CoPropel

Composite material technology for next-generation Marine Vessel **Propel**lers

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Glossary

Abbreviation / acronym	Description
CA	Consortium Agreement
DOA	Description of action
EC	European Commission
GA	Grant Agreement
WP	Work Package
SHM	Structural Health Monitoring
CFD	Computational Fluid Dynamics
BEM	Boundary Element Method
NAB	Nickel Aluminium Bronze alloy
FEA	Finite Element Analysis
FSI	Fluid Structure Interaction
TRL	Technology Readiness Level

1. Executive Summary

This document contains the results of the state-of-the-art review and gap analysis (Task 1.1) conducted by all partners based on their respective tasks in WP1. The tasks in WP1 cover all the technical aspects in the project to develop the desired composite propeller (Task 1.2 propeller design, Task 1.3 propeller manufacturing, Task 1.4 propeller SHM system and Task 1.5 propeller certification) which involves evaluating the technical requirements, project objectives and the actions required to achieve the objectives with current capabilities. The discussions from each task team are summarized here as individual state –of-the-art reviews and gap analysis (Sections 5, 6, 7 and 8). The output of this document lays out the initial assessment of work required to achieve the project objectives and feeds into the subsequent WPs (as laid out in section 3).

2. Deviations

An extension to the original submission date (originally month 3, which would be end of August 2022) was requested and approved due to the fact that many consortium members being on annual leave during the summer months. The submission date for this deliverable was thus extended to month 4 (end of September 2022).

3. Dependencies with other Tasks and WPs

The work in this deliverable links to the subsequent WPs as below :

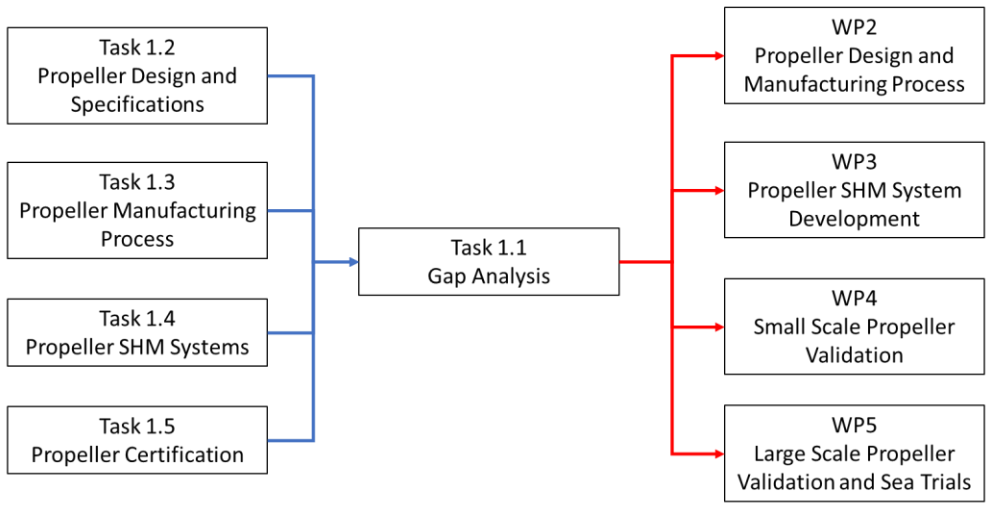

Figure 1. Diagram of dependencies between deliverable 1.1 and subsequent WPs

4. Introduction

Regulations in the marine industry have evolved with time and current environmental problems. The use of boats in society inevitably involves fuel consumption as well as underwater noise where the boats are located. Ship owners are therefore looking for technical solutions to reduce fuel consumption in order to comply with international agreements that have been signed to reduce CO2 emissions to combat global warming. In a world where animal welfare is a societal issue, in view of the impact of human activities on species such as those living on the seabed, international agreements have been put in place. This includes agreements on underwater noise that ships make when travelling and when docked.

To achieve this, the project aims to apply composite material technology that will open the potential for hydroelastic tailoring of composite propellers to achieve optimum propulsive efficiency (through adaptive pitch) and reduced noise (through increased flexibility and reduced cavitation) [ref]. As the technology is relatively new, a state – of – the – art review and gap analysis is conducted to evaluate what technologies and capabilities are currently available and what actions are required to achieve the project goals.

The state-of-the-art review and gap analysis presented in this deliverable will be split into 4 sections (Sections 5, 6, 7 and 8) encompassing all technical aspects covered in WP1 tasks 1.2 – 1.5 (propeller design, manufacturing process, SHM system development and road to commercialization/certification). Each section will be structured starting with a brief background of the technical section, followed by a review of the current state of the art, identification of desired outcomes and gap analysis.

The background is intended to provide a very brief introduction on how the technical aspect is required to achieve the objectives of the project. The state-of-the-art review provides a summary of the current level of technical capabilities in the field, what is widely available commercially and the existing standards/regulations. The desired outcomes section is intended to translate the project objectives to specific technical requirements in each aspect. Finally, the gap analysis will identify the gap in desired technical requirements with what is currently available in the state of the art and provide an analysis of actions required to bridge any gaps between them.

5. Propeller Design State of the Art Review and Gap Analysis

5.1. Background

The application of composite materials in ships is relatively new and not many have been produced compared to more conventional metallic (i.e. NAB) propellers [1,2]. Annex 11.1 provides a review on existing composite propellers and their specifications. From the existing composite propellers, it can be seen that there is no specific trend to the design of these propellers and it highly depends on the intended vessel and operational conditions.

The objective of the design phase is to determine the optimum configuration and specification of the propeller to provide the optimum propulsive efficiency whist being able to withstand the loads imparted on the structure. This includes the hydrodynamic aspects governed by the outer geometry of the propeller blades and also the structural aspects governed by the configuration of materials inside the blade.

Compared to common solid cast metal propellers, composite propellers have structural properties (mainly stiffness/elasticity and the subsequent deformation) that can be tailored by varying the configuration of the constituting materials (i.e. fibre orientation and layup configuration) [3,4]. Thus, the application of composite materials for ship propellers, also opens up new aspects of propeller design that take advantage of these controllable properties to increase the performance and efficiency of the propeller [3,4].

The tailoring of structural behaviour based on the coupling between aerodynamic loads and structural elasticity (aeroelastic tailoring) has been widely applied in wind turbines and aerospace applications (i.e aircraft wings and helicopter blades) [5]. Similar tailoring can be applied to the coupling between hydrodynamic loads and the structural elasticity (hydroelastic tailoring) of marine propellers [3,4]. By doing so it may be possible to tailor the propeller deformation such that the pitch is optimum for a wide range of rotation speeds (unlike conventional fixed pitch propellers) and also to reduce cavitation (reducing wear on the propeller) [3,4].

