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Review of Composite Propeller Developments and Strategy for Modeling Composite Propellers using PVAST

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PWGSC Contract Number: W7707-088100 Task 10
CSA: Layton Gilroy, 902-426-3100

Defence R&D Canada – Atlantic

Contract Report
DRDC Atlantic CR 2011-156
September 2012

Canada

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Abstract

A number of issues have been identified with the current Nickel Aluminum Bronze (NAB) submarine propellers, including vibration, electric signature, and possibly excess weight. A possible solution to all of these is to fabricate the entire propeller (or a significant portion) out of composite materials, because of the advantages these materials offer, such as corrosion resistance, light weight, tailoring of material properties, low electric signature and acoustic properties. This study represents the first of proposed multi-phase efforts to investigate the development of a Canadian Navy composite propeller technology in order to exploit the potential benefits that composite materials offer. Several successful small composite propeller applications have been developed worldwide. These include a modular composite propeller developed by the Swedish company ProPulse AB; composite propellers made by injection moulding by Pirhana (USA); and Comprop composite propellers developed by Composite Marine Propellers (USA). For larger scale applications, the Contur® composite propellers developed by the German company AIR Fertigung-Technologie GmbH appear to be the most successful composite propeller development and consist of carbon fibre-based composite blades fitted on metallic hubs. Several navies, including those of the UK, USA, Dutch, and Germany have undertaken composite propeller technology demonstration projects involving the design, analysis and manufacturing of composite propellers for surface ships and submarines. Based on the successful applications of composite propellers for small craft, naval surface ships and submarines presented above, it is concluded that the Canadian Navy will benefit from the development of a composite propeller technology.

Résumé

Les hélices actuelles de sous-marins faites de bronze d'aluminium-nickel (NAB) présentent de nombreux problèmes; elles génèrent, notamment, des vibrations, une signature électrique, et peuvent être plus lourdes que d'autres types d'hélices. Pour remédier à ces problèmes, on pourrait fabriquer une hélice entière (ou une partie significative de celle-ci) avec des matériaux composites, car ceux-ci offrent des avantages. En effet, ces matériaux sont résistants à la corrosion, légers, personnalisables, et possèdent des caractéristiques acoustiques tout en ayant une faible signature électrique. La présente étude constitue la première étape d'un projet à phases multiples de la marine canadienne qui permet d'enquêter sur l'élaboration d'une technologie qui utilise et maximise les matériaux composites lors de la fabrication d'hélices. Plusieurs petites applications d'hélices en matériaux composites gagnantes ont été développées dans le monde, comme l'hélice modulaire en matériaux composites conçue par l'entreprise suédoise Pulse AB, l'hélice en matériaux composites fabriquée par moulage par injection de Pirhana (États-Unis) et l'hélice en matériaux composites Comprop de Composite Marine Propellers (États-Unis). Pour les applications à grande échelle, l'hélice en matériaux composites Contur® créée par l'entreprise allemande AIR Fertigung-Technologie GmbH semble être la plus populaire; elle est faite de pales en fibres de carbone installées sur des moyeux en métal. Plusieurs marines, y compris celle du Royaume-Uni, des États-Unis, des Pays-Bas et de l'Allemagne, ont des projets qui démontrent leur technologie, soit la conception, l'analyse et la fabrication d'hélices en matériaux composites destinées à des navires de surface et à des sous-marins. En se fondant sur le succès de l'utilisation d'hélices en matériaux composites pour les petits navires, les navires de surface et les sous-marins mentionné ci-dessus, il a été conclu que la marine canadienne bénéficierait de l'élaboration d'une technologie d'hélices en matériaux composites.

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Executive summary

Review of Composite Propeller Developments and Strategy for Modeling Composite Propellers using PVAST

T.S. Koko; K.O. Shahin; U.O. Akpan; M.E. Norwood; DRDC Atlantic CR 2011-156; Defence R&D Canada – Atlantic; September 2012.

Introduction or background: A number of issues have been identified with the current Nickel Aluminum Bronze (NAB) submarine propellers, including vibration, electric signature, and possibly excess weight. A possible solution to all of these is to fabricate the entire propeller (or a significant portion) out of composite materials, because of the advantages these materials offer, such as corrosion resistance, light weight, tailoring of material properties, low electric signature and acoustic properties. This study represents the first of proposed multi-phase efforts to investigate the development of a Canadian Navy composite propeller technology in order to exploit the potential benefits that composite materials offer. The objectives of the present study include (a) reviewing worldwide developments of composite propellers; and (b) developing a strategy for modeling composite propeller blades in the PVAST/Trident FEA software.

