2023 27TH INTERNATIONAL CONGRESS OF MECHANICAL ENGINEERING

Brazilian Society of Mechanical Sciences and Engineering
27th ABCM International Congress of Mechanical Engineering
December 04-08, 2023, Florianópolis-SC, Brazil

COB-2023-0277
DEVELOPMENT OF A MARINE COMPOSITE PROPELLER

Felipe Santos de Castro
André Mitsuo Kogishi
Institute for Technological Research - Av. Prof. Almeida Prado, 532 - Cid. Universitária - São Paulo/SP - Brazil
fscatro@ipt; amkogishi@ipt.br

Helio Correa da Silva Junior
University of São Paulo - Av. Prof. Mello Moraes, 2231 - Cid. Universitária - São Paulo/SP - Brazil
helio.correa@usp.br

João Lucas Dozzi Dantas
FORCE Technology - Kogens Lyngby, 2800 – Copenhagen - Denamark
joda@forcetechnology.com

Luís Augusto Steffen
Daniel Teixeira
NTC Company - ERS-122 KM 62,92 6390 - Caxias do Sul/RS - Brazil
augusto@ntc.ind.br; daniel@ntc.ind.br

Abstract. *The use of composite materials in the construction of marine propellers has been a topic of interest for researchers worldwide. These materials have several advantages over traditional metallic ones, including being lighter in weight, requiring less complex machining and finishing processes, and offering noise reduction capabilities suitable for military submarine vehicles. This paper presents the results of a study on the development of a scale-size carbon fiber marine propeller, which was compared to an aluminum propeller with the same geometry. The aluminum propeller was fabricated using a conventional procedure for an autonomous underwater vehicle. Both models used in the study were a DARPA MOD5, a seven-blade propeller designed to operate in moderately and lightly loaded conditions near the maximum efficiency point of operation. Tests were conducted at the IPT's Cavitation Tunnel to measure the torque and thrust coefficients for both propellers. The study also utilized Particle Image Velocimetry (PIV) techniques to measure deformation at the blade tip and determine if the carbon fiber model could achieve similar stiffness compared to the aluminum one. The results of the study showed that the composite model performed comparably to the aluminum model, demonstrating the viability of composite materials for marine propeller construction. Deflections were similar, with a difference varying at the same level of uncertainty. Efficiency results for the carbon fiber model were slightly lower than the aluminum one, probably due to the leading edge finishing and minor deflections, but in acceptable range. This research has significant implications for the marine industry, as the use of composite materials in marine propeller construction could lead to reduced manufacturing costs, improved performance, and reduced noise levels. Future research in this area could explore the development of composite materials specifically tailored for marine applications, leading to further improvements in the efficiency and effectiveness of marine propulsion systems.*

Keywords: *ship propeller, experimental hydrodynamics, composite propeller, cavitation tunnel*

1. INTRODUCTION

Marine propellers are rotating devices that generate propulsion through the hydrodynamics interaction with water. They experience substantial loads, in both axial and radial directions, and fluctuating forces, enduring vibrations and even collision episodes while operating in a diverse flow caused by the distinctive wake of a vessel. They are rigid structures, with fixed geometries that have been refined to reach their peak performance throughout the years. However, as most of the propellers being traditionally manufactured of stiff metal materials, such as manganese bronze, nickel-aluminum-bronze (NAB), aluminum, and steel, they are subject to typical disadvantages associated with them. These include corrosion, cavitation, formation of galvanic cell, and maintenance cost (Kumar *et al.*, 2019a,b; Yamatogi *et al.*, 2011; Uddin *et al.*, 2021)

Composite materials have found widespread demand in aviation, maritime, automotive, and many other sectors. Their higher specific strength-stiffness ratio and corrosion resistance make them attractive to industrial applications (Lee and Lin, 2004). In marine applications, composites are typically employed for constructing hulls of smaller boats and yachts, while larger vessels are often excluded (Hara *et al.*, 2011). In the past few years, extensive research has been conducted on marine propellers made from composite materials, because of their superior benefits compared to conventional propellers. When it comes to high-speed rotating marine propellers that demand precise vibration management and hydroelastic stability, the potential advantages offered by composites play a crucial role in enhancing the dynamic performance of the structure (He *et al.*, 2012).