In order to achieve this, analysis tools are required during the design phase that are capable of simulating the coupling between hydrodynamics from the fluid flow around the propeller and the behaviour of the structure. This involves both fluid flow analysis and structural analysis simultaneously, as the hydrodynamic loads cause the structure to deform which in turn causes a change in the original hydrodynamic load profile and so on resulting in a feedback loop [ref]. Such tools allow the validation of configurations and specifications during the design iterations. Subsequent experimental testing campaigns are also necessary to ascertain the correlation between simulations and real life performance to ensure the final product performs as designed.

Unlike conventional metal propellers that can be as a single piece (with integrated hub and blades), existing composite propellers are commonly built up of separate blades attached to a hub (Annex 11.1). Although on one hand it is due to the limitations of the composite manufacturing process (not allowing the same geometric freedom as metal casting), this split configuration may also provide advantages such as the capability to replace a damaged blade without changing the whole propeller (saving on repair effort and cost). Thus, aside from the design of the propeller blade for performance, it is also vital to design the joint between the blade and hub as it is an area where the highest loads are expected during operation (due to bending from hydrodynamic pressure) [6].

5.2. State of the Art Review

5.2.1. Propeller Configuration Design

The initial phase of propeller design is the determination of the design constraints (vessel type, rpm range, etc.) which define the design space of options/range of propeller parameters (diameter, blade profile, etc.) [6]. Once the constraints have been compiled, empirical equations [6] are available to determine initial propeller parameters based on target performance levels. This provides the initial geometry of the propeller and also defines the propeller operating conditions.

With the initial propeller parameters defined, it is then possible to estimate the loads acting on the blade and the allowables/safety margins [6,7]. Carlton (2012 [6]), NI 663 [7], NR 546 [8] and DNVGL-CG-0039 [9] provide guidelines and empirical formulas for analysis of loads and stresses due to hydrodynamic loads and fatigue. These serve as the design constraints for the structural and material configuration of the propeller. For composite propellers this includes the initial configuration of the layup and core material, as well as the configuration of the blade to hub joint [6,7]. As the blade joint is the area with the highest load due to hydrodynamic loads along the blade, the design of the joint is critical to ensure it can withstand the loads expected during operation [6,7].

Once the initial propeller parameters are determined, the iterative process of optimizing the blade using more accurate analysis tools (for fluid flow and structural analysis) is conducted to obtain the most optimum design [6]. This includes consideration of more advanced design criteria such as hydroelastic tailoring and cavitation that is difficult to evaluate using empirical methods [4,6]. After the design is optimised, prototype testing is conducted to assess the actual performance of the design in real life.

5.2.2. Fluid Flow Analysis

Although it is possible to estimate the pressure field (and hydrodynamic load) on a simplified propeller blade using analytical methods such as the lifting surface theory, the actual 3D flow in real propeller blades is complex and requires more sophisticated modelling techniques [4,6]. The main numerical methods for hydrodynamic simulation currently available are CFD, BEM and VLM [4,10].

CFD discretizes the volume of fluid around the propeller into a grid of smaller elements with the flow behaviour represented by the Navier – Stokes equation for each element (Figure 2). Numerically solving the Navier – Stokes equation for each element is computationally expensive but provides the most accurate results compared to the other methods [11–13]. BEM only discretizes the boundary between the structure and the flow into a grid of “panel” elements (Figure 2) with a simplified flow behaviour assumed (inviscid, irrotational and incompressible) for each element [10,12]. Due to the simplified grid and flow behaviour model, it is much faster to solve than CFD but at the cost of accuracy [10,12]. VLM is similar to BEM, but with the distinction that the discretization is only conducted on the camber plane of the propeller blade (Figure 2), thus making the grid and computation even more simple compared to BEM but also sacrificing accuracy (disregarding thickness, thus valid only for thin blades) [10,13]. CFD is currently the most accessible method due to numerous commercial/opensource packages available (ANSYS Fluent, OpenFOAM, COMSOL, STAR-CCM+, etc.) compared to BEM and VLM which are still predominantly under development and used in research settings [10].

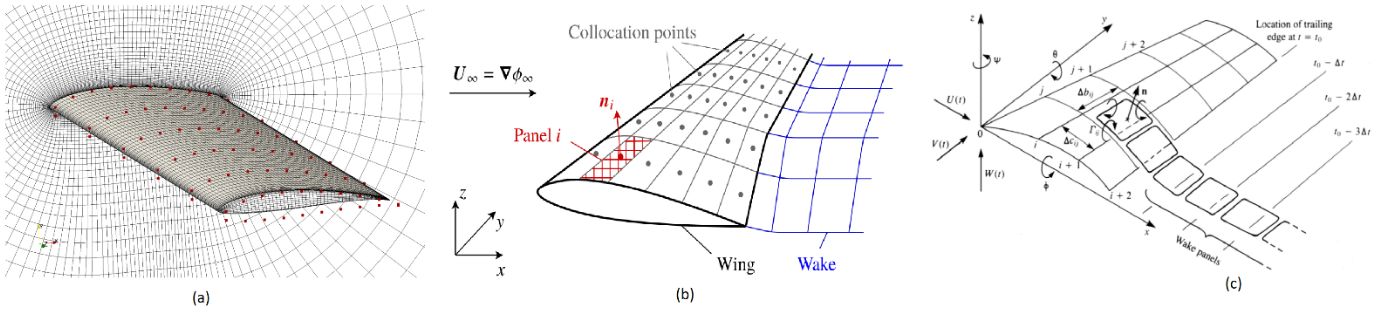

Figure 2. Different numerical approaches for fluid flow analysis : CFD (a) [14]], BEM (b)[12], and VLM (c) [13]

Both BEM and CFD have been shown to be able to simulate the turbulent flow that may be found in the vicinity of a propeller blade as it rotates [10]. For CFD, there are several methods to solve the Navier - Stokes equation for turbulent conditions, namely DNS, LES and RANS[11]. Out of these 3 methods, they trade off accuracy of simulating the turbulent vortex structures with computational cost with the DNS being the most accurate (but impractical cost wise) and RANS the least (but acceptable for a wide range of engineering applications) [11]. For the RANS method, there are several turbulence models (comprised of a number of equations) that are available with the k – ε and k – ω being the most widely used models for general application [11].

Cavitation is the transition of water around the propeller blade from liquid to water vapour due when the pressure around the blade drops near the vapour pressure [10]. As the transition is related to pressure, it is possible to get an estimate of the extent of cavitation by looking at the pressure profile of the blade [10]. However, to simulate the actual cavitation occurrence, additional multiphasic models such as mass transfer or isolated bubble dynamics are needed[10].

As can be seen, there are many methods available to model the fluid flow in rotating propellers. For CFD, many commercial/opensource software packages are available[3,4,10]. In terms of accuracy, these CFD and BEM models are capable of producing relatively accurate and consistent estimates of the flow (pressure distribution, qualitative cavitation profile, etc.) compared to experimental data[10]. However, some parameters (i.e. the cavitation volume) are still subject to uncertainty and differences in certain aspects of each model may have a significant effect on the output (i.e. model type, meshing method)[10]. Thus, it is highly important to have some form of experimental data to verify the correlation between simulation and real life.