Results: Several successful small composite propeller applications have been developed worldwide. These composite propellers are said to be stronger, lighter, and have superior chemical and corrosion resistance than traditional aluminum propellers. These include (a) the modular composite propeller developed by the Swedish company ProPulse AB; (b) composite propellers made by injection moulding by Pirhana (USA); and (c) Comprop composite propellers developed by the US company Composite Marine Propellers. For larger scale applications, the Contur® composite propellers developed by the German company AIR Fertigung-Technologie GmbH appear to be the most successful composite propeller development. These are carbon fibre based composite blades fitted on metallic hubs. Several navies, including those of the UK, USA, Dutch, and Germany have undertaken composite propeller technology demonstration projects involving the design, analysis and manufacturing of composite propellers for surface ships and submarines.

Significance: Based on the successful applications of composite propellers for small craft, naval surface ships and submarines presented above, it is concluded that the Canadian Navy will benefit from the development of a composite propeller technology.

Future plans: The next step should involve the conceptual design of a composite propeller to meet or exceed Canadian Navy requirements. The PVAST/ Trident FEA system can be used to facilitate the design analysis process. With small enhancements to its composite modeling capabilities, the PVAST/Trident FEA system can be used to automatically generate composite propeller models, which would allow several design iterations to be assessed. It is also recommended that DRDC seek collaboration with other navies, such as the German, UK, Royal Dutch and US navies. This will provide avenues for lessons learned and reduce development costs to the Canadian Navy.

Sommaire

Review of Composite Propeller Developments and Strategy for Modeling Composite Propellers using PVAST

T.S. Koko; K.O. Shahin; U.O. Akpan; M.E. Norwood; DRDC Atlantic CR 2011-156; R & D pour la défense Canada – Atlantique; septembre 2012.

Introduction : Les hélices actuelles de sous-marins faites de bronze d'aluminium-nickel (NAB) présentent de nombreux problèmes; elles génèrent, notamment, des vibrations, une signature électrique, et peuvent être plus lourdes que d'autres types d'hélices. Pour remédier à ces problèmes, on pourrait fabriquer une hélice entière (ou une partie significative de celle-ci) avec des matériaux composites, car ceux-ci offrent des avantages. En effet, ces matériaux sont résistants à la corrosion, légers, personnalisables, et possèdent des caractéristiques acoustiques tout en ayant une faible signature électrique. La présente étude constitue la première étape d'un projet à phases multiples de la marine canadienne qui permet d'enquêter sur l'élaboration d'une technologie qui utilise et maximise les matériaux composites lors de la fabrication d'hélices. Les objectifs de la présente étude comprennent : a) la révision à l'échelle mondiale des développements relatifs aux hélices en matériaux composites, et b) l'élaboration d'une stratégie de modélisation de pales d'hélices en matériaux composites à l'aide du logiciel PVAST/Trident FEA.

Résultats : Plusieurs petites applications d'hélices en matériaux composites gagnantes ont été développées dans le monde. Ces hélices sont dites plus résistantes, plus légères et plus résistantes à la corrosion que les hélices classiques faites en aluminium. Il s'agit : a) de l'hélice modulaire en matériaux composites développée par l'entreprise suédoise ProPulse AB; b) des hélices en matériaux composites fabriquées par moulage par injection de l'entreprise américaine Pirhana; et c) de l'hélice en matériaux composites Comprop créée par l'entreprise américaine Composite Marine Propellers. Pour les applications à grande échelle, l'hélice en matériaux composites Contur® créée par l'entreprise allemande AIR Fertigung-Technologie GmbH semble être la plus populaire; elle est faite de pales en fibres de carbone installées sur des moyeux en métal. Plusieurs marines, y compris celle du Royaume-Uni, des États-Unis, des Pays-Bas et de l'Allemagne, ont des projets qui démontrent leur technologie, soit la conception, l'analyse et la fabrication d'hélices en matériaux composites destinées à des navires de surface et à des sous-marins.

Portée : En se fondant sur le succès de l'utilisation d'hélices en matériaux composites pour les petits navires, les navires de surface et les sous-marins mentionné ci-dessus, il a été conclu que la marine canadienne bénéficierait de l'élaboration d'une technologie d'hélices en matériaux composites.