Carbon fiber (CF) propellers offer a multitude of advantages over traditional metallic counterparts within the maritime context, specially lightweight properties, strength, and resistance to corrosion in marine environments. These composite propellers exhibit significantly reduced weight in comparison to their metallic counterparts, thereby alleviating the overall mechanical burden imposed on the engine. Consequently, this weight reduction engenders enhanced operational efficiency and diminished fuel consumption. The utilization of CF composite materials confers a high degree of impact resistance, rendering them considerably more resilient when encountering accidental impacts with submerged objects or debris. The superior strength-to-weight ratio inherent to this material renders it less susceptible to fatigue, cracks, and deformations when compared to conventional metallic materials (Vardhan *et al.*, 2019). Moreover, CF propellers feature exceptional damping characteristics, which contribute to a notable reduction in vibration and noise levels when juxtaposed with metallic propellers. The mitigation of vibrations, in turn, engenders smoother operational dynamics, an enhanced capacity for acoustic subtlety in underwater environments, and reduced stress on the propulsion system (ITTC, 2005).

The distinctive attributes position it as a highly desirable alternative to be considered as material for marine propellers and because of that, a great field of study with several approaches (Kumar *et al.*, 2019a; Lin *et al.*, 2009; Vardhan *et al.*, 2019). Yamatogi *et al.* (2011) have performed some tensile and bending tests using propeller models, comparing two types of CF propeller with a NAB propeller, obtaining very similar strength results, while vibrations tests achieved superior damping characteristics for the CF specimens while the cavitation erosion resistance of the NAB body was much superior compared to a CF one. The main disadvantage of these propellers is their upfront cost compared to metallic materials. However, the long-term benefits, such as improved fuel efficiency, durability, and performance, can make them an economic choice, particularly for high-performance or commercial marine applications.

The primary attribute of a marine propeller is its capacity to retain its hydrodynamic form when subjected to external forces, ensuring efficient propulsion of a vessel under all conditions. That is the reason why most studies on CF propellers, or even those made from a general composite, focus on their hydroelastic behavior, using numerical and experimental approaches. The combination of structural and fluid simulations to optimize composite marine propellers is extensively reported in literature (Vardhan *et al.*, 2019). Kumar *et al.* (2019b) and Hara *et al.* (2011) compared CF and metal scaled-model propellers using CFD-FEM solvers to estimate open water efficiency and deflection on the blade tips, comparing them with experimental results. In terms of experimental procedures, several techniques such as Digital Image Correlation (Shiraishi *et al.*, 2019), Combination line CCD camera method (Grasso *et al.*, 2019), and Particle Image Velocimetry (Souza *et al.*, 2018) can be used to estimate deflection on propeller blades.

The main objective of this work is to assess the performance and structural stability of two scale-model propellers. These propellers have identical geometry and are tested under the same operational conditions, but made of different materials. One is made of aluminium while the second one is made of nationally-produced CF composite.

2. METHODS

The adopted methods of this study are presented in the following subsections.

2.1 Data analysis - Open water test

The evaluation of the propeller performance is carried out by comparing the open water characteristics curves for both propellers. These curves were obtained by tests in the cavitation tunnel without imposing any pressure drop, i.e., without inducing cavitation. The standard test measures the propeller thrust T and torque Q in several conditions defined by the speed of advance (test section speed) V_a and propeller rotation n. These quantities are mathematically expressed as non-dimensional coefficients: advance ratio J, which relates the speed of advance, rate of rotation, and propeller diameter D, given by

$$J = \frac{V_a}{nD}; \tag{1}$$

thrust coefficient, which relates the thrust produced by a propeller with water density ρ, propeller rotation and diameter, and it is given by