5.2.3. Structural Analysis

Structural analysis in the design phase is required to verify 2 aspects of the propeller design : the deformation with regards to hydroelastic tailoring and stress analysis to ensure structural integrity under expected operational loads. Traditionally, structural analysis has been conducted using simplified analytical beam or shell methods (which may include effects from skew, rake and centrifugal force) mainly to verify the integrity of the propeller blade at the point of maximum stress due to simplified hydrodynamic bending loads at the root [6].

However, simplified models are unable to accommodate more advanced analyses such as hydroelastic tailoring where detail hydrodynamic pressure distribution and the subsequent deformation profile across the blade is important to assess [6]. For such purposes numerical methods such as BEM and FEA are more suitable for detail analysis of the structure's behaviour. FEA is similar to CFD in fluid flow analysis (as mentioned in the previous section) in the sense that the volume of interest is discretised into smaller elements containing the behaviour formulation of the material within [6,15]. Here however, the volume of interest is the blade itself and the behaviour defined in the elements are the stiffness of the materials. On the other hand, BEM in structural analysis is also similar to BEM in fluid flow analysis in that only the boundary of the structure is discretized into elements containing the stiffness formulation[6,15]. However, unlike in fluid flow analysis, the formulation in structural BEM is not simplified compared to FEA and as such structural BEM can provide significant computational saving without a significant drop in accuracy [6,15]. The drawback, however, is that it is less flexible in discretizing the structure especially when it is complex and comprised of different structural elements and materials. In terms of availability, FEA commercial/ open source software is more widely available (Simulia Abaqus, MSC Nastran, LS-DYNA, etc.) than BEM software which tends to be in-house.

As the composite material used is highly anisotropic, is it is necessary to include this effect and the correct orientation of each ply in the analysis [6]. This ties in with the hydroelastic tailoring where the specific configuration of these plies is tailored to produce the desired deformation profile under load[4,6,16,17]. Thus, aside from the structural analysis itself, an optimization approach is needed during the design iteration to obtain the best stacking sequence of plies [4,6,16].

Structural analysis may be conducted in two ways: static or dynamic [6]. Static analysis is suitable when the loading can be assumed to be constant with time such as when the ship is cruising at constant velocity and the propeller is rotating at constant rpm[6]. This also follows the testing conditions prescribed for structural integrity certification[6,7]. However, other loads (such as impact) are also expected to occur (and are outlined in certification testing requirements[7]) which cannot be analysed through static analysis. For such cases, dynamic time domain analysis using implicit/explicit integration method are required [18].

For hydroelastic tailoring, the strain output of FEA or BEM is enough to validate the deformation behaviour of the propeller blade. However, for assessment of structural integrity, using the strain or stress output and comparing with material allowables may not be sufficient. This is due to the anisotropic nature of the composite plies and how they interact with each layer, causing each stress component to interact in a specific way to trigger damage [19]. Thus, it is also necessary to include damage initiation models specific for composite materials (i.e. Hashin) to account for this [19].

Most available software packages can readily incorporate the features mentioned above (anisotropic materials, static and dynamic analysis, as well as composite failure models) [20]. The main consideration is then which software is available to the consortium and which software can be optimally coupled with the chosen fluid flow analysis software.

5.2.4. Fluid Structure Interaction

As mentioned previously, the coupling of fluid flow and structural analysis is necessary to realize the hydroelastic tailoring which is one of the main objectives of the propeller design. This coupling is commonly referred to as fluid structure interaction (FSI) and is currently available in commercial software packages. Some software packages (such as Ansys) are able to do both fluid flow and structural analysis as well as accommodate the FSI coupling between the models in one package [21]. Other software packages that only conduct fluid flow analysis or structural analysis can also be linked together to perform FSI coupling (e.g. Abaqus FEA and Fluent CFD [22], Abaqus FEA and StarCCM+ CFD [4], or TRIDENT FEM and PROCAL BEM [3]).

The most common way to conduct the coupling between a fluid flow solver and a structural analysis solver is to transfer the result of the fluid flow analysis (hydrodynamic pressure loads) to be used as the loads for the structural analysis [3]. To achieve that coupling two different approaches are utilised, the one - way (weak) and the two - way (strong)[3]. In one – way coupling the transfer of data from fluid flow analysis occurs only once and serves only to provide the structural analysis with a load profile [22]. This approach provides better accuracy than when no FSI is accounted for in the analysis [22]. However, due to the one – way transfer of data, it cannot take into account the change in fluid flow behaviour due to the deformation of the blade[22].

The two – way approach addresses this by creating a feedback loop between the fluid flow and structural models : the deformation of the blade is fed back to the fluid flow analysis which then provides an updated hydrodynamic load profile to the structural model [21]. This loop continues until the solution converges. Because of this feedback loop, the two – way approach provides more accurate results than the one – way approach [21].

Thus, for FSI, the main considerations are which software packages are available to the consortium and what method of data transfer between models is used [3,4,21,22]. The data transfer methodology is important not only for accuracy of the FSI analysis (e.g. one - way vs two - way), but also to optimize the design iteration workflow as transferring data manually between models requires much more time than software accommodated coupling (e.g. two – way coupling in Ansys workbench between FEA and CFD [21]).

5.2.5. Experimental Testing and Validation

In order to validate the design of the propeller, testing is vital to assess whether the proposed design meets the intended requirements. In this case, there are 2 main parameters : hydrodynamic performance and structural integrity requirements. These tests are not only conducted at the end to validate the final design, but conducted in a building block approach [ref] to feed data as the design progresses from small scale prototypes to the final full - scale propeller.

For structural integrity requirements, NI 663 [7] provides guidelines on the mechanical testing and validation throughout the design phase. This covers sample tests to confirm mechanical properties and manufacturing effects, prototype testing to confirm design features (blade and joint) under load, as well as full – scale propeller quality control and sea trials [7]. Mechanical tests for strength verification of samples and design prototypes include static strength tests (tensile, bending, interlaminar shear), fatigue, and impact [6,7].

For hydrodynamic performance, the main parameters of interest are propulsive performance and cavitation behaviour [4,10]. Propulsive performance (e.g. thrust and torque) can be measured through testing in cavitation tunnels and to some degree in towing tanks [4,10]. The cavitation behaviour of the propeller can also be tested using scale models in cavitation tunnels [4,10]. However, it is important to take into account that since the propeller design intends to utilize hydroelastic behaviour to affect hydrodynamic behaviour, the scale models used for these tests must be designed such that it deforms the same way as the final full – scale propeller.

