INTRODUCTION TO COPROPEL: COMPOSITE MATERIALS FOR MARINE PROPELLERS TO REDUCE FUEL CONSUMPTION AND UNDERWATER RADIATED NOISE

Maël Moret [1], Clement Retiere [1], Aldyandra Hami Seno[2], Nithin Amirth Jayasree[2] and Mihalis Kazilas[2]

[1]Loiretech, Bouguenais, France
Email: mael.moret@loiretech.com, Web Page: https://www.loiretech.fr
[2] Brunel Composites Centre, Brunel University London, Cambridge, UK, Web Page : https://www.brunel.ac.uk/research/Centres/Brunel-Composites-Centre

Keywords: Composite, Propeller, Marine, Manufacturing, Manufacturing simulations, Process monitoring

Abstract

Marine propellers, a complex and important structural element of a ship, are traditionally manufactured in expensive nickel-aluminium-bronze (NAB) or manganese-aluminium-bronze (MAB) alloys to operate under high cyclic loads underwater, and to withstand high stresses due to cavitation phenomena. These propellers require precision machining, long production times and are very heavy to transport. All this translates into propeller prices that typically run into the hundreds of thousands of euros, and long lead times that can result in the immobilization of vessels. The consortium of CoPropel (a project funded by Horizon EU and Innovate UK) proposes a holistic approach for the shipping industry by introducing a marine propeller made from composite materials. By itself, utilizing composite materials offers better corrosion resistance significantly lighter weight, as well as low electrical and acoustic signature. Additionally, due to the composite construction it is possible to optimize the material stiffness such that it deforms in a controlled manner under its operational load, creating an adaptive hydrodynamic behaviour that can potentially improve the boat's propulsive performance, reduce fuel consumption. Taking into account the non-monolithic construction of the composite propeller, the consortium is also developing an integrated structural health monitoring system. This paper will highlight the main challenges involved in developing the novel propeller with a specific focus on the development of the manufacturing related aspects including the methodology, process simulation and process monitoring.

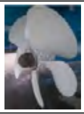
1. Introduction

Today, due to the challenges of climate change and new objectives set by International Maritime Organization (IMO) [1], the energy efficiency of vessels is a crucial topic for shipowners and is highly dependent on the performance of propellers [2,3]. Marine propellers are commonly made from metals using a combination of casting and machining to obtain a monolithic component with a smooth hydrodynamic shape. The result is a strong and stiff component that can have very complex geometries. However, this also comes with drawbacks associated with operation and maintenance throughout its lifetime. Large diameter metallic propellers on large ships can be very heavy which results in the need for special equipment for handling and installation. The weight also results in large inertia which creates the need for a stronger and more powerful engine/shaft setup to rotate the propeller. Hydrodynamics wise, metallic propellers are geometrically rigid and thus are optimised for a specific operational regime which is mainly the RPM range for cruising [2,3].

The use of composite materials allows for a lighter structure with lower inertia [4]. This reduces the requirements from the handling and burden on the propulsion system side leading to potential cost savings from maintenance and fuel efficiency. An added benefit is the inherent fatigue tolerance of composite materials which results in better long-term reliability. With composite propellers there is also the possibility to tailor the stiffness of the blade by varying the reinforcement configuration (fibre angles, etc.) resulting in a "flexible" blade [4]. This flexible behaviour can be designed in such a way that the blade will hydroelastically deform to match the optimum shape at a wider range of RPMs resulting in better overall fuel efficiency [2,5]. Additionally, this flexible behaviour can be tailored to reduce very low-pressure regions on the blade edges which commonly cause cavitation at high RPMs [2,5]. This leads to increased operational life of the blade as cavitation can chip away at the blade surface and significantly reduce its efficiency. Finally, flexible propellers produce less underwater radiated noise when they rotate, leading to lower environmental impact during operation [4].

However, given the requirements of the final product (a propeller) which is very geometrically complex, a manufacturing process has to be found that can produce composite parts with a high fiber content and variable thickness, while controlling the orientation of the fibers within the confines of the propeller geometry. Table 1 Provides an overview of existing studies on composite marine propellers where it can be seen that currently there is no consensus yet on what kind of configuration and manufacturing process is best for such propellers. Thus, this study will elaborate the manufacturing challenges faced in the development of the CoPropel propeller and the steps that have been taken to overcome them.

