmed and Wei, 2012). Importance of these effects is explained by Lin et al (Lin et al., 2009): the propulsion efficiency increases when the inflow angle is close to the pitch angle. Since the inflow angle is proportional to the ship speed, “if the pitch angle can be reduced when inflow angle is low, then the efficiency of the propeller can be improved” (Lin et al., 2009). The bend-twist coupling effect generated by the water pressure over the propeller blades changes the pitch of the propeller and, hence, its performance.

Studies performed by Motley et al. (2009) demonstrated that the bending-twisting coupling effects and the load-dependent self-adaptation behaviour of blades that composite propellers are subject to, are the primary sources for performance improvement.

They evaluated systematically designed self-twisting composite propellers under both steady and unsteady operating conditions. Fluid structure interaction effects were identified and analysed and it was shown that self-twisting propellers lead to significant improvement in energy efficiency.

2.3 Analysis of Composite Propellers

Lin et al. (2005) evaluated the strength of a composite propeller by performing a nonlinear hydro-elastic analysis. Further studies were performed by Young (2008) and (Liu and Young, 2009) using a boundary element method coupled with a finite element software. The studies confirmed that the stacking sequence and the material composition strongly affect the stress distribution and the deflection patterns. Moreover, the propeller can be designed to de-pitch near the tip. Other studies agreed that the tip deflection helps to delay cavitation inception due to reduced tip loading (Gowing *et al.*, 1998) and results presented in Chen et al (2006) confirmed that a properly designed flexible propeller can have a higher efficiency under off-design conditions and that cavitation inception can be delayed significantly.

A major extension to Young’s research was completed by Lin et al (2009), who demonstrated, through experimental results, the changeable pitch effect in composite propellers. Results showed that, for small values of the advance coefficient, a non-optimised propeller efficiency decreases, due to the increasing pitch angle. For an optimised propeller the pitch automatically changes with the inflow angle, reducing torque and increasing efficiency.

Another aspect of flexible propeller optimisation was addressed by Blasques et al (2010) through the development of a hydro-elastic model to control the deformed shape of the propeller and consequently the thrust developed and the torque force. Further research projects investigated the influence of other parameters on composite marine propeller performance. Ghassemi et al. (2011) studied the influence of the skew angle on the hydro-elastic behaviour of composite propellers. The influence of the advance velocity, rotational speed and stacking sequence on the performance of composite marine propellers was investigated by Raj and Reddy (2011).

3 STRUCTURAL ANALYSIS

The structural analysis on a nickel-aluminium bronze (NAB) base case and a series of carbon fibre-reinforced plastic (CFRP) blades are presented. The blade geometry of a controllable pitch propeller of 3000mm diameter is chosen to create the finite element model. The pressure distribution acting on the propeller blades is computed for three different values of the advance coefficient. The pressure data, which are obtained in propeller coordinates, are post-processed in order to define the pressure field in

Cartesian coordinates. The composite blade is modelled in carbon/epoxy with a metal stud. In order to assess the influence of the laminate lay-up on the blade structural response, four balanced stacking sequences are considered. The mechanical properties of the laminates are computed on the basis of the classical laminate plate theory. The effect of the stud geometry on the blade deflection under applied external loads is investigated by considering three studs with different geometries.

3.1 Propeller Geometry

The chosen propeller in this study was originally developed by SVA Potsdam GmbH as a benchmark propeller for the Second International Symposium on Marine Propulsors 2011 (smp'11). The propeller geometry and test results are presented under the name PPTC (Potsdam Propeller Test Case).¹

The propeller is a five blade controllable-pitch propeller named SVA-VP1304. In order to perform the structural analysis, the model propeller was scaled with a scale ratio $\lambda=12$. This resulted in a real scale propeller diameter of 3000mm for a model scale diameter of 250mm. The main data of the propeller VP1304 are given in Table 1.