Recherches futures : La prochaine étape devrait comprendre le schéma théorique d'une hélice en matériaux composites qui respecterait ou dépasserait les exigences de la marine canadienne. Le logiciel PVAST/ Trident FEA pourrait servir à faciliter le processus d'analyse conceptuelle. En effet, il peut, en modifiant quelque peu ses capacités de modélisation de matériaux composites, servir à générer automatiquement des modèles d'hélices en matériaux composites, ce qui permettrait d'évaluer plusieurs modifications de conception. On recommande aussi que RDDC tente d'obtenir la collaboration d'autres marines, comme celle de l'Allemagne, du Royaume-Uni, des Pays-Bas et des États-Unis, ce qui offrirait des sources potentielles de leçons apprises et permettrait de réduire les coûts de développement pour la marine canadienne.

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Acknowledgements

The authors would like to extend their appreciation to Layton Gilroy and Dave Noble of DRDC Atlantic for their comments and contributions to the development of this report.

1 Introduction

1.1 Background

There are a number of issues with current Nickel Aluminum Bronze (NAB) submarine propellers including vibration, electric signature, and possibly excess weight. A possible solution to all of these is to fabricate the entire propeller (or a significant portion) out of composite materials such as carbon fibre. There are no known current large naval vessels operating with composite propellers, although some testing has been performed, including the UK trimaran Triton and an RNlN mine hunter, typically using some combination of composite propeller blades on a NAB hub.

It is possible that a composite propeller could address the three problems outlined above. It is possible to optimize the damping of such a propeller to minimize vibration (and other structural issues) and there may be advantages for cavitation performance with designed blade flexibility. The most significant component of the electric signature of a naval vessel is a result of the corrosion circuit induced between the bronze propeller and the rest of the steel ship. This could be significantly reduced or possibly eliminated by the use of a composite propeller resulting in a significant reduction in vulnerability and, possibly, a significant reduction in the need for corrosion protection. Finally, a composite structure is often much lighter than its metal counterpart. A lighter propeller would result in a potential improvement in draft or loading capacity while reducing bearing loads. Lighter materials also would allow for thicker blade sections which may end up improving cavitation performance.

1.2 Objectives and Scope

The overall goal of the study is to investigate the development of a Canadian DND composite propeller technology in order to exploit the potential benefits that composite materials offer. It is planned to undertake the development in a multi-phase approach. This document provides a report of the work undertaken in the first phase of the project. The study and is aimed at (a) reviewing worldwide developments of composite propellers; and (b) developing a strategy for modeling composite propeller blades in the PVAST/Trident FEA software.

1.3 Organization of this Document

The remainder of this document is organized as follows:

- Chapter 2 provides the review of worldwide composite propeller developments.
- Chapter 3 discusses the strategy for the use of PVAST/Trident system for modeling and analysis of composite propellers.
- Chapter 4 provides a summary of the work, conclusions reached and recommendations for future work.

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2 Review of Composite Propeller Developments