5.3. Desired State and Outcomes

Based on the project objectives, the intended goal of the design phase of the propeller is to :

1. Provide analysis tools to predict the deformation of the propeller blades under hydroelastic coupling
2. Design propeller blades that will deform under hydrodynamic load in such a way that it provides the optimum pitch angle for maximum propulsive efficiency under a wide range of rotation speeds
3. Design propeller blades with reduced cavitation
4. Design propeller blades that will be able to withstand expected operational loads
5. Provide geometric and material configuration specifications for manufacturing propeller blades for testing and demonstrators
6. Provide experimental validation for the performance/behaviour of designed propeller blades

5.4. Gap Analysis

Based on the available technologies and capabilities identified in the state – of – the – art review, the following actions are needed to achieve the desired objectives :

- ✓ Evaluation of fluid flow and structural analysis software to be used for design and validation of fluid structure interaction between them.
- ✓ Evaluation of target parameters based on chosen vessel and initial configuration based on empirical methods
- ✓ Design iteration of propeller using chosen software to achieve improvements in performance through hydroelastic tailoring as well as fulfil structural integrity requirements
- ✓ Design and conduct testing on scale model to validate design concepts
- ✓ Produce full scale model and conduct sea trials to validate design for real life application

6. Manufacturing Process

6.1. Background

The use of composite materials for boat propellers is still rare nowadays compared to metal propellers [23]. This is due to the complexity of making a composite propeller with the same final quality as a conventional metal propeller [23,24]. However, due to the demand for lighter and equally strong parts in many industrial sectors (such as aeronautics, automotive and others), industrial actors have developed and increased their skills in the field of composite manufacturing [25]. As a result, companies manufacturing elementary parts are becoming increasingly proficient in the use of composites and associated manufacturing processes [23,25].

For marine propellers, the composites used are commonly polymer based which is composed of a matrix, such as epoxy resin, and a reinforcement, such as carbon fibre [23,25]. The process of combining these constituent materials and curing the material results in higher complexity of manufacturing compared to singular materials such as metals [23,25]. Many manufacturing methods have been developed for composite materials, including manual and mechanised methods [23,25–27].However, manufacturers are still finding it difficult to produce composite blades industrially in a repeatable manner, thus allowing for certifiable blades [25]. In recent years, research on the manufacturing defects and their detection allows manufacturers to anticipate defects and know how to repair them [25]. The CoPropel project does not seek to innovate in the field of materials, nor in the means of shaping. The objective is to produce composite blades by industrially mastering the manufacturing process and the production of the blades by incorporating new technologies to ensure repeatability.

6.2. State of the Art Review

6.2.1. Composite Blade Shaping

To begin the state of the art on the production of composite ship blades, it is necessary to look at the means of shaping the blade. As described above, there are manual and mechanised means of shaping. Among the manual means, we will find [23,25,27,28] :

- Contact moulding: an operator places the reinforcements in an open mould and then applies the matrix (resin) using a roller. The whole is then put into an oven to solidify.
- Vacuum moulding: the process is identical to the previous one, however, before solidification, an absorbent tissue is placed on the composite and then a waterproof sheet is added. Excess air and resin is then sucked out by the vacuum.
- Infusion: an operator positions the fibres in an open mould, adds a draining fabric and then closes the whole with a vacuum bag. This cover is connected to containers of resin and a vacuum system. During the vacuum process, the resin gradually impregnates the reinforcement. Then, the part must be cured to solidify the whole.
- Pre-impregnation: an operator positions the resin pre-impregnated fibres by hand in an open mould and then closes the assembly with a waterproof sheet. This sheet is connected to a vacuum system. Solidification is carried out at high temperature and under pressure, in a vacuum bag placed in an oven or autoclave.

These means of manually shaping a composite part are not suitable for large-scale industrial applications. Indeed, it is complicated to have a good repeatability with these means because the operations are carried out manually. This is why we also have mechanised shaping methods to remedy this problem [25,27]:

- RTM (Resin Transfer Molding): it involves placing the fibres in a closed mould into which resin is injected under pressure using a pump. Compared to infusion, the use of a closed mould allows for better control of part thickness of the parts, but with much more expensive tooling.

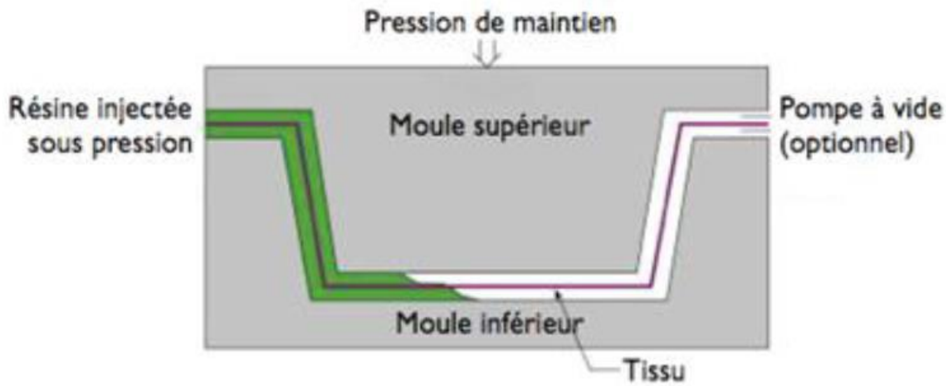

Figure 3. RTM process schematic

- Filament winding: this is used to manufacture tubes by winding resin-impregnated fibres around a mandrel which acts as an inner mould.

Except for filament winding, the installation of the reinforcements remains manual, which creates potential problems for the repeatability of the parts produced [25]. With the emergence of composite parts in the aeronautical sector, a new method has emerged: automatic fibre placement (AFP) [29]. This method consists of positioning the fibres with the help of robots and/or automatic machines with a view of the tooling (camera). In this way, the reinforcements are always positioned in the same way at the same place. However, this kind of solution, which is suitable for simple shapes, is not easily applicable for ship's blades because of their concave and convex shapes. In the CoPropel project, the partners will evaluate the possibility of implementing such a technology.

6.2.2.Manufacturing Processes Used by Other Projects

Now that the state of the art on shaping processes has been achieved, it is necessary to take an interest in previous projects aimed at producing composite blades but also in industrial productions in the world producing this kind of part.

Nowadays, the only 'serial' composite propellers are manufactured by NAKASHIMA, Japan. Manufacturing process is the following (macro process) [30]:

1. Infusion of blade with extra thickness on a master model
2. Milling on the B-Face to get the final surface (less than to 2 thin plies of carbon fiber)
3. Infusion of 2 carbon fibre plies

The process they use is called VaRTM (Vacuum assisted Resin Transfer Moulding), described in class NK guideline. This process required several manufacturing steps as we have seen.

Advantage of existing technologies:

- No difficult steps in the process

Drawback:

- Leading and trailing edges are sensitive to impact
- Huge level of hand work as the part is not net shape (risk not to archive profile tolerance: milling could involve distortion, surface waviness due to hand work)
- Economic competitiveness

This type of blade production highlights a major problem in achieving good repeatability in the production of the part: a lot of manual work is required.