Table 1. Propeller data

Scale ratio	λ		12	1
Propeller diameter	D	[mm]	250.00	3000.00
Pitch at $r/R=0.7$	$P_{0.7}$	[mm]	408.75	4905.00
Mean pitch	P_{mean}	[mm]	391.88	4702.56
Chord length at $r/R=0.70$	$C_{0.7}$	[mm]	104.17	1250.04
Thickness at $r/R=0.75$	$T_{0.75}$	[mm]	3.79	45.48
Pitch ratio	$P_{0.7}/D$		1.64	
Mean pitch ratio	P_{mean}/D		1.57	
Area ratio	A_E/A_o		0.78	
Skew	Q_{eff}	[deg]	18.80	
Hub diameter ratio	D_h/D		0.15	
Number of blades	z		5	
Direction of rotation			right-handed	
Type			controllable pitch

Figure 1. Model propeller geometry (left). Details of the blade-hub attachment for the controllable pitch (top-right) and the fixed pitch (bottom-right) layouts.

Since the propeller model is a controllable pitch propeller, the blade design near the hub is affected

by the rotation mechanism. This results in a 0.3mm gap between hub and propeller blade near the leading and trailing edge of the blade. However, for the purpose of this study, the propeller was considered to have a fixed blade-hub attachment. Hence, the gap between hub and blade was replaced by closed hub fillets, as shown in Figure 1.

3.2 Pressure Distribution

The pressure distribution was computed for three different values of the advance coefficient $J = 0.8, 1.1$ and 1.4 . These are representative of the propeller operational range, varying from the high loaded to the maximum efficiency condition. The pressure distribution over the pressure side and suction side of the propeller was calculated using the software UPCA91, developed by Newcastle University. The values of the advance coefficient were obtained by varying the propeller rotational speed for a fixed advance speed of 7 m/s. This resulted in rotational speeds of 2.92, 2.12 and 1.67 rps.

From UPCA91 the pressure distribution was given in terms of pressure coefficient, c_p , in propeller coordinates r/R and x/X . However, this coordinate system was not compatible with the coordinate systems recognised by finite element software. It was therefore necessary to translate the results into Cartesian coordinates. This was done by linearly interpolating the pressure values over the propeller disc plane, hence considering only the Y and Z coordinates, as shown in Figure 2. Pressure values are computed by UPCA91 at each black point, which is defined in propeller coordinates as function of radial section and the distance of the chord station from the leading edge. Red points represent the pressure distribution in Cartesian coordinates.

Figure 2. Propeller disc plane (YZ-plane) used for interpolation of the pressure values from propeller to Cartesian coordinates.

¹ available at www.sva-potsdam.de

3.3 Composite Layup

CFRP blades are made of carbon/epoxy and other reinforcement materials, which are employed with different purposes other than the structural reinforcement one. In particular, E-glass protection layers, because of their small thickness and the inferior mechanical properties, do not really contribute to the structural stiffness and strength of the blade. Therefore, from the structural point of view, the blade can be considered to be made entirely of carbon fibre/epoxy with a metal stud. The mechanical properties of the laminae are shown in Table 2.

Table 2. Mechanical properties of reinforcement

Property	Symbol	T300/976 UD tape
Tensile Modulus	E_x	135GPa
	E_y, E_z	9.26GPa
Shear Modulus	G_{xy}, G_{xz}	6.15GPa
	G_{yz}	3.07GPa
Poisson's Ratio	ν_{xy}, ν_{xz}	0.32
	ν_{yz}	0.51
Ult Tensile Strength	σ_y, σ_z	39MPa
	σ_x	1455MPa
Ult Compressive Strength	σ_y, σ_z	207MPa
	σ_x	1296MPa
Ult Shear Strength	σ_{xy}	77MPa
Density	ρ	1580kg/m ³
Thickness	T	0.14mm

Four different lay-ups were considered in the structural analysis, with properties varying from highly anisotropic to quasi-isotropic, as shown in Table 3. All the laminates are symmetric about the mid-plane. Symmetric laminates do not possess coupling between in-plane and flexural behaviour and their use is common practice in many applications.

Table 3. Laminate lay-ups for structural analysis

Laminate	Layup
Unidirectional	[0]
Cross-ply	[0/90] _s
Angle-ply	[0/+45/-45] _s
Quasi-isotropic	[0/90/+45/-45] _s

3.4 Stud Geometry

Composite blades can be keyed and fastened to the hub through a metal stud. When this method is used, the blade becomes actually composed by two materials with different mechanical properties: metal and fibre reinforced composite laminate. Since these materials are glued and fastened together, the blade structural response under applied external loads is different from that of the composite blade only.

When the blade is subject to external loads, the structural response of stud and composite is different; since they are structurally joined together, shear stress arises at their interface. Moreover, the blade stiffness is greater in the region reinforced by the

stud. If the change in the mechanical response is abrupt, stress concentrations occur, especially at the stud tip when the blade is subject to bending stress.