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

and torque coefficient, which relates the torque delivered to the propeller with the density, rotation and diameter and is expressed by

$$K_Q = \frac{Q}{\rho n^2 D^5}. \tag{3}$$

Finally, using these parameters the propeller efficiency can be expressed by

$$\eta = \frac{TV_a}{2\pi n Q} = \frac{K_T J}{2\pi K_Q}. \tag{4}$$

The tests were conducted in a cavitation tunnel under steady-state conditions, with both the advance speed and propeller rotation speed held constant. Consecutive tests were performed across all relevant conditions by systematically increasing and decreasing the advance speed to investigate the presence of hysteresis.

2.2 Facilities

The IPT's Cavitation Tunnel (Fig. 1) is a Kempf and Remmers K22, with a test section of 0.5 x 0.5 x 2 m and can reach a flow speed of up to 10 m/s. It is used to test propellers up to 200 mm of diameter. More details about this cavitation tunnel can be seen in Katsuno and Dantas (2017, 2022), together with an investigation of blockage effects on the thrust and cavitation patterns.

Figure 1. Cavitation tunnel of the IPT.

2.3 Propeller models

This study aims to evaluate the hydro-mechanical performance of a CF propeller model through testing. The model is a seven-blade propeller design for a DARPA suboff model (Groves *et al.*, 1989), designed to operate in moderately and lightly loaded conditions near operation maximum efficiency point (Chreim, 2019). An aluminum model, typically used for model scale tests, has been tested in the same conditions for comparison purposes. Fig. 2 shows a frontal view of the CF model (left) and it installed at the IPT's Cavitation Tunnel (right).

The CF propeller model was designed and manufactured in parts, considering individual blades and a two-part hub that allows blade replacement in case of damage. Each blade was built individually using an injection molding process. The composite material used was developed specifically for the application in propellers and is based on Polyphtalamide (PPA) reinforced with 40% CF obtained through an extrusion process. This process involves incorporating reinforcing loads (carbon fiber), into a polymeric matrix, ensuring uniform dispersion of the fibers in the molten polymer. The result is a composite material with improved properties. In addition to a favorable relationship between high rigidity and impact resistance, the low water absorption of this composite is also highlighted, compared to other engineering polymers. This characteristic contributes to maintaining the composite's properties and and dimensional stability throughout the product's lifespan. PPA composites reinforced with CF exhibit significant technical potential, making them competitive, compared to metallic alloys, in various industries, including automotive, aerospace, petroleum, electronics and maritime sectors. Theses composites can be tailored to specific application needs, optimizing their performance, which provides a technical advantage considering the unique requirements of each project.

2.4 Blade deflection measurement

The geometric stability is established by measuring the deformation of the tip of the blades with the propellers operating at the design point. The measurements were performed with a Particle Image Velocimetry (PIV) setup synchronized with the rotation of the propellers, allowing measuring the dimensions of the blade at the same angular phase. The equipment is composed of a camera with double exposure, a high-frequency laser cannon and a control-acquisition system.