There is also the Yeo company [31] which manufactures a GFRP propeller by hand lay-up with two pieces mould type designed to produce detachable blade, with 3 bleeding paths in the lower mould to evacuate excess of resin and air bubbles. It was highlighted the need to optimize the process with various tests before obtaining an acceptable final product. The problem encountered were the following:

- Insufficient amount of resin : pressure and suction surface depleted
- Insufficient release agent : difficulty to detach the blade
- Additional curing pressure : mating texture on a surface

Then, Fabheli project [27], in which several CoPropel partners were involved, made possible to demonstrate the production of a composite blade using the RTM process and the robustness performance in sea trials. The composite blade obtained was net shape as the RTM process allows not to have any machining of the blade afterwards. Carbon leading and trailing edges have been integrated to reinforce the edges of the blade. The different steps of making the blade were as follows:

1. Preforming of Intrados side
2. Preforming of Extrados side
3. Preforming of Blade join area
4. 3D printing internal sand core
5. Leading edge carbon protection layup in the RTM tooling
6. Trailing edge carbon protection layup in the RTM tooling
7. Preform assembly in the RTM in the RTM tooling
8. Injection of epoxy resin
9. Epoxy resin curing

10. Unmolding + Flash of resin sanding
11. Coating of the blade
12. Assembly of the blade on the hub
13. Full propeller balancing to avoid mechanical inertia

During the Fabheli project, LRT was able to test the following materials for the production of their blade:

- Matrix : Epoxy resin SR8100 with hardener SD8822
- Fiber : T300 carbon fiber, mixture of unidirectional fiber and TWILL2/2.

The prototype propeller has shown high performance potential during sea trials. However, some difficulties with the thickness of trailing edges have been highlighted.

6.2.3. Manufacturing Defect Detection and Control

For the end, it is interesting to look at the studies that have been carried out on the defects of composite parts. Fu and Yao (2022) [25] has reviewed the types of defects that can be created during manufacturing:

- Resin matrix defects: Formation of residual stresses, void defects, resin rich defects
- Fiber wrinkle and waviness
- Delamination and debonding on the interface
- Machining defects: drilling and cutting

Detection methods exist to control the quality of the product, such as visual and optical testing, ultrasonic, acoustic emission, infrared thermography, X-ray radiography. Also, to reduce the impact of the manufacturing defects on the design of propellers, safety factors (BV NI663 [7]) are used, testing/inspection of the products (e.g. tensile, bending, interlaminar shear, CND, dimensions). Approval procedure of manufacturing process (e.g. coupon tests, element test, examination) such as described in ClassNK [32] Guideline can be conducted. Lastly, the manufactured parts need to comply to tolerances detailed in standards, such as ISO 484 [33] for geometric tolerances, or ISO 1940 [34] for balancing class.

Simulation of the manufacturing process using software packages such as PAM-RTM [35] during the design phase of the manufacturing process allows the evaluation of defect formation prior to manufacturing and provides the ability to optimize the process to prevent defects. Additionally, monitoring of the vital parameters (e.g. temperature, degree of cure, pressure) during the manufacturing process using embedded sensors in the tooling allows for the assessment of the consistency of the manufacturing process (will be elaborated further in section 7) [26,36].

6.3. Desired State and Outcomes

At the end of the CoPropel project, several elements are expected for the manufacturer:

- Manufacturing monitoring system equipment integrated in the RTM tooling

- Identification of materials, resins and matrices, allowing to have a composite blade meeting the requirements of the CoPropel project.
- Manufacture flexible propeller based on optimized design
- Integration of Part SHM equipment / components during manufacturing process
- Optimization of RTM manufacturing process to improve efficiency and quality through:
  - RTM simulations
  - RTM monitoring system
  - Automation of certain steps if possible as preforming process to be supported by Laser projectors
- Realize a certifiable composite blade for sale on the market.
- Demonstrate through tests the performance of a composite blade compared to a metal blade.
- Demonstrate through tests the mastery of the manufacturing process using new generation tools

6.4. Gap Analysis

Compared to the objectives of the CoPropel project and the state of the art on the targeted technologies, we can identify the important points:

- Advantages of RTM: 2 sides of blade out of the tooling, low void content, control of properties, repeatable results, flexibility of mould design, reduction in labour and material waste, good for large components…
- The implementation of an AFP technology will be very complicated given the shapes of a composite blade.
- NI 663: design assessment, safety factors, C_F taking into account the fabrication process and the reproducibility of the fabrication, directly linked to the mechanical characteristics of the laminates
- Sample tests to validate mechanical properties
- Simulation of the process and SHM to optimize the steps and control the quality
- Integration of the SHM system directly into the composite blade to know the state of health of the part in use on the boat.

7. SHM System

7.1. Background

The low weight, high mechanical strength, high stiffness, and vibration damping ability make composite materials very attractive for application in many industrial areas such as aerospace, automotive, maritime, and wind energy. However, there is a main disadvantage which is related to existing delaminations inside the structure. This damage is located within the composite, is invisible and may lead to unexpected structural failure [37]. For these reasons, there is a need to develop methods which can detect, localize and quantify defects. Many researchers focus on the development of structural health monitoring (SHM) systems and methods that could be utilized for composite structures.

Sensors in an SHM system detect signals related to physical properties that can be interconnected to damage initiation and growth (temperature, pressure, charge, voltage, etc.). SHM systems can be divided generally into passive and active systems [38]. In an active system, SHM actuators and sensors are utilized. Actuators generate diagnostic signals, when the sensors receive these signals in various locations of the structure. In a passive system only the sensing ability, which detects signals generated by propagating damage, is utilized [39]. In SHM systems, many different methods are utilized to assess the state of a structure.

Aside from monitoring the health of the propeller structure, sensors can also be integrated to the manufacturing tools to monitor the process (via critical parameters such as pressure, temperature and degree of cure) to assess the degree consistency [26,36].

7.2. State of the Art Review

7.2.1. SHM Sensors

A lot of wired and wireless types of sensors have been developed to monitor structural condition through real-time data collection. One of the critical steps in designing a proper SHM system is deciding on an appropriate type of sensor that can efficiently meet the scopes of the targeted structure to be monitored.

Structural health monitoring relies on collecting real-time measurements of the structural element condition, transferring this information to a control system, and signalling necessary warnings. The most employed SHM sensors for structural health monitoring are Fiber Optic Sensors, accelerometers, vibrating Wire Transducers, Linear Variable Differential Transformer (LVDT), Load Cells, Strain Gauges, Inclinometers (Slope Indicators), Tiltmeters, Acoustic Emission Sensors, Temperature Sensors and RFID (Radiofrequency identification) sensors.