Table 1. Summary of current studies on composite propellers [4–10]

Name	Contur® propeller	Lin et. Al. (2009)	Greenprop project	Yamatogi	Nakashima/ ClassNK	Fab-Heli project	COMPROP project
Year	2006	2009	2010	2011	2014	2018	2018
							
Materials	high performance carbon fibre composite	Carbon fibre Toho HTA1200 / ACD8801 epoxy prepreg	glass fibre/epoxy core + carbon fibre/epoxy skins	carbon fibre (UD and fabric) / epoxy	carbon fibre (UD tow and fabric) / resin	carbon fibre (UD and fabric) / epoxy	glass fibre/epoxy
Lay-up		$[-45_2/90_2/45_2/0_2/-45_2/90_2/45_2/0_2/-45_2/90_2/45_2/0_2]s$ $[45_2/90_2/45_2/45_2/45_2/45_2/0_2/0_2/0_2/0_2/0_2/45_2]s$		quasi-isotropic		$[0_3/\pm45]_n$	"Propeller 45": $[45/-45]_n$ "Propeller 90": $[0/90]_n$
Manufacturing process	closed mould (RTM-like) process	autoclave 130 °C at 30 psi (2 bar) for 40 min	infusion moulding	prepreg moulding	infusion moulding	RTM	
Prop. Diam. (D)	610 mm	200 mm	2500 mm	680 mm	2120 mm	1050 mm	340 mm
Hub radius (r_h)	122 mm	20 mm		68 mm	110mm	100 mm	
Prop. pitch H/D				1.647			
Blades (Z)	6	5	5	3	4	5	2
Propeller speed	780 rpm	1200 rpm		1008 rpm	355 rpm	730 rpm	900, 1100, 1400 rpm
Blade to hub connection	groove and boss - retaining screws	groove and boss	bronze "blade foot" + radial bolt	groove and boss - retaining ring	groove and boss - retaining plate	radial screws on "blade foot"	
Flexibility analysis	yes			2.5 to 4 time more flexible than NAB			
Performance tests	efficiency improved 3% to 5%, cavitation decrease observed	No		No	At same speed, shaft power reduced by 9% Less vibration measured		

2. Propeller design

The propeller design is based on individual detachable blades on a metallic hub in order to meet the boat owner's need to be able to change a blade underwater. The design methodology of the composite layup to optimize the deformation of the blade to achieve the proposed performance benefits uses coupled fluid-structure interaction simulations and has been presented previously by consortium partners MECA and Bureau Veritas [11]. A small scale test blade (for hydrodynamic testing) and a full scale blade (for sea trials) will be manufactured during the course of the project.

3. Manufacturing process selection

There is a strong link between manufacturing processes and the quality of produced composite material components [12]. It is said that the manufacturing process is essential from the moment a material is selected. In industry, we often find variants of the same manufacturing process or even mixed techniques.

Composite part manufacturing processes can be distinguished according to the type of fabric and the type of tooling. There are processes based on dry fabrics and those based on prepreg (pre-impregnated) fabrics [12]. For dry fabrics, it is first started by forming the stack/layup of fabric layers, which can often be done on a preform mold (draping) to create complex shapes. This fabric preform is then impregnated with resin (using various methods) which will cure and form the composite part. On the other hand, processes using pre-impregnated fabrics provide good environmental control of the process while ensuring good impregnation of the matrix. However, it is more complicated to make composite parts with complex shapes because of the preimpregnated fibres (as opposed to dry fibre preforming). Since the target part is very complex in shape, the CoPropel consortium has opted to use a dry fabric preform, which is then impregnated with resin.

Focusing on dry fabric processes, there are: Contact molding, compression molding, filament winding, and liquid molding [12]. Liquid molding includes the classic RTM (Resin Tranfer Molding) process using a closed mold under press. There are also variants of the classic process, see figure 1, including infusion using an open mold.