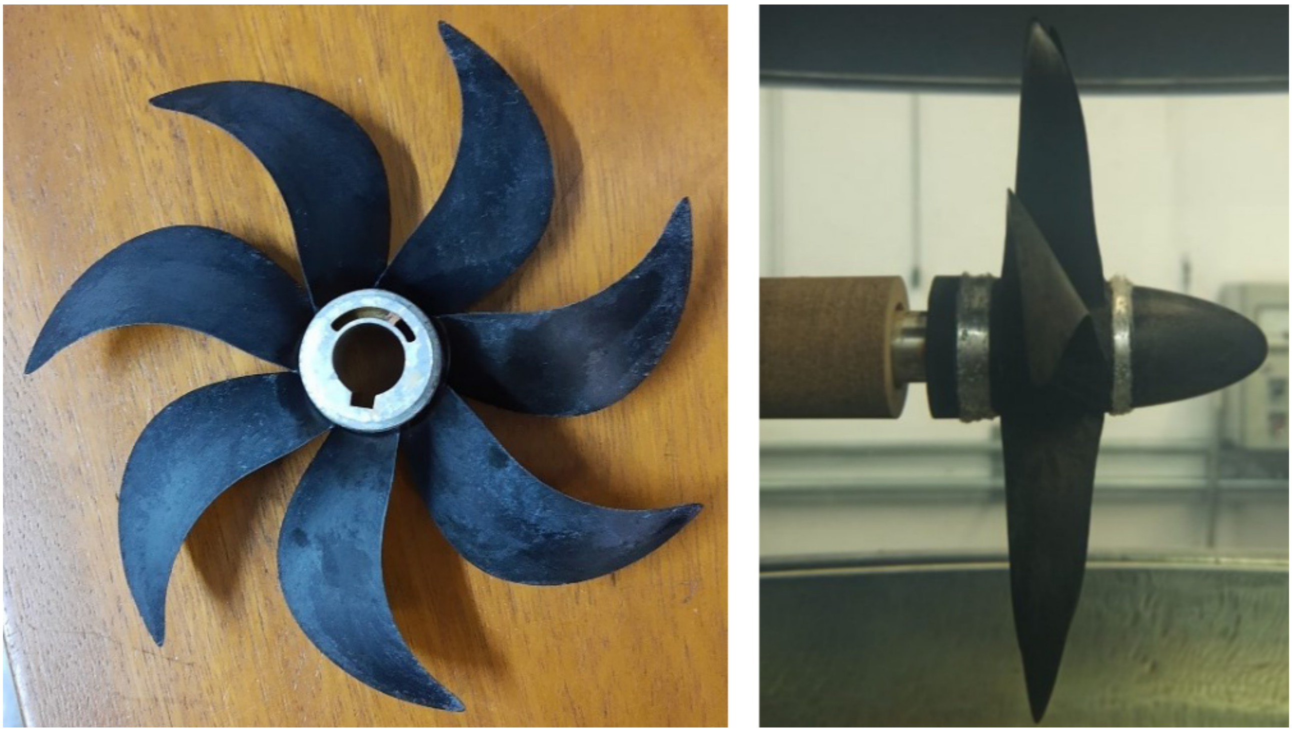

Figure 2. CF propeller investigated. On the left is the front view and on the right is the propeller installed in the cavitation tunnel.

Based on the calibration procedure using a reference plate (standard procedure), it is possible to obtain a scaled lateral picture of the propeller blade for loaded and unloaded conditions. That procedure correlates the pixels in the image with a real length measure.

The tip deflection was obtained by comparing the images without any load, i.e., stationary, to images acquired in different load conditions. The deflection was defined as the distance, in the image plane, between the same geometry feature of the propeller in these two conditions. This study presented only the results for the tip of the propeller blade.Assuming that the main uncertainties of this method have no covariance, one can estimate the systematic uncertainty for the tip displacement as

$$u = \sqrt{u_m^2 + u_c^2}; \tag{5}$$

in which u_m is called the measurement uncertainty, and comes from the uncertainty originated from the cameras and laser system mensuration of reference object, in the same color of the propeller, marked with known distances; while u_c is called the calibration uncertainty, and it is given by the software uncertainty for the calibration process. Another source of uncertainty comes from the repeatability of images at the same instant for different tests and is not represented in this study due to a limitation on the experimental approach.

3. RESULTS

The compilation of the main results is presented in the following subsections.

3.1 Open water characteristics curve

This section compiles the hydrodynamic performance results from the experimental campaign. Figure 3 presents the thrust (K_T), torque coefficients (K_Q) and efficiency (η) as a function of the advance coefficient (J) from both metallic and composite propellers in the tests carried out in the IPT's cavitation tunnel. The thrust and torque were measured by dynamometers installed at the end of the shaft that connected to the propellers.