7.2.2. Fibre Optic Sensors

Research work on FOS began in the 1960s, but it is the development of modern low-loss optical fibers that has enabled the transition from the experimental stage to practical applications. Some of the first sensing experiments using low-loss optical fibers were demonstrated during the early 1970s. The field of FOS has continued to progress and has developed enormously since that time. For instance, distributed fiber-optic sensors have now been installed in bridges and dams to monitor the performance of and structural damage to these facilities. Optical fiber sensors are used to monitor the conditions within oil wells and pipelines, railways, wings of airplanes, wind turbines and propellers.

The concept of a fiber-optic sensing system is that the fiber (guided laser light) interacts with an external parameter and carries the modulated light signal from the source to the detector. The input measurement and information can be extracted from this modulated optical signal. Depending on the type of fiber sensor and its operating principle, the sensor system can operate either in transmission mode or in reflection mode, which is elaborated in later sections of this chapter.

One of the biggest advantages of fiber sensors is that they have the capability to measure a wide range of parameters based on the end user requirement, once a proper fiber sensor type is used [37,40,41]. Some of the measurement capabilities of fiber sensors are :

- Strain, pressure, force
- Rotation, acceleration
- Electric and magnetic fields
- Acoustics and vibration
- Temperature, humidity
- Liquid level
- pH and viscosity
- Bio-sensing

Optical fiber sensors are excellent candidates for monitoring environmental/external changes. Fiber sensors are superior to conventional electronic sensors in various aspects :

- Light weight
- Passive/low power
- Resistance to electromagnetic interference
- High sensitivity and bandwidth
- Complementarity to telecom/optoelectronics
- Multiplexing capability
- Multifunctional sensing ability
- Easy integration into a wide variety of structures
- Robustness, greater resistance to harsh environments

Though optical fiber sensors have many advantages compared with their electrical counterparts, there are also some concerns over this technology. Major drawbacks include cost, long-term stability, less efficient transduction mechanism, and complexity in their interrogation systems.

To cover all the range of structural needs a lot of sensor types were developed. The different types of FOSs reported for strain/temperature measurements for composite materials are Fiber Bragg Grating (FBG) sensors, interferometric OFSs, polarimetric sensors, distributed sensors (using techniques such as Rayleigh scattering, Raman scattering, and Brillouin scattering), and hybrid sensors [37,42].

7.2.3. Rayleigh Scattering

The distributed sensing technique uses the interference of the light waves which are backscattered within the resolution range of a reflectometer to detect changes in the optical path in a single-mode fiber. Rayleigh backscattering is a recent development in distributed fiber optic sensing for the interrogation of strain and temperature along an optical fiber. Concerning previous distributed sensors, a standard optical fiber can be applied as the sensor, providing distributed measurements over large distances, without expensive individual sensors. Gifford et al. applied swept-wavelength interferometry (SWI) to measure the backscattered signal in silica and POFs [43]. This interrogation method is fundamentally different from optical time-domain reflectometry measurements, since SWI measures phase shifts rather than amplitudes in the backscattered signal. While the spectrum of the backscattered signal is random, it is deterministic. Local changes in temperature or strain create a wavelength shift in the response, similar to the effect measured by FBG sensors. Interrogating the backscatter spectrum with SWI can provide a high spatial resolution (up to 10 s of microns) with strain resolution up to 1 με and temperature resolution up to 0.1 °C. A similar set-up can also be used to produce a distributed acoustic sensor that can be used for intrusion detection and localization.

7.2.4. Fiber Optic Sensor Integration

In general, an optic fiber sensing instrument consists of a laser source, detectors, modulators, and couplers or circulators. Off-the shelf systems, additionally, have data acquisition and processing modules to acquire measurement data from the detector signal and an interface to output or display the data. Optic fiber sensors can be both on the surface of the structure or embedded in it.

The most important thing that should be considered, concerning the embedding process, is to find a way in which the optical fiber can be maintained in the initial position after the curing of the laminate. This can be accomplished in various ways, and different methods will work better for different applications. The most used methods are: In Epoxy, Pre-Preg Tack Woven in Veil, Tacked to Veil, Tacked to or Woven into Ply, Tape Dots, Woven in with the Composite Structure [44].

Embedding fiber HD-FOS sensors in composite structures provides many advantages including:

- The ability to gain insight into the complex internal strains that build up during a structural test.
- Greater sensor coverage due to the continuous high spatial resolution nature of the measurement.
- The ability to elevate the structure into a smart structure that both monitors and reports on their current state of health. In this way, critical manufactured parts can be monitored throughout the manufacturing process, the transport schedule, and their service life, increasing the efficiency of the bring-up and tear-down processes.
- The ability to protect the sensor. The sensor is made of silica and while very strong in tension, is weak in shear.

Despite the plenty advantages of embedding fiber sensors , there are some remaining challenges and concerns. The most common challenge is the possibility of micro-bending, which affects the signal to noise ratio of the measurements. Micro bending takes place when a compressive force bends, locally, the optical fiber between the reinforcement fibers of the composite. To alleviate this, a possible solution is to align the fiber sensor with the reinforcing fibers. Delamination is another challenge that should be overcome, especially when it occurs at the ingress location of tubing at the edge or composite's surface. This is the main reason that the location of the insertion point needs to be cautiously selected, so as not to coincide with a high load area [44]. The question also arises, of whether a surface bonded fiber sensor is sufficient for the application. Typically surface bonded sensors will display the highest strain value, as it is the furthest away from the neutral axis, whereas an embedded fiber will show a reduced strain for a given load. However, internal defects will be missed if the strain gradient has sufficiently decayed between the interior and exterior of the composite part.

7.2.5. Rotary Joints

Another challenge in the application of a FOS system to monitor a part that is in service is the coupling of the laser delivery and acquisition system with the interogation system that performs the signal analysis and display. This challenge is even bigger when the interrogated part is rotating and shall be coupled with a stationary structure where the interrogation system is placed. A possible solution to this coupling challenge is the use of a rotary joint.

Fiber Optic Rotary Joints (FORJs) are to optical signals what electrical slip rings are to electrical signals, a means to pass signals across rotating interfaces, particularly when transmitting large amounts of data. FORJs maintain the intrinsic advantages of fiber end to end. Fibre optic rotary joints (FORJ) are passive optomechanical components which provide a continuous fibre optic connection between rotating and stationary equipment. A FORJ is the optical analogue of an electrical slip ring as required in many tethered, rotating and articulated systems.

James W. Snow in 1998 [45], used one prototype planetary rover (NASA Carnegie-Melon Dante II project) for his studies. Fibre optic rotary joints fulfill the mating requirements of a connector while allowing continuous rotation between the two bodies which are attached. The technical challenge is to passively transmit and collect light over 360 degrees of rotation with minimum light loss, dispersion and modulation, as well as crosstalk between adjacent channels. The difficulty is that light is directional and can only be redirected through reflection, refraction or interference. The simplest configuration is a single pass FORJ, be it for single-mode or multimode optical fibre. This can be achieved by coaxial, opposing fibres usually terminated with a lens.