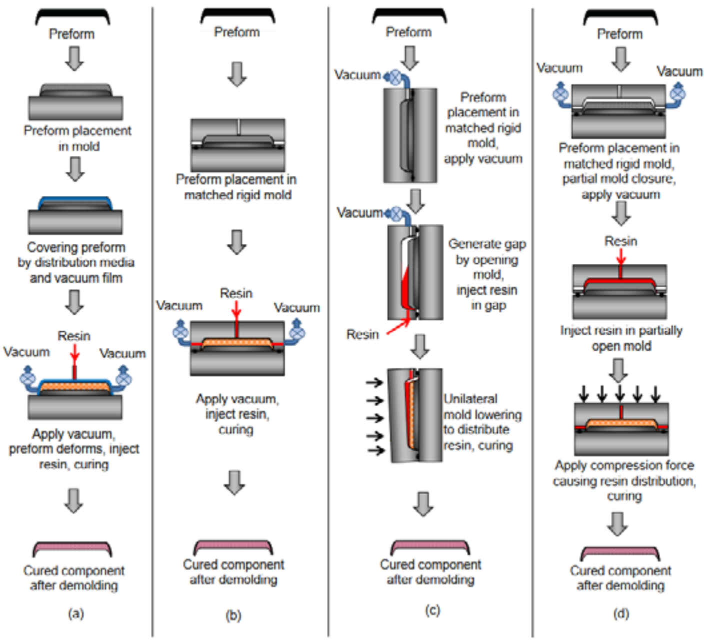


Figure 1. Variants of the liquid composite molding process; (a) vacuum infusion process, (b) RTM, (c) gap impregnation RTM, (d) compression RTM. [12]

Since the target part is very sensitive towards the angle of the fibres (due to optimization of deformation characteristics) and surface finish (due to hydrodynamic considerations of the propeller), the CoPropel consortium chose to implement a vacuum-assisted RTM closed-mold manufacturing process to produce a net-shape composite blade, i.e. without post-processing machining.

4. Manufacturing process specification

The design of the CoPropel propeller is composed of composite blades assembled on a metal hub. However, this paper focuses only on the manufacturing stages of the composite blades. The blade manufacturer will integrate sensors (fiber optics and strain gauges) into the composite material for added structural health monitoring capabilities (not discussed in this study) and as such, the tooling must also allow for this implementation. As previously described, for the manufacture of CoPropel composite blades, it was decided to use resin injection into a dry carbon fabric preform contained in a closed mold using the RTM (Resin Transfer Molding) process. There are 3 main stages in this process: 1.) dry fabric shaping, 2.) resin injection, 3.) curing and post-treatment of the blade.

As shown in the figure 2, this manufacturing process is suitable for industrial sequential production. A laser projector was used to facilitate the work of stacking the dry fabric plies on the preforming mold. This tool also enables us to ensure the orientation of fabric fibers on the tooling. This is a crucial parameter for optimizing the material and achieving the desired results.

The resin is injected into the fabric preform in a vacuum-assisted closed mold. Once the preform has been placed in the self-heating mold, the resin is injected at pressures of up to 3 bar, while drawing a vacuum at the mold outlet. Once the part has been injected, it can be demolded once the polymerization time has been respected.

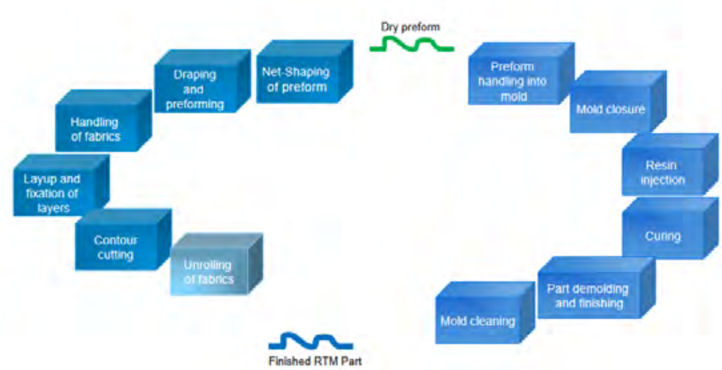


Figure 2. The resin transfer molding process based on sequential preforming. [12]

In order to inject the resin into the core of the blade and successfully infuse the resin into the fabric on the thickest part of the blade, the foot, the manufacturer creates a core at the heart of the blade on which to drape the fabric. The composite blade therefore has a sandwich structure, with a core. This facilitates resin infusion and reduces the amount of dry fiber fabric. To carry out the resin injection, a set-up similar to the one described below is required:

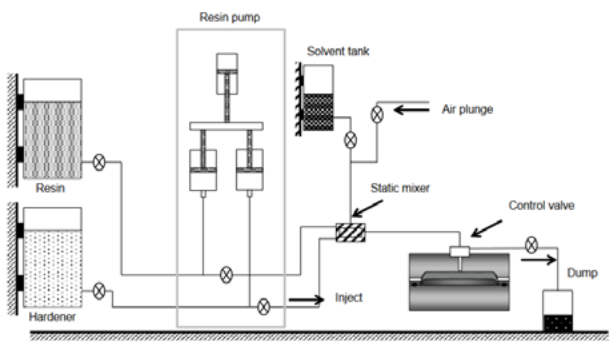


Figure 3. Schematic of two component RTM injection system. [12]

5. Manufacture of samples for material characterization

Within the CoPropel project, the consortium is following its roadmap to develop the composite propeller. At the moment, material characterization of the propeller is underway. RTM tooling has been designed and manufactured to produce composite plates using the same manufacturing process as for composite blades as shown in Figure 4. Several composite plates using different fabric configurations have been made:

- 0° unidirectional carbon fiber fabric only.
- 90° unidirectional carbon fiber fabric only.
- 0° unidirectional carbon fiber fabrics and twill2/2 carbon fiber fabrics.

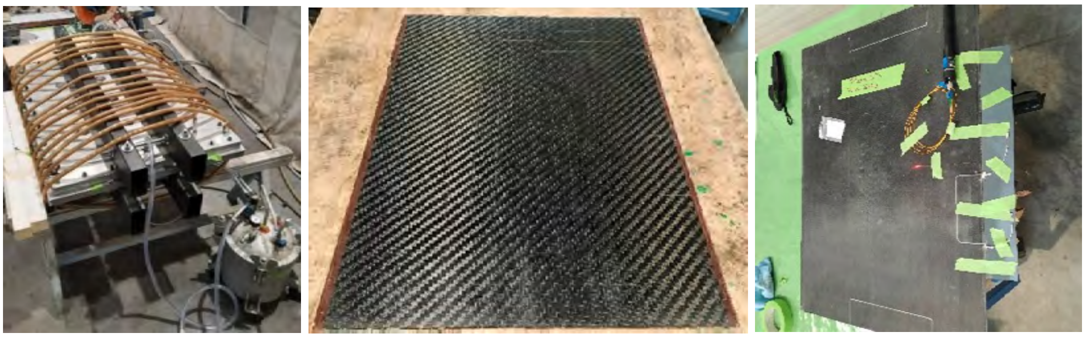


Figure 4. RTM tooling to manufacture composite plates (left), basic composite plate (centre) and composite plate with sensors (right).

During the manufacture of these plates, several systems for monitoring the health of the material, which will later be used in the blade, were integrated (Figure 4). These plates are then water-jet cut to produce coupons, which are then tested to characterize the material. The manufacture of these plates has made it possible to define not only the parameters of the manufacturing process, but also the calibration information for the numerical simulations of the manufacturing stages for the blades themselves.

6. Numerical simulation of manufacturing steps

As mentioned previously, there are 3 steps for manufacturing the blades : draping, injection and curing. Using ESI PAM-RTM software it is possible to simulate all 3 phases in a single chain of simulations. Using the specifications and information from the sample manufacturing, we were able to create injection simulations for the small scale test propeller as can be seen in Figure 5 and 6. Figure 5 shows the model of the small scale blade with color coded regions where the layup changes as it becomes thinner since the plies terminate gradually from root to tip. The simulation allows the assessment of the effets of inlet positioning, outlet vacuum pressure, etc. to optimize the design for the RTM tooling for the full scale blade. Figure 5 shows how changing the number of inlets (from 1 to 2) as well as adding vacuum at the outlets (no vacuum to -0.6 bars) has a significant effect on the resin flow front and the injection time, reducing it by 32.8% from the original configuration. For the draping and curing simulations, a material characterization campaign is currently underway to obtain the required information for the models.