It is observed a good agreement between the thrust curves for both propellers, especially near J =0.92 – the design point. The torque curve of the CF propeller exhibits a value slightly higher than the aluminum propeller, possibly indicating a deflection of the blades or some minor geometry imperfection in the blades' leading or trailing edges. As a consequence, the efficiency curve of the CF propeller is lower than that of the metallic propeller, indicating that this propeller will require more power to operate.

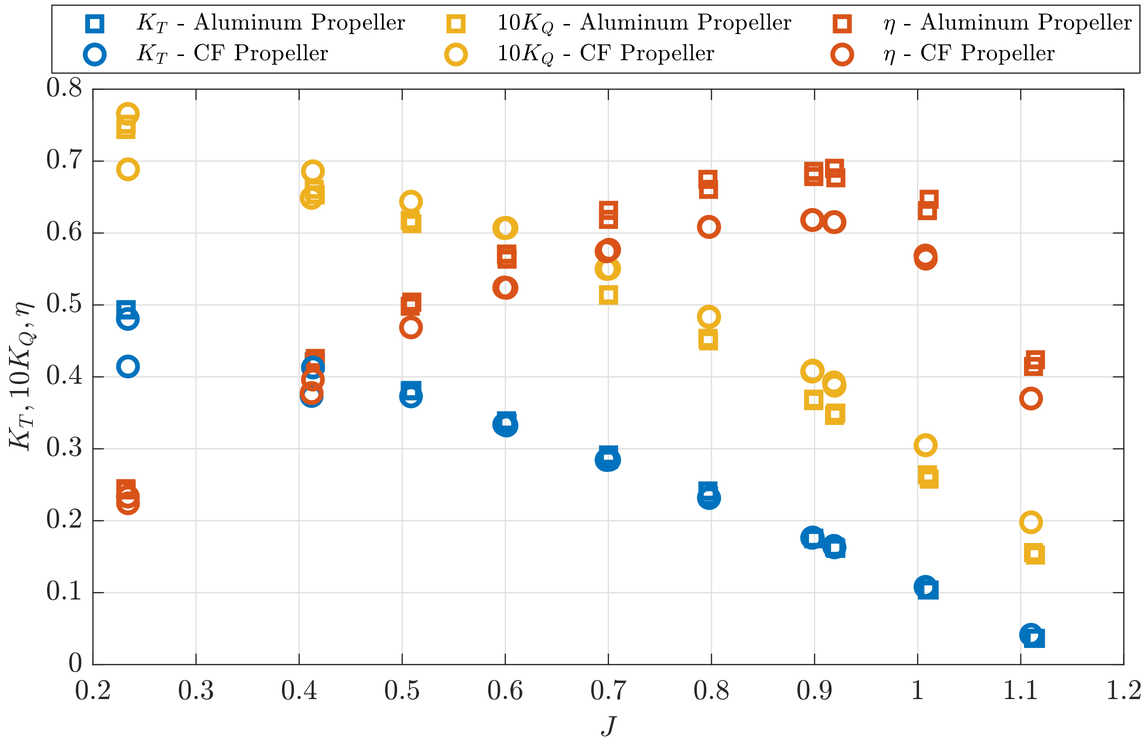

Figure 3. Comparison between the performance curves of thrust (K_T), torque ($10K_Q$), and efficiency (η) for the aluminum propeller and carbon fibre propeller.

3.2 Blade deflection

The tip deflection of the propeller blade was used to evaluate the structural flexibility of the propellers in this study in relation to the imposed hydrodynamic load. Typically, the propellers were designed to not present any deflection, as large deflections can lower the hydrodynamic performance and reduce the propeller lifespan.