Hence, due to the difference in the material stiffness, the design of the stud geometry becomes critical. Different stud shapes can be adopted in order to varying the blade stiffness gradually, hence keeping shear stress low and avoiding stress concentrations.

In order to assess the stud contribution to the structural response of the composite blade, three different studs were designed, as shown in Figure 3.

STUD ONE: airfoil-section geometry obtained by scaling each blade section with a scale factor $\lambda=0.4$. Each stud section is then offset from the blade trailing edge by 20% of the correspondent blade section length. The stud sections are adjusted to be tapered at the tip and to fit inside the composite blade with a minimum laminate thickness of 25mm at each side (face and back) of the blade.

STUD TWO: airfoil-section geometry obtained by scaling each blade section with a scale factor $\lambda=0.4$. Each stud section is then offset to lie across the vertical axis on the propeller disc plane. The stud sections are adjusted to be tapered at the tip and to fit inside the composite blade with a minimum laminate thickness of 25mm at each side (face and back) of the blade.

STUD THREE: tapered bar designed to be removable also after the composite blade is manufactured. The stud has protruding edges to ease the extraction from the composite shell. Dimensions are determined so that the stud fits inside the composite blade with a minimum laminate thickness of 25mm at each side (face and back) of the blade.

Figure 3. Propeller stud 1 (left), 2 (middle) and 3 (right)

3.5 Finite Element Analysis

3.5.1 Element Type and Mesh

The structural analysis was performed using the finite element package ANSYS 13.0. The finite element model consisted of one blade of the propeller, positioned with zero angle of rotation from upward.

Based on consideration of the design loads and the materials employed, structural deformations and stresses on the blade were expected to be small, hence the blade structural response to be elastic. All the finite element analyses were therefore performed as linear, assuming elastic material behaviour.

The blade geometry was meshed entirely with three dimensional 8-node solid elements SOLID185. This element type is suitable for 3-D modelling of

solid structures. It is defined by eight nodes having three degrees of freedom at each node: translations in the nodal x, y, and z directions.

The blade model was free meshed with tetrahedral elements. A mesh adaptation study, using H-refinement type, was performed for both the NAB and composite blade. Displacement convergence was found with element size of 18mm for both blades, with additional refinement at the laminate-stud interface for the composite blade.

3.5.2 Material Properties

The composite laminate was modelled as homogeneous material with orthotropic properties. The mechanical properties of each laminate, which depend on the laminate lay-up, were calculated using classical laminate plate theory. Table 4 shows the mechanical properties of carbon/epoxy laminate for different laminate lay-ups.

Table 4. Mechanical properties of carbon/epoxy unidirectional reinforcement

			[0]	[0 ₂ /90] _s	[0/45/-45] _s	[0/90/45/-45] _s
Tensile Modulus	Ex	[GPa]	135.100	93.629	59.611	53.193
	Ey	[GPa]	92.63	51.472	25.886	53.193
	Ez	[GPa]	92.63	11.633	11.502	11.723
Shear Modulus	Gxy	[GPa]	6.154	6.154	25.301	20.514
	Gxz	[GPa]	6.154	5.129	5.129	4.616
	Gyz	[GPa]	3.078	4.103	4.103	4.616
Poisson's Ratio	u _{xy}		0.315	0.057	0.681	0.297
	u _{xz}		0.315	0.461	0.148	0.349
	u _{yz}		0.505	0.487	0.357	0.349
Density	ρ	[kg/m ³]	1580	1580	1580	1580

Orthotropic properties are oriented so as to represent the actual laminate properties and plies orientation. Orthotropic material directions are defined in ANSYS by the element coordinate system, whose default orientation is along the global directions. A new local coordinate system was defined and oriented as shown in Figure 4.

Figure 4. Coordinate system

3.5.3 Boundary Conditions

NAB blades, either in mono-block or built-up form, are cast together with the hub or the blade foot. At the blade root any material discontinuity really occurs. However, the finite element model includes one blade only, which has to be constrained at the blade root. A NAB blade is subject to small defor-

mations due to the high material stiffness and it can be considered fully clamped at the blade-hub interface. Hence, translations were constrained in the x, y and z directions.