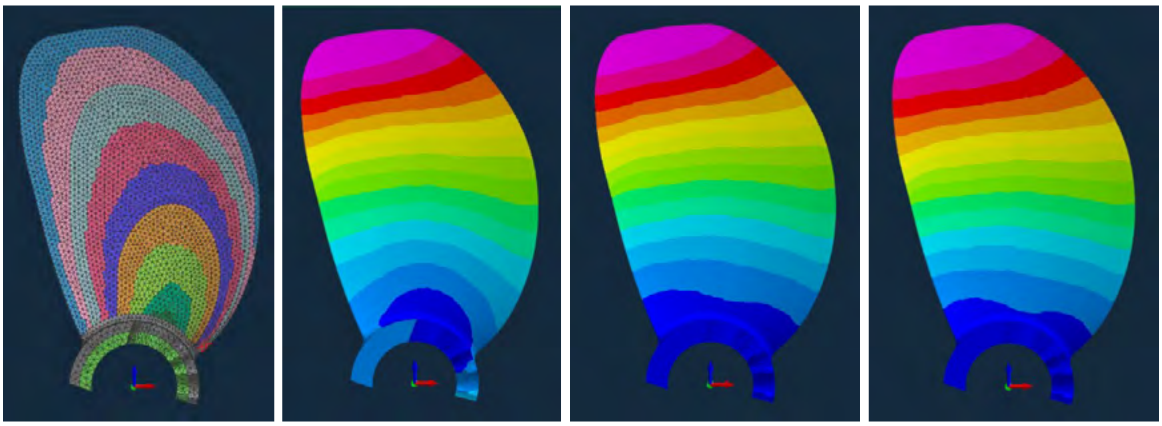


Figure 5. RTM injection simulation model showing regions with differing layup configuration [left] and flow front simulation results with different inlet/outlet configurations : 1 inlet at root (3 bars), 6 outlets at sides (no vacuum) injection time 122.5s [middle left], 2 inlets at root (3 bars), 6 outlets (no vacuum) injection time 102.4s [middle right] and 2 inlets at root (3 bars), 6 outlets (-0.6 bars) injection time 82.3s [right].

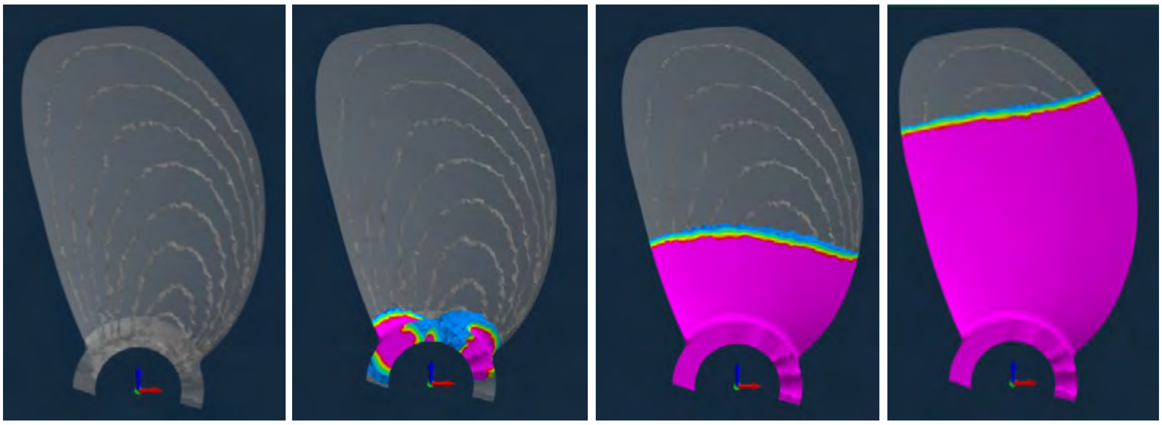


Figure 7. RTM injection flow front simulation model with 2 inlets at root (3 bars), 6 outlets (-0.6 bars) injection time 82.3s at different stages : 0s (left), 2.6s (middle left), 20.2s (middle right), 62.3s (right).

7. Process Monitoring System

In order to ensure the quality of the part during manufacturing, the consortium is developing a process monitoring system for the mold to monitor the most vital parameters (temperature, pressure and cure state) at various points of the blade. As mentioned previously, the objective is to have a net shape process and as such this constrains the methodologies for monitoring to non-contact methods that do not interfere with the mold surface. Thus this presents an added challenge and the consortium is currently validating approaches to monitor the temperature, pressure and cure state during the manufacturing process. In this paper we will present the validation of the cure state monitoring approach.