A PIV setup was used to capture images of the propeller blades. The PIV cameras can be calibrated to capture a specific plane of measurement. The blades were imaged at the same angular position using an electronic synchronization device. This setup enabled the acquisition of the coordinates of the propeller blade tips under the influence of the flow. The deflection is calculated based on the tip coordinates in both unloaded and loaded conditions. Figure 4 displays the scaled image of the same blade tip under three loading conditions (no load, $J = 0$, slight load $J = 0.92$, and high load $J = 0.2$). The images were presented in the scaled PIV coordinate system, which indicates that the size of the images correlates to a real length. The color scale was adjusted to distinguish between the background and the propeller, making it easier to locate tits tip.

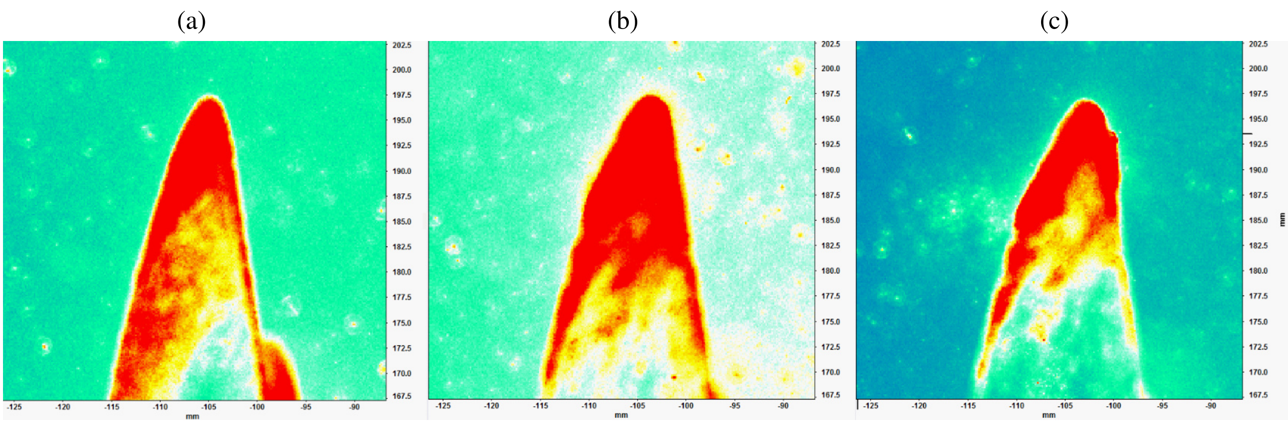

Figure 4. Picture of the CF blade from the PIV measurement system for three different advance ratios: (a) - no load condition, $J = 0$; (b) - slight load condition, $J = 0.92$; and, (c) - high load condition - $J = 0.2$.

The tip displacement results for both propellers as a function of the advanced coefficient (J) are presented in Fig. 5. The tip displacement was calculated as the sum of squares of the displacement in each direction of the plane, i.e., total