The composite blade is fastened to the metal stud and bonded to the hub at the blade root. Since the stud is usually forged together with the blade foot, or fastened to the hub, it is reasonable to assume that it is rigidly held at its base. However the bonding layer, which is more elastic, is not completely exempted from deformations. The finite element model was constrained at the blade-hub interface, with zero translation imposed in the x, y and z direction. However, it must be noticed that stress concentrations may arise at the blade root due to boundary effects.

3.5.4 Loads

A propeller in operation conditions is subject to various loads acting in different directions. Traditional submerged propellers are mostly subject to weight force, centripetal force and the dynamic pressure that gives rise to thrust and drag (torque). Depending on the propeller size and rotational speed, the weight force and the centripetal force may be significant and are to be taken into account when assessing the structural performance of the propeller at its design stage. However, when only the blade deflection is concerned, the effect of weight force and centripetal force is, to a certain extent, negligible.

Therefore the dynamic pressure was the only load applied to the blade model. The pressure values, as computed by UPCA91 and transformed into Cartesian coordinates, were imported into ANSYS. The software automatically applied the pressure to the finite element model as surface load acting orthogonally to the blade surfaces.

4 RESULTS

The influence of the different studs, laminates and advance coefficients on the blade deflection are presented. The blade deflection is discussed in terms of z-direction displacement in the local coordinate system, which is shown in Figure 4.

4.1 Deformed Shape

Although all propellers are subject to hydroelastic effects, the structural response of traditional metal propellers is such that these effects are, in most of cases, negligible. As it can be seen from Figure 5 (left), the deformed shape of the metal blade when heavily loaded ($J=0.8$), is similar to its non-deformed one. The blade is mostly subject to bending, whilst no twisting around its radial axis occurs. The displacement contour plot highlights how the blade deflection varies radially. By looking at the distance of the deformed blade from its non-

deformed shape at the leading and trailing edge it can be seen that the pitch remains almost constant.

The deformed shape of the composite blade (Figure 5, right) shows how the bending-twisting coupling is much more evident when anisotropic materials are employed. As the load is taken up by the propeller, blade deflection occurs in both the radial and the chordal directions. As a consequence, the blade pitch reduces gradually whilst bending in the radial direction increases. Bending and twisting of the blade change with relation to the laminate lay-up, propeller loading condition and stud geometry. The effect of these parameters is further discussed in the following sections.

Figure 5. Deformed shape of NAB blade (left) and composite blade (STUD 3, Unidirectional [0]) (right). $J=0.8$. Displacement scale factor = 30.

4.2 Laminate Lay-up

The blade deflection is primarily influenced by the laminate lay-up. Figure 6, which shows the displacement contour plot of the composite blade with different stacking sequences, gives a first insight of the difference in stiffness between lay-ups with different levels of anisotropy.

Figure 6. Blade deflection in z-direction (local coordinate system). STUD 1; $J=0.8$

A better understanding of the effect of the laminate lay-up on the blade structural response can be gained by looking at Figure 7. The NAB blade presents a quite uniform deflection in the chordal direc-

tion, with a slightly more cambered shape at $r/R=0.7$; while the response of the composite blade is considerably different, depending on the laminate lay-up.

Figure 7. Blade deflection along the blade section chord at $r/R=0.96$ and $r/R=0.7$. STUD 1; $J=0.8$

Near the blade tip ($r/R=0.96$), the unidirectional lay-up provides high stiffness in the central part of the blade, where fibres run from the blade root to the tip. However, it becomes ineffective near the trailing edge, where the deflection increases considerably. This is likely to be a consequence of the blade skew and it can be expected that the effect becomes more pronounced with highly skewed blade geometries. At the blade radius $r/R=0.7$, the displacement pattern is different and the deflection becomes significant at the leading edge too. The deformed blade assumes the shape of a cambered section with opposite curvature, since both the leading and the trailing edges are more displaced than the central part. This can be deeply detrimental to the hydrodynamic performance of the blade, with significant changes in the lift and drag characteristics.

A more uniform deflection pattern can be achieved by using the [02/90]s cross-ply and the [0/45/-45]s angle-ply laminates. Near the tip ($r/R=0.96$), the deformed shape of the blade is quite similar, with the deflection increasing gradually from the leading to the trailing edge. Contrarily, at $r/R=0.7$ these two lay-ups give a different response. The [0/45/-45]s lay-up provides the blade with significantly greater stiffness at the leading edge. The cross-ply laminate, which has more 0-angle plies, has lower deflection near the central part of the blade.