For cure state monitoring, the consortium has opted to go with ultrasonic based methods[13] and has validated the approach using a dummy mold setup as shown in figure 8. The method works by sending an ultrasound pulse from a transmitting piezoelectric transducer on the outer surface of the mold into the inner surface that is in contact with the part (figure 8). When the pulse reaches the inner surface, a portion of the pulse will pass through the boundary of the material whlist another portion will be reflected back and measured by a receiver piezoelectric transducer (also called a pitch-catch approach). The proportion of the reflected pulse is influenced by the difference in acoustic impedance between the materials at the boundary in this case the mold and the part/resin. The greater the difference in acoustic impedance, the larger the reflected signal will be. Thus, as the part transitions from dry (air), filled (liquid resin), to cured (solid resin) and the acoustic impedance becomes closer to that of the mold (since it is also a solid), it is expected that the reflected signal magnitude will decrease. When the part is cured and there is no longer any changes in the material, the reflected signal magnitude should remain constant.

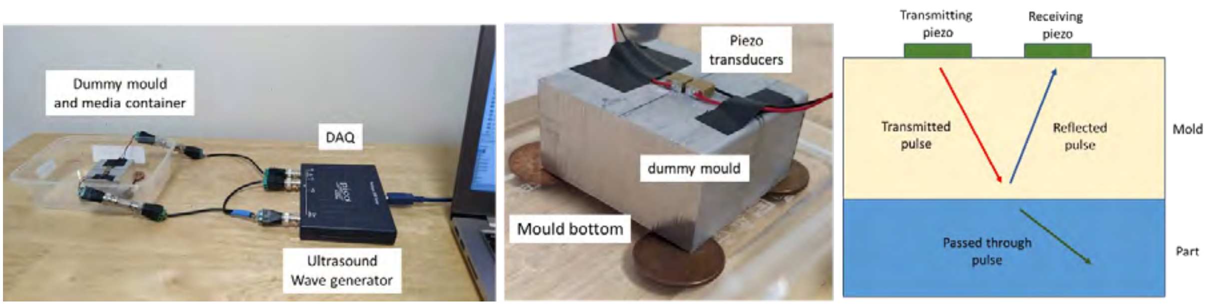


Figure 8. Dummy mold setup for validating ultrasonic cure monitoring approach (left and middle) and schematic of pitch-catch ultrasound approach (right)

To test the approach, a 5 cycle 500 kHz pulse is sent from one of the transducers through the aluminum dummy mold (material and thickness representative to mold for small scale blade) and the response is measured by the receiving transducer. There is a gap underneath the dummy mold which simulates the part under the mold. The validation test starts with the nothing underneath the mold and a signal measurement is taken to assess the initial response of the "empty" mold as can be seen in figure 9. Then, epoxy resin is poured in to fill the cavity under the dummy mold followed by another signal measurement to assess the response after mold is "filled". Finally, resin is left to cure for 24 hours with measurements taken every 1 hour (figure 9).