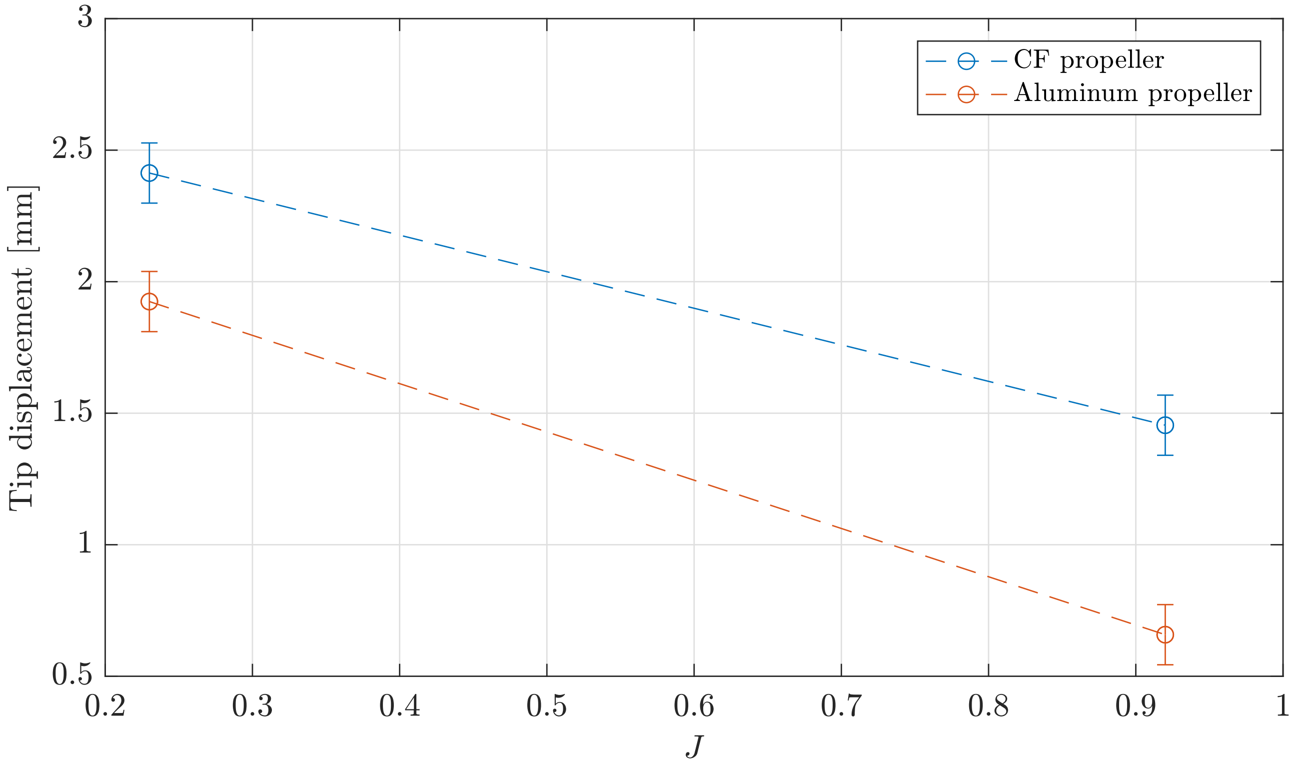

Figure 5. Tip displacement for both propellers.

displacement. It is important to note that the resolution of the measurement of displacement is strongly dependent on the camera's definition, as the applied techniques rely on transforming image pixels into a length scale. Additionally, the the method to measure the displacement has an uncertainty magnitude, which is expressed in the error bars in the results shown in Fig. 5.

4. CONCLUSIONS

In summary, the findings of this study have contribute to the understanding of composite propellers' performance. Through an experimental analysis in a cavitation tunnel, the present study was able to asses and compare the hydrodynamic performance and blade deflection of scale-model propellers made of aluminum and carbon fiber. The results of this investigation have demonstrated a very similar behavior for both specimens in terms of thrust, but with a higher torque requirement of the CF model, resulting in a slightly lower efficiency. This may be associate with the greater value of tip displacement, compared to the aluminum propeller. Furthermore, the study has provided a solid foundation, specially in terms of conceiving a model with composite material, to explore thematic related to other issues on marine propellers, such as cavitation and hydroacoustics.

5. ACKNOWLEDGEMENTS

Authors would like to thank the colleagues Fillipe Rocha Esteves and Eduardo Tadashi Katsuno for helping out with some activities of this study. Authors also would like to acknowledge the Centro Tecnológico da Marinha em São Paulo, the Centro Industrial Nuclear de Aramar, the Instituto de Pesquisas Tecnológicas do Estado de São Paulo, the Fundação de Apoio ao Instituto de Pesquisas Tecnológicas (FIPT), and NTC Company for the support in the realization of this work.

6. REFERENCES

Chreim, J.R., 2019. *Development of a propeller lifting-line tool for analysis and design*. Master's thesis, Graduate Program in Mechanical Engineering, University of São Paulo, Brazil.