2.1 Overview of Marine Propellers

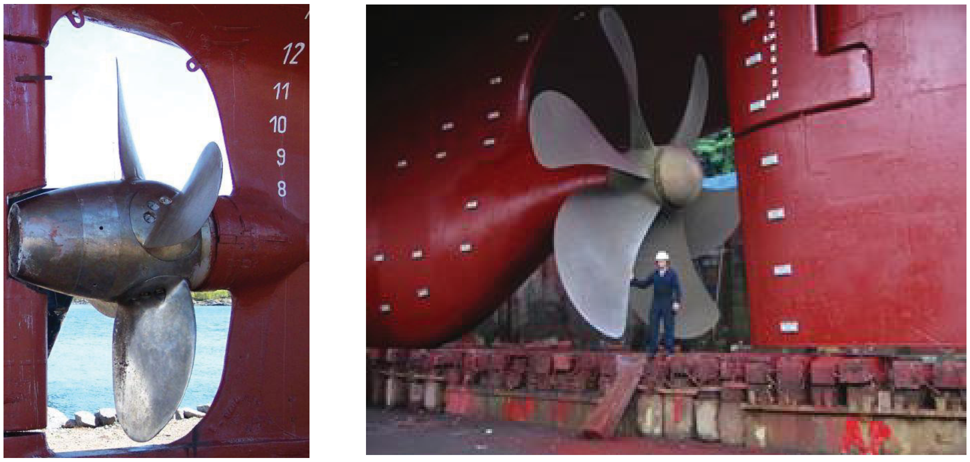
2.1.1 Propeller Types

A marine propeller is a complex three-dimensional structure, the shape and material properties of which must be described adequately for manufacture, determination of the strength, and for both acoustic and hydrodynamic performance. Two types of propeller are generally in use for marine applications. These are the controllable pitch propeller (CPP), also known as a variable pitch propeller (VPP), shown in Figure 1(a) and the fixed pitch propeller (FPP), shown in Figure 1 1(b). The CPP can rotate each blade around its spindle axis. The blade sits on a blade palm that has a circular base centered on the spindle axis. The palm forms a portion of the hub. The blade is bolted to the hub via bolt holes in the palm as shown in Figure 1(a). On the other hand, the FPP has blades that are cast integrally to the hub or bolted to the hub (Figure 1(b)).

The CPP for marine propulsion systems has been designed to give the highest propulsive efficiency for any load condition. When the vessel is fully loaded with cargo the propulsion required at a given ship speed is much higher than when the vessel is empty. By adjusting the blade pitch, the optimum efficiency can be obtained and fuel can be saved. The CPP also improves manoeuvrability of a vessel. The increased manoeuvrability can eliminate the need for docking tugs while berthing.

Ships that are not suitable for a CPP are large vessels that make long trips at a constant service speed, for example crude oil tankers or the largest container ships which have so much power that a CPP is not yet designed for them. A CPP can mostly be found on harbour or ocean-going tugs, dredgers, cruise ships, ferries and cargo vessels that sail to ports with limited or no tug assistance. Currently the range of CPP offers a maximum output of 44000 kW (60,000 hp).

An FPP can be more efficient than a CPP; however, it can only be so at the designed load condition. At that load, it is able to absorb all the power that the engine can produce. At any other vessel loading, the FPP cannot, either being over pitched or under pitched. A correctly-sized controllable pitch propeller can be efficient for a wide range of rotational speeds, since pitch can be adjusted to absorb all the power that the engine is capable of producing at nearly any rotational speed. The Canadian Navy’s submarine propellers are of the FPP type while the frigates are CPP.



(a) Controllable Pitch Propeller (b) Fixed Pitch Propeller

Figure 1: Types of Propellers.

2.1.2 Materials of Construction

The fundamental properties of materials for propeller application include strength, stiffness, weight, fatigue, durability, impact/erosion resistance, and workability into complex geometric shapes. In addition for military applications, stealth performance (low acoustic and electromagnetic signatures) is also required. Most marine propellers are commonly made from metal alloys. These materials have different advantages and disadvantages with regards to the above listed characteristics. Common metallic propeller construction materials are aluminum, stainless steel, bronze, and nickel aluminum bronze (Nibral or NAB). Some of the characteristics of these metals are summarized in Table 1.

Table 1: Characteristics/Features of Metallic Propeller Materials.

MATERIAL	**CHARACTERISTICS/FEATURES**
Aluminum	• Has a tensile strength of up to 276 MPa • Light (has density of 2700 kg/m^3) • Popular material for outboards and stern drive recreational boat propellers • Is inexpensive and easily repaired
Stainless steel	• Has a tensile strength of up to 552 MPa • Heavy (has density of 7800 kg/ m^3) • Strongest and most durable material used for outboard and stern drive propellers • Repair costs are approximately double the cost of the same propeller

	made of aluminum
Manganese bronze	• Has a tensile strength of up to 449 MPa • Heavy (density of 8300 kg/m^3) • Used on inboard drive boats of up to moderate horsepower • Reasonably priced and repairable
NAB	• Has a tensile strength of up to 656 MPa • Heavy (density of 7600 kg/m^3) • Very durable • Typically used on high performance applications such as naval vessels • Repairable • Initial cost is higher than manganese bronze

The main advantage of metals is that there is significant experience in their use for marine propeller applications. They are generally strong, durable and impact resistant. On the other hand they are usually heavy and susceptible to cavitation damage (see Figure 2). Furthermore, metals have high acoustic and electromagnetic signatures which could limit their use for military applications.