7.2.6. Wireless Sensors

There is a limitation regarding the study of wireless fiber optic sensors. Due to the nature of the sensors which use a light source, their wireless application is restricted to only data transmission. Therefore, all the available efforts until now, which are described below, are focused only on data transmission and not data acquisition.

Mendoza et all, developed a light weight, high-speed, and self-powered wireless fiber optic sensor (WiFOSTM) structural health monitor system suitable for the onboard and in-flight unattended detection, localization, and classification of load, fatigue, and structural damage in advanced composite materials commonly used in avionics and aerospace systems [46]. The WiFOSTM system was based on ROI's advancements on monolithic photonic integrated circuit microchip technology, integrated with smart power management, on-board data processing, wireless data transmission optoelectronics, and self-power using energy harvesting tools such as solar, vibration, thermoelectric, and magneto-electric.

Yuxiang Liu et. all developed a wireless integrated micro-optical sensor system to measure dynamic strain and pressure fields on rotating rotor blades [47]. The system was based on low coherent interferometry, which is insensitive to wavelength or intensity induced noise, allows high sensitivity, higher resolution, and fast demodulation. The sensing system worked with both wired and wireless DAQ systems. The authors claimed that the wireless system may remove wires from the sensors to the hub ring, and hence may reduce noises and make real-time measurements on rotating blades possible. The same authors reported on the preparation of a spin beam for future spin test.

Unlike fibre optics, wireless technology for more conventional sensors such as strain gauges have seen more development [48]. The individual components to develop such a system (sensors, data acquisition system, data transmission modules) are at a higher TRL level and are available commercially [48]. The drawback however is larger footprint and discreet points of measurement (not continuous as Rayleigh Scattering fibre optics). Thus, it is a viable lower risk (albeit providing not as much measurement) alternative to fibre optics.

7.3. Desired State and Outcomes

There are 2 monitoring systems desired to be developed for the project : a system to monitor the RTM process and a system to monitor the health of the propeller structure. Below are the identified required specifications for each structure.

7.3.1. Resin Transfer Moulding monitoring system

- Goal :
  - ✓ Monitor parameters of interest within mould during RTM process (pressure, temperature, degree of cure)
- Approximate Operating conditions :
  - ✓ Pressure range : 0 bars – 7 bars
  - ✓ Temperature range : room temperature – 80^{0}C (approx.)
  - ✓ Material system : Epoxy resin SR8100 (with hardener SD8822), T300 carbon fibre (mix of UD and TWILL2/2) and sand core.

7.3.2. Structural Health Monitoring system

- Goal :
  - ✓ Monitor structural integrity of blade during operation

- Approximate Operating conditions :
  - ✓ Sensors on blade, submerged in sea water
  - ✓ Approximate operating period : xx months
  - ✓ Temperature range : 0^0C to 35°C
  - ✓ Propeller RPM range : up to 700 rpm
  - ✓ Viable connection routes for data transmission : wireless, cable through shaft

7.4. Gap Analysis

Based on the state-of-the-art review and desired outcomes, below are the identified viable monitoring strategies for the RTM and SHM systems.

7.4.1. Resin Transfer Moulding monitoring system

- Monitoring strategy :
  - ✓ Determine vital locations for sensor placement during mould design and RTM simulations (PAM RTM)
  - ✓ Determine ideal range of values for parameter of interest (temperature, pressure and cure)
  - ✓ Determine action in event parameters fall out of ideal range (i.e. stop process, change resin flow rate)
  - ✓ Conduct RTM process and maintain parameters within ideal range, followed up by quality control to ascertain product quality
- Apparatus :
  - ✓ Temperature (thermocouple), pressure and dielectric sensors (curing) embedded in specific locations in mould
  - ✓ Depending on the type of SHM system embedded in the blade, these sensor can be used as well for monitoring certain parameters (to be benchmarked initially with mould sensors)

7.4.2. Propeller monitoring system

- Monitoring strategy :
  - ✓ Design and testing phase of propeller provides allowable strain envelope under prescribed operating conditions
  - ✓ Strain sensors are integrated at vital locations where highest load / failure occurs
  - ✓ Strain measurements are taken at specific intervals (shorter than rotation period as to capture the load profile during rotation) to continuously monitor load on propeller blades
  - ✓ If at any point strain passes allowable value, warning is given to indicate possible damage scenario

- ✓ Potential damage is isolated (based on which sensor reading passes threshold) and maintenance decision is taken

- Apparatus :
    - ✓ Available options for strain monitoring with considerations on what is needed to be developed can be seen in Figure 4 and Table 1.

Table 1 Possible alternative systems for strain measurement

Priority	System	Pros (+)	Cons (-)
1	Rayleigh Back Scatter (RBS) fibre optics	• Fibre optic sensor has small footprint • RBS sensor provides best continuous sensing over entire area covered by sensor	• Low sampling rate (10 – 100 S/s), must consider propeller RPM • DAQ system is large and cannot rotate with shaft/blades • Wireless data transmission is unlikely, need to figure out wired connection route
2	Fibre Bragg Grating (FBG) fibre optics	• Fibre optic sensor has small footprint • Higher sampling rate (> kS/s range) • Wireless data transmission may be possible but system may still be large	• Non continuous measurement, discreet locations only • Wireless system may still be too large to rotate or embed in blade, need to verify • Need to verify wireless transmission through water
3	RFID sensors (AMD Nano)	• Printed RFID sensor has small footprint • Higher sampling rate (> kS/s range) • Wireless data transmission possible, no batteries needed	• Non continuous measurement, discreet locations only • Need to verify wireless transmission through water and carbon fibre
4	Wireless strain gauge system (to be developed)	• Strain gauge has small footprint • Higher sampling rate (> MS/s range) • Wireless data transmission possible • Components widely available	• Non continuous measurement, discreet locations only • Need to verify wireless transmission through water • Need to develop system if want smallest possible footprint (commercial products can be larger than necessary).