The quasi-isotropic [0/90/45/-45]s laminate presents a more uniform deflection pattern, with bending in the radial direction being more pronounced than for the other lay-ups.

Both the [0/90/45/-45]s and [02/90]s laminates show the lowest displacement at $r/R=0.96$ in correspondence of the trailing edge. This is likely to be due to the 90-degrees oriented plies that provide the blade with high stiffness in the transverse direction. This ply orientation is the most effective when transversal stiffness is to be given to the tip region of skewed blade geometries.

4.3 Stud Geometry

The effect of the stud geometry on the blade twisting decreases with the distance from the blade root to such an extent that it is negligible at $r/R=0.96$. At radial sections closer to the root, the presence of the metal stud increases gradually the blade stiffness. Figure 8 compares the blade displacements at the radial section $r/R=0.7$ and in heavy load condition ($J=0.8$) for the different stud geometries considered.

Figure 8. Blade deflection for different lay-ups and studs at $r/R=0.7$; $J=0.8$.

The STUD 3 (removable stud) is considered as reference case, since the small stud size is not supposed to influence the blade response. With respect to this, STUD 1 (fore position) provides more stiffness near the leading edge, with the unidirectional lay-up being the most influenced. Moving from the leading towards the trailing edge, smallest displace-

ments are found for the STUD 2 (central position). Although, at $r/R=0.7$ the contribution of the central stud to the blade stiffness is only slightly visible, its effect is expected to increase near to the blade root.

4.4 Advance Coefficient

The loading condition of the propeller does not really influence the deflection pattern of the NAB blade. As it can be seen from Figure 9, the blade displacements through the chord section are consistent for different values of the advance coefficient J . The blade twisting remains almost unchanged, whilst bending increases progressively as the propeller becomes heavily loaded.

Figure 9. Blade deflection for different advance coefficients at $r/R=0.7$. J varies. STUD 3.

The effect of the advance coefficient on the composite blade is much more evident. In light loading condition ($J=1.4$), the blade deflection is generally low for all laminate lay-ups. As soon as the load is taken up by the propeller, the blade deflection in the chordal direction becomes strongly influenced by the level of anisotropy of the laminate. The displacement at the leading edge of the unidirectional and the [02/90]s laminates increases deeply and the deflection pattern along the chord section becomes highly

sinusoidal. A possible explanation is that in light loading condition the transverse stiffness, which is given by the polymer matrix and the plies oriented transversally, is enough to keep the displacements small. But when the propeller is heavily loaded, the laminate proves to be excessively elastic in the transverse direction and the deflection pattern changes considerably.

The variation of twisting and bending from light to heavy loading condition is more uniform with the [0/45/-45]_s and the [0/90/45/-45]_s laminates. This can be seen in Figure 10, where the blade deflection at $r/R=0.7$ is plotted for different advance coefficient values. The black line highlights the coupling that occurs when the propeller passes from light load to heavy load condition. At each loading condition, the displacement increases gradually through the chord section from the leading to the trailing edge. This results not only in bending in the radial direction, but also in a quite uniform twisting that can be thought in terms of variation of the sectional pitch angle.

The use of 45 degrees oriented plies proves to be very effective when stiffness in all directions is of concern. The response is generally uniform, without abrupt changes of deflection throughout the propeller operational range. Moreover, the bending-twisting coupling that results from the elastic properties of blades made by angle-ply laminates provides space for improvement. The deflection patterns experienced by these blades show that the hydroelasticity of composites could be successfully exploited to vary the blade pitch.

5 CONCLUSIONS

The deflection results of the CFRP blade confirm the greater deflection experienced by composite blades and how the bending-twisting coupling is much more evident when anisotropic materials are employed. Unlike NAB blades, deflection of composite blades occurs in both the radial and the chordal directions. The deflection pattern is strongly influenced by the laminate and propeller loading.

The results of the analysis suggest that the ability to exploit the bending-twisting coupling of composite blades to dynamically vary the pitch angle is feasible. However, achieving successful results in terms of hydrodynamic performance requires the structural design of the propeller to account for the laminate lay-up and the whole propeller operational range.