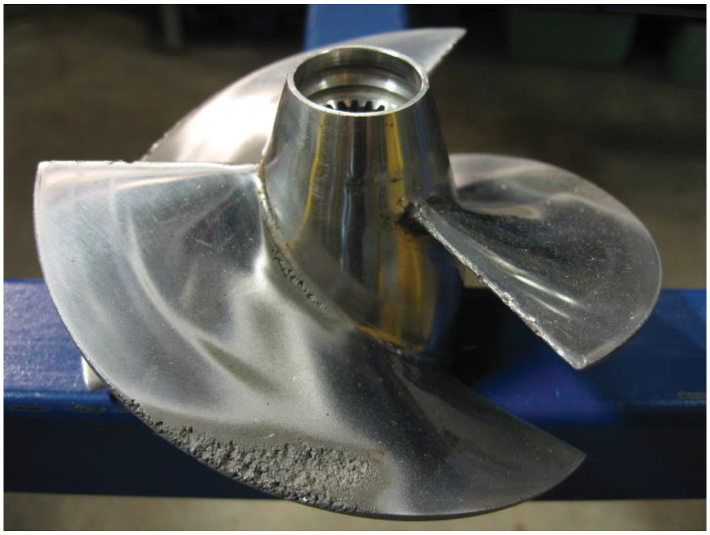


Figure 2: Illustration of Cavitation Damage in Metallic Propeller.

In order to overcome the disadvantages of metallic propellers, composite materials are now being investigated for use as a propeller material. These are mostly materials made of very high strength ceramic fibres bound together by a polymer resin which gives the material shape and volume and provides the toughness and impact strength. The composite materials can be tailored to achieve specific physical, mechanical, or acoustic properties.

The properties of FRP composites have been discussed extensively in the literature (e.g. Greene 1997, Smith 1990, Jones 1975). Table 2 shows properties of typical fibre, resin, laminate and core materials used in marine structures. Properties of conventional materials such as steel, aluminum and wood are also shown for comparison.

Table 2: Properties of Selected Composite Materials (Adapted from Greene 1997).

Material	**Tensile Modulus (GPa)**	**Tensile Strength (MPa)**	**Density (kg/m^3)**
E-Glass (24 oz WR) Fibres	72.45	3450	2600
S-Glass	86.94	4589	2490
Carbon Fibres	227-393	2415-4830	1760
Polyester resin	4.07	48.3	1230
Epoxy Resin	3.66	48-76	1200
Balsa Core	2.55	9.11	110
PVC foam Core	0.06	1.38	80-100
Glass/Polyester laminate (hand layup)	9.66	138	1540
Carbon/Epoxy Laminate (filament wound)	60	607	1550
Glass/Polyester Balsa sandwich (vacuum assisted)	2.76	41	380
Glass/Vinyl Ester PVC sandwich (SCRIMP)	2.76	41	290
Steel (ABS Grade A, ASTM 131)	204	400	7860
Aluminum (6061-T6)	69	310	2710

In addition to the strength and elastic properties, there are several other properties and characteristics of composites which distinguish them from metals and must be considered in their use. The important properties to be considered depend on the type of application. Smith (1990) has provided a detailed discussion on the properties/characteristics of composites which need to be considered when assessing the suitability of composites for application in the marine environment. Some of these are listed below:

- Stiffness properties (tensile, compressive, in-plane shear, interlaminar shear, etc.);
- Strength properties (tensile, compressive, in-plane shear, interlaminar shear, etc.);
- Low and high temperature characteristics;
- Chemical resistance;
- Fire resistance;
- Fatigue life;
- Water absorption characteristics/weathering;
- Electromagnetic characteristics;
- Impact resistance;
- Ballistic resistance;
- Creep resistance; and
- Acoustic/damping properties.

2.2 Overview of Composite Propeller Developments

Marsh (2004) has provided an overview of developments of composite propellers for small and large vessels up to 2004 in an article presented in the Reinforced Plastics journal. According to Marsh (2004), a number of companies have shown the viability of composite propellers, although, so far, mainly those for small craft. The following are significant successful applications of composite propellers for small craft developed in various countries.

2.2.1 ProPulse Composite Propeller (Sweden)

Marsh discusses the modular composite propeller developed by the Swedish company ProPulse AB. The ProPulse® modular propeller comprises a metal hub with replaceable composite blades whose pitch can jointly be adjusted (at blade installation) to one of five settings. Suitable for motors of 20-300 hp, the propellers are made from an undisclosed ‘high quality composite’. Tests have shown the blades to be stronger than equivalents in aluminum, the ‘stock’ material used for outboard motor and stern drive props. Despite weighing up to 40% less than their aluminum counterparts, it is stated that the blades are tough and resilient and resist impact, light grounding and damage from cavitation. In case of damage, blades can be removed on the spot and replaced individually. A trolling fisherman could, for example, quickly remove two opposite blades of a damaged four-blade prop, re-adjust the pitch of the remaining two and continue operating with those (see Figure 3).