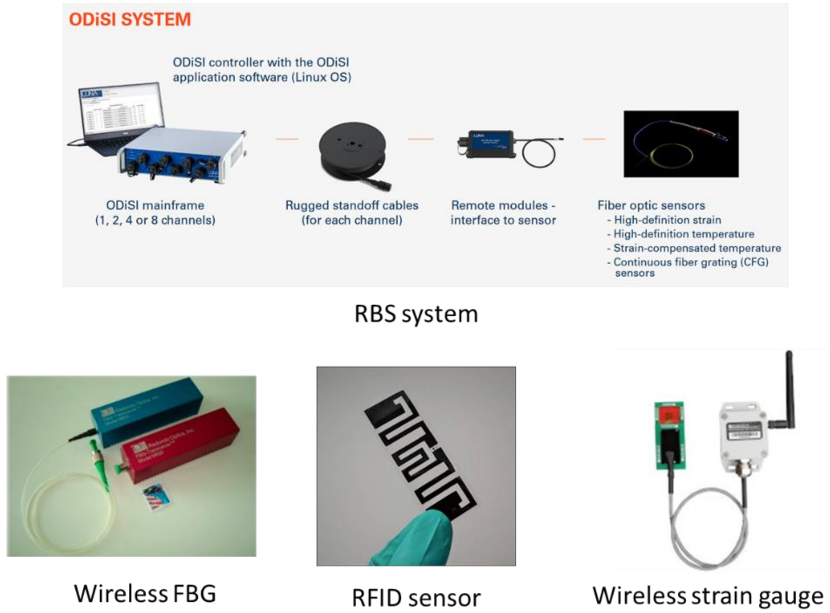

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Figure 4. Alternative sensor options for strain monitoring

8. Road to Commercialisation/Certification

8.1. Background

Propellers are one of the principal propulsion devices in a marine vessel and its robustness and reliability are essential to ensure the safety of the vessel and passengers [6,7]. Composite propellers are a potential alternative to conventional metallic propeller because of their superior properties [23]. Indeed, in addition to the use of composite materials for their lightweight, lack of corrosion, dampening of vibration and noise, their flexibility offers some advantages to improve hydrodynamic efficiency [30]. However, few rules concerning the certification of composite propeller have been issued by Classification Society to validate such equipment and to accelerate their development. Only ClassNK [32], the Japanese Class Society and Bureau Veritas [7], the French counterpart, propose guideline for composite propellers. These documents apply in addition to other rules and standards applicable to the vessel.

8.2. State of the Art Review

8.2.1. ClassNK

ClassNK issued in 2015 a guideline for the manufacturing and the testing/inspection of propeller made in composite materials [32].

The document is composed of 4 chapters:

1. General
2. Application of Composite Material to the Propeller
3. Approval of Manufacturing Process
4. Testing/inspection of the Product

Requirements, for the certification of composite propeller, are mainly based on testing at different scales, see Figure 1.

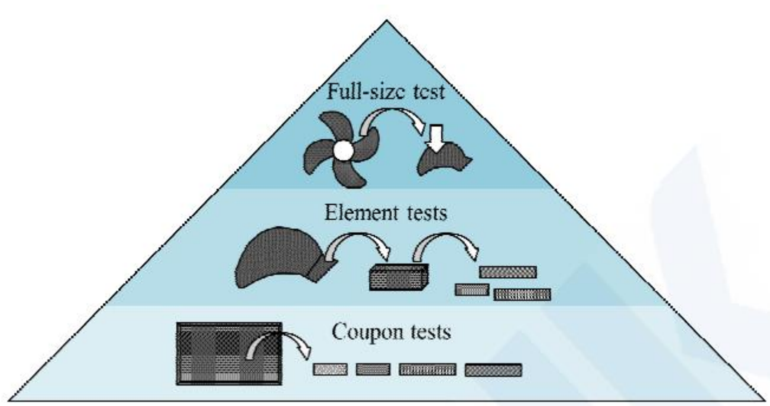

Figure 5 Conceptual diagram of the manufacturing approval test

Coupon tests are used for the characterisation of materials, fibre and resin, will be used for the fabrication of propeller blades. Tensile, bending, interlaminar tests are to be performed as well as fatigue and ageing. Element test samples are obtained by extending the root of the blade during the manufacturing. Same tests than coupons, excepted ageing, are to be carried out. Finally, full-size test is required on a full-size propeller blade loaded at 2 radius positions: 0.25R and 0.6R with a load twice the design load.

8.2.2. Bureau Veritas

Bureau Veritas published a Guidance Note NI663 Propeller in Composite Materials [7] in October 2020. This note is divided in 8 sections and 2 appendix:

- Section 1: General
- Section 2: Certification Scheme
- Section 3: Composite Material Certification
- Section 4: Design Assessment of Propeller
- Section 5: Testing Procedures
- Section 6: Inspection at Works and Surveys
- Appendix 1: Individual Layers for Laminates
- Appendix 2: Laminates Characteristics and Analysis

A large part of the document is dedicated to the design assessment of blade in composite materials based on 2 methods: an analytical method for basic design and a numerical method for final design. The analytical method is simple and approximate (no pressure distribution along the blade) but allows to assess a pre-scantling of the propeller blade on the basis of the propeller performance characteristics. The numerical method is based on hydrodynamic calculations (CFD) and Finite Element Analysis (FEA) and validates the final design of the propeller.

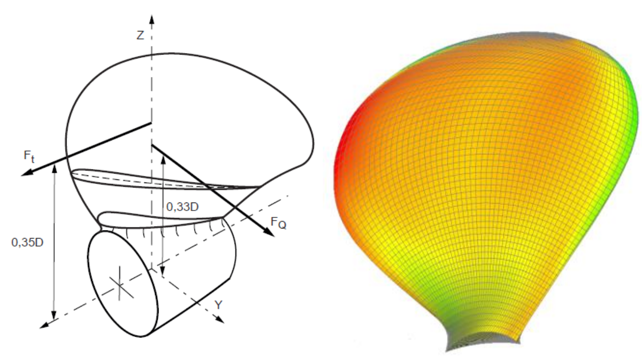

Figure 6 Force application points with analytical method (left) and Pressure distribution with numerical simulations (right)

The certification process, including design phase and production phase, is fully detailed in the guidance note as well as the testing procedures. The testing procedures consist of the completion of following successive stages:

1. Mechanical sample tests of laminate for the characterisation of materials,
2. Prototype tests in static and in fatigue,
3. Full scale blade controls for checking dimensions, weight.
4. Sea trials.

8.3. Desired State and Outcomes

Due to few applications of composite propellers in the shipbuilding industry, the CoPropel project will allow to apply methodologies indicated in BV NI663 [7]. Results will be used for improving and validating methods especially analytical and numerical approaches for the design assessment. Moreover, the manufacturing and testing of large propeller will be valuable for confirming the interest of such propeller as well as updating BV NI663.

8.4. Gap Analysis

To obtain data to validate and improve BV NI663, the guidelines present in the document will be accounted for starting from the design phase. Subsequent tests starting from coupon to full structure will be conducted to validate the parameters used in the design phase to ascertain whether the guidance from BV NI663 does indeed produce satisfactory results.

9. Conclusions

The work in this deliverable has summarized the work conducted in WP1 which was to identify the current state of the art on all the technical aspects related to the subsequent WPs and identify the gaps between the objectives of the project and what is available. The resulting gap analysis will direct the actions conducted in the subsequent WPs.

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11. Annex

11.1. Review of Existing Composite Propellers

Name	Contur® propeller [49]	Lin et. Al. (2009) [16]	Greenprop project [50]	Yamagoti [51]	Nakashima/ ClassNK [30]	Fab-Heli project [27]	COMPROP project [52]
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		