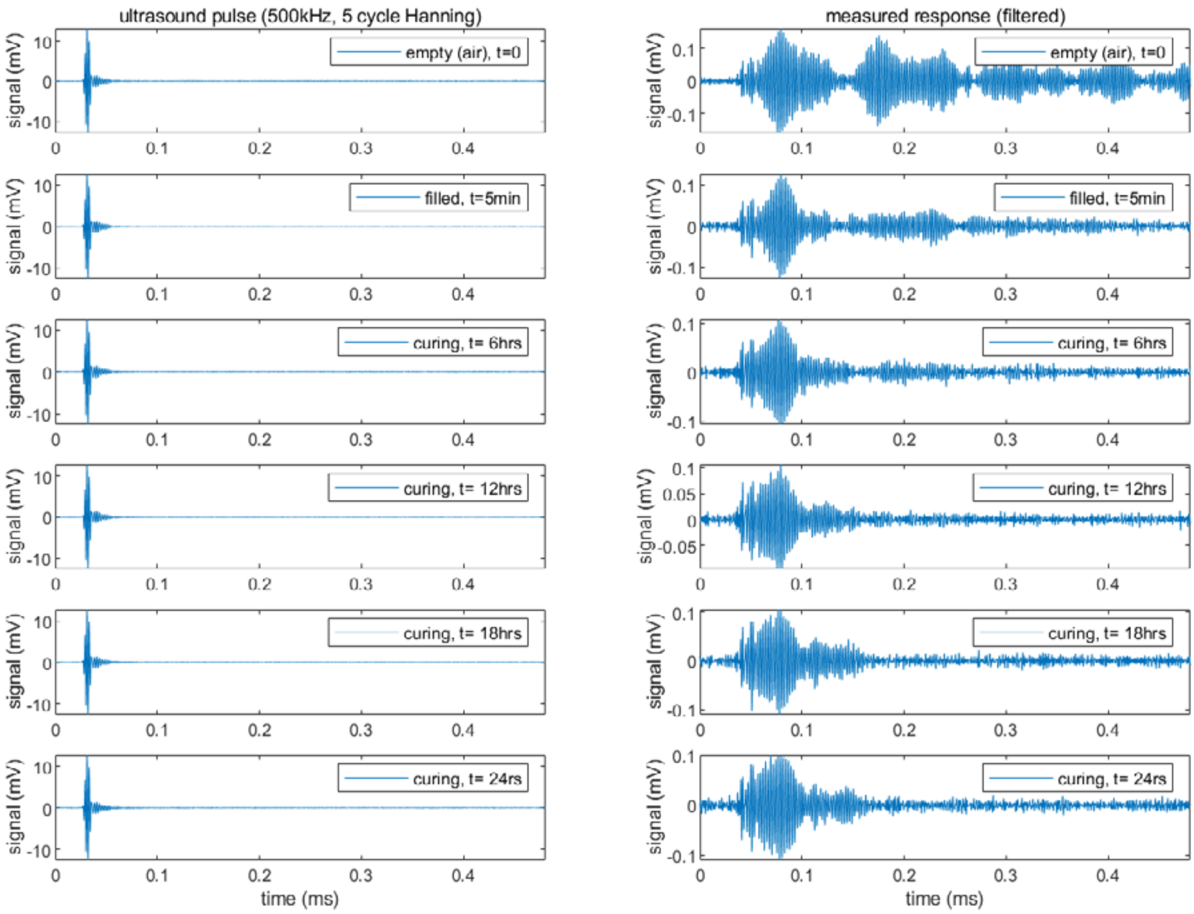


Figure 9. Measured signals (sampled at 250 MS/s, averaged from 5 repeats) from dummy mold setup from empty, filled and every 6 hours until cure (at 24 hours)