Figure 3: ProPulse Composite Propeller.

2.2.2 Pirhana Composite Propeller (USA)

The US company Pirhana has also developed composite propellers made by injection moulding of LNG Engineering Plastics' Verton long glass fibre reinforced polyamide thermoplastic. The propellers are reported to be 10-15% stronger than traditional die-cast aluminum, and possess far superior chemical and corrosion resistance. They are also reported to resist abrasion better than metals and suffer less from leading-edge erosion in water made abrasive by suspended grit. They have low hydrodynamic friction and high propulsive efficiency. The composite material used is said to retain its strength even after prolonged immersion in water and the propellers can be replaced individually. The company also introduced a modular composite prop-wrench to facilitate propeller removal. Reported to be 60% stiffer than a conventional metal wrench, the tool has the additional benefit that it is self-buoyant, which can result in fewer lost wrenches when working afloat. The hubs have a core of high strength aluminum over moulded with Verton (see Figure 4), which is provided with a life-type warranty. The Pirhana composite propellers are generally suitable for motors of 120 – 290 hp.

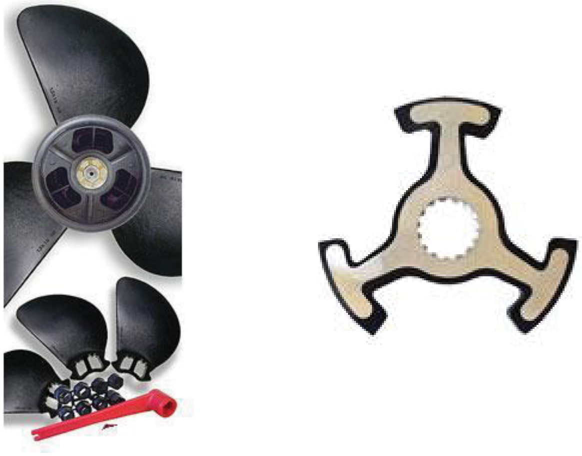


Figure 4: Pirhana Composite Propeller (a) blade assembly kit; (b) Cutaway view of aluminum hub cutaway.

2.2.3 Composite Marine Propellers (USA)

Using proprietary ‘fibre-filled resins’ the US company Composite Marine Propellers has developed its Comprop composite propellers that are single-piece four-blade props, up to 55 cm in diameter, which are offered as original equipment on Regal, Wellcraft, Glastron and Corona boats, as well as being recommended for spares or replacements on a variety of craft powered by engines up to 225 hp. The Comprop are said to be approximately 40% lighter and more affordable than an equivalent aluminum prop. The blades are designed to flex slightly or break off should they hit an obstruction, so that drive shafts and bearings remain undamaged. Outboard Marine Corp (OMC), one of the world’s leading outboard producers and owner of the Evinrude and Johnson brands, now offers composite propellers alongside the aluminum and top-of-the range stainless steel props that have been standard for years. Mercury Outboards offers a line of composite propellers as spares.

Figure 5: Comprop Composite Propeller.

In spite of the above successful small unit composite propeller applications, scaling up these small units to larger propeller sizes suitable for ships remains a challenge. Reinforced plastic composite tend to be less stiff than metals and early blades made from them were known to lose propulsive efficiency by flexing. Nevertheless, efforts to overcome the difficulties have continued because of the potential advantages such as reduced weight and increased durability. The following are some developments in this regards.

2.2.4 AIR. Fertigung-Technologie GmbH's Contur Advanced Composite Propellers (Germany)

The German company AIR Fertigung-Technologie GmbH has teamed up with the University of Rostock to develop a carbon fibre-based composite propeller called Contur® that is intended for super yachts and ships (see Figure 6). According to Marsh (2004) hundreds of ship sets of Contur advanced composite propellers have been sold, ranging in diameter from 50 cm to 5 m. AIR states that its propellers weigh only a third as much as conventional NAB equivalents. Composite blades can be thinner at the tips than metal, reducing propeller noise typically by 5 dB.

Figure 6: Contur Marine Composite Propeller.

AIR and Rostock University has also developed a "smart" Contur propeller that positively exploits the flexible qualities of composites. These are comprised of carbon, aramid and drawn polyethylene fibres that are distributed within the composite in such a way as to provide hydroelasticity. This enables the blades to react to changing load conditions by altering