In order to assess the deformed blade from a hydrodynamic point of view, a fluid analysis is necessary. However, on the basis of airfoil theory, it can be presumed that an effective change of pitch occurs if the whole blade section rotates uniformly, as for a controllable pitch propeller, or if the blade tends to de-pitch near the tip at the trailing edge. Under these conditions, the lift/drag characteristic changes with possible improvements in the efficiency.

Figure 10. Blade deflection for different lay-ups at $r/R=0.7$. J varies. STUD 3.

Highly anisotropic laminates are critical due to the excessive elasticity in the transverse direction. When the propeller is heavily loaded, both the leading and the trailing edges deflect more than the central part of the blade. The cambered shape assumed by the blade section may affect the hydrodynamic performance, with significant changes in the lift and drag characteristics. The use of quasi-isotropic laminates is not effective either, resulting in high bending in the radial direction.

A suitable starting point for the design of composite blade was found with the angle-ply [0/45/-45]_s laminate, which proves to be very effective when stiffness in all directions is of concern. The blade response is generally uniform, without any abrupt change in deflection throughout the propeller operational range. The blade sections experience a clear rotation with the varying of the loading conditions. An approximate centre of rotation was found to be upstream of the leading edge.

Depending on the deflection pattern, additional unidirectional plies may be added in the radial direction to increase the stiffness of the central part of the blade, hence obtaining a uniform rotation of the blade sections. 90-degree oriented plies, which provide the blade with high stiffness in the transverse direction, were found to be the most effective when transversal stiffness is to be given to the tip region of skewed blade geometries.

The high deflection implies that structural analyses on composite propellers must be fully hydroelastic to determine the real blade deformations and stresses. Hence, the finite element analysis is to be coupled with a hydrodynamic analysis.

6 REFERENCES

- Ahmed, A. and Wei, L. (2012) 'Theoretical and experimental methods on bend-twist coupling and damping properties with the relationship to lay-up of the composite propeller marine: A review', *International Journal of Engineering Science and Technology*.
- Almeida, F.S. and Awruch, A.M. (2009) 'Design optimization of composite laminated structures using genetic algorithms and finite element analysis', *Composite Structures*, 88(3), pp. 443-454.
- Blasques, J.P., Berggreen, C. and Andersen, P. (2010) 'Hydroelastic analysis and optimization of a composite marine propeller', *Marine Structures*, 23(1), pp. 22-38.
- Chen, B., Neely, S., Michael, T., Gowing, S., Szwerc, R., Buchler, D. and Schult, R. (2006) *The SNAME propeller/shafting symposium*, Williamsburg, VA.
- Chung, D.D.L. (2001) 'Review: Materials for vibration damping', *Journal of Materials Science*, 36(24), pp. 5733-5737.
- Ghassemi, H., Saryazdi, M.G. and Ghassabzadeh, M. (2011) 'Influence of the skew angle on the hydroelastic behaviour of a composite marine propeller', *Journal of Engineering for the Maritime Environment*.
- Gowing, S., Coffin, P. and Dai, C. (1998) 25th American towing tank conference. Iowa City, IA. USA.
- Lin, C.-C., Lee, Y.-J. and Hung, C.-S. (2009) 'Optimization and experiment of composite marine propellers', *Composite Structures*, 89(2), pp. 206-215.
- Lin, H.J., Lin, J.J. and Chuang, T.J. (2005) 'Strength Evaluation of a Composite Marine Propeller Blade', *Journal of Reinforced Plastics and Composites*.
- Liu, Z. and Young, Y.L. (2009) 'Utilization of bend-twist coupling for performance enhancement of composite marine propellers', *Journal of Fluids and Structures*, 25(6), pp. 1102-1116.
- Motley, M.R., Liu, Z. and Young, Y.L. (2009) 'Utilizing fluid-structure interactions to improve energy efficiency of composite marine propellers in spatially varying wake', *Composite Structures*, 90(3), pp. 304-313.
- Raj, S.S. and Reddy, P.R. (2011) 'Performance evaluation of composite marine propeller using L8 orthogonal array', *International Journal of Engineering Science and Technology*.
- Selvaraju, S. and Ilaiyavel, S. (2011) 'Applications of Composites in Marine Industry', *Journal of Engineering Research and Studies*, 2, pp. 89-91.
- Young, Y.L. (2008) 'Fluid-structure interaction analysis of flexible composite marine propellers', *Journal of Fluids and Structures*, 24(6), pp. 799-818.