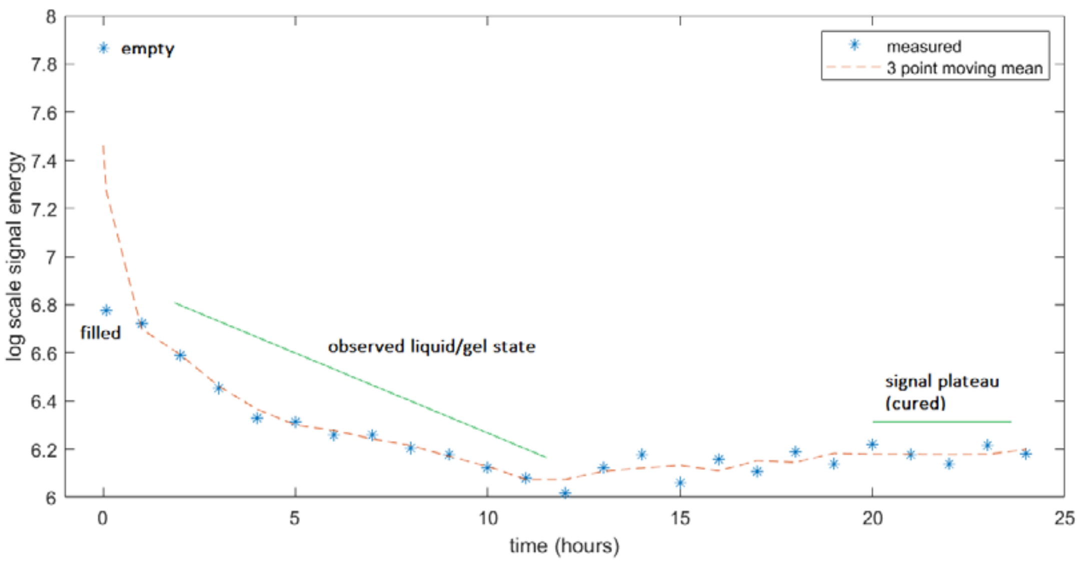


Figure 10. Measured signal energy as epoxy resin cures over 24 hours

From figure 9 it can be seen that the measured response signal changes significantly between each measurement showing that it does pick up on the change in the resin underneath the dummy mold. To compare the magnitude between each signal, a parameter dubbed the signal energy was calculated as the sum of the absolute value of all the sample points within each signal. This is calculated after the initial wave packet (before 0.15ms in figure 10) which is the wave packet that travelled between the transducers (shortest distance thus first arrival) and did not go through thickness (thus not affected significantly by the change in resin). Plotting the signal energy during the 24 hours (figure 10) it can be seen that as previously predicted, the signal energy of the reflected signal decreases as the mold transitions from empty, to filled and finally to when the resin fully cures. When the resin has cured and there is little to no change in the material the signal energy plateaus closer to the 24 hour mark. Thus using the proposed system it is possible to identify the cure state of the resin within the mold.

8. Conclusions

In this study we present the challenges faced during the development of a novel composite marine propeller blade with specific focus on the manufacturing aspects. With the specific requirements of the propeller blade, it was decided that a dry fibre with RTM injection was the most feasible approach due to the complexities of the geometries and the need for smooth surface finish. Manufacturing simulations were developed using information from coupon samples to provide a tool to design the manufacturing process for the small and large scale propellers. To ensure manufacturing quality, an ultrasonic cure monitoring system was validated on a dummy setup representing the material of the eventual mold.

Acknowledgments

This project has received funding from the European Union's Horizon Research and Innovation Actions, under grant agreement No 101056911, project CoPropel [14] "Composite material technology for next-generation Marine Vessel Propellers" as well as Innovate UK under grant agreement No 10037872 and 10037982.

References

1. International Maritime Organization International Maritime Organization, Our Work : Marine Environment Available online: https://www.imo.org/en/OurWork/Environment/Pages/Default.aspx (accessed on 15 May 2024).
2. Maljaars, P.J.; Kaminski, M.L. Hydro-Elastic Analysis of Flexible Propellers: An Overview. 13.
3. Harsha Vardhan, D.; Ramesh, A.; Chandra Mohan Reddy, B. A Review On Materials Used For Marine Propellers. *Materials Today: Proceedings* **2019**, *18*, 4482–4490, doi:10.1016/j.matpr.2019.07.418.
4. Guillaume, D.; Samuel, D.; Franck, B.; Pol, M.; Frederique, L.L. Composite Propeller in Marine Industry: First Steps toward a Technological Breakthrough. In Proceedings of the OCEANS 2019 - Marseille; IEEE: Marseille, France, June 2019; pp. 1–6.
5. Maljaars, P.; Bronswijk, L.; Windt, J.; Grasso, N.; Kaminski, M. Experimental Validation of Fluid–Structure Interaction Computations of Flexible Composite Propellers in Open Water Conditions Using BEM-FEM and RANS-FEM Methods. *Journal of Marine Science and Engineering* **2018**, *6*, 51.
6. Fleetwater Marine UK - Contur Carbon Fibre Propellers Available online: http://www.fleetwatermarine.com/carbon_fibre_propellers.htm (accessed on 30 September 2022).
7. Lin, C.-C.; Lee, Y.-J.; Hung, C.-S. Optimization and Experiment of Composite Marine Propellers. *Composite Structures* **2009**, *89*, 206–215, doi:10.1016/j.compstruct.2008.07.020.
8. Composite Propeller - Solico Available online: https://www.solico.nl/composite-news/greenprop-composite-propeller (accessed on 30 September 2022).
9. Yamatogi, T.; Murayama, H.; Uzawa, K.; Mishima, T.; Ishihara, Y. Study on Composite Material Marine Propellers. マリンエンジニアリング **2011**, *46*, 330–340.
10. Benefits of Carbon Composite Marine Propeller 2015.
11. Larreur, M.; Paboeuf, S. COPROPEL Project: Composite Propeller Design Considering Fluid-Structure Interaction. *E-LASS Seminar Day* **2023**.
12. Chaudhari, R. *Characterization of High-Pressure Resin Transfer Molding Process Variants for Manufacturing High-Performance Composites*; Fraunhofer Verlag Pfinztal, 2014; ISBN 3-8396-0669-1.
13. Lionetto, F.; Maffezzoli, A. Monitoring the Cure State of Thermosetting Resins by Ultrasound. *Materials* **2013**, *6*, 3783–3804, doi:10.3390/ma6093783.
14. CoPropel Project Website Available online: https://www.copropel.com/ (accessed on 23 September 2023).