Grasso, N., Hallmann, R., Scholcz, T., Zondervan, G., Maljaars, P. and Schouten, R., 2019. "Measurements of the hydro-elastic behaviour of flexible composite propellers in non-uniform flow at model and full scale". In *Proceedings of the Sixth International Symposium on Marine Propulsors - SMP'19*. Italy.

Groves, N.C., Huang, T.T. and Chang, M.S., 1989. "Geometric characteristics of darpa suboff models (dtrc model numbers 5470 and 5471)". Technical Report. David Taylor Research Center - Ship Hydromechanics Department.

Hara, Y., Yamatogi, T., Murayama, H., Uzawa, K. and Kageyama, K., 2011. "Performance evaluation of composite marine propeller for a fishing boat by fluid-structure interaction analysis". In *Proceedings of the 18th International Conference on Composite Materials*. South Korea.

He, X.D., Hong, Y. and Wang, R.G., 2012. "Hydroelastic optimisation of a composite marine propeller in a non-uniform wake". *Ocean Engineering*, Vol. 39, pp. 14–23.

ITTC, 2005. "The propulsion committee - final report and recommendations to the 24th ITTC". Proceedings of the 24th ITTC - Volume I, Edinburg, https://ittc.info/media/5834/volume-i-propulsion-committee.pdf. Acessed 19 October 2023.

Katsuno, E.T. and Dantas, J.L.D., 2017. "Analysis of the blockage effect on a cavitation tunnel using CFD tools". In *Proceedings of the ASME 2017 36th International Conference on Ocean, Offshore and Arctic Engineering. Volume 7B: Ocean Engineering*. Norway.

Katsuno, E.T. and Dantas, J.L.D., 2022. "Blockage effect influence on model-scale marine propeller performance and cavitation pattern". *Applied Ocean Research*, Vol. 120, p. 103019.

Kumar, A., Krishna, G.L. and Subramanian, V.A., 2019a. "Design and analysis of a carbon composite propeller for podded propulsion". In *Proceedings of the Fourth International Conference in Ocean Engineering (ICOE2018)*. Singapore.

Kumar, A., Subramanian, V.A. and Vijayakumar, R., 2019b. "Hydro-elastic analysis of carbon composite marine propeller using co-simulation technique". In *Conference Proceedings of the International Conference on Marine Engineering and Technology ICMET2019*. Oman.

Lee, Y. and Lin, C., 2004. "Optimized design of composite propeller". *Mechanics of Advanced Materials and Structures*, Vol. 11, pp. 17–30.

Lin, C., Lee, Y. and Hung, C., 2009. "Optimization and experiment of composite marine propellers". *Composite Structures*, Vol. 89, pp. 206–215.

Shiraishi, K., Sawada, Y., Arakawa, D. and Kimura, K., 2019. "A study on deformation measurements and hydrodynamic investigation of the flexible composite marine propeller". In *Proceedings of the Sixth International Symposium on Marine Propulsors - SMP'19*. Italy.

Souza, J.P.S., Dantas, J.L.D. and Santiago, R.C., 2018. "Projeto e fabricação de um hélice naval com manufatura aditiva e materiais compósitos". In *Anais do 27º Congresso Internacional de Transporte Aquaviário, Construção Naval e Offshore*. Brazil.

Uddin, M.M., Hossen, M.P., Jahan, M.M. and Islam, M.I., 2021. "Structural analysis of composite propeller of ship using FEM". In *Proceedings of the 13th International Conference on Mechanical Engineering (ICME2019)*. Bangladesh.

Vardhan, D.H., R, A. and Reddy, B.C.M., 2019. "A review on materials used for marine propellers". *Materials Today: Proceedings*, Vol. 18, pp. 4482–4490.

Yamatogi, T., Murayama, H., Uzawa, K., Mishima, T. and Ishihara, Y., 2011. "Study on composite material marine propellers". *Journal of The Japan Institute of Marine Engineering*, Vol. 46, pp. 330–340.

7. RESPONSIBILITY NOTICE

The author(s) is (are) solely responsible for the printed material included in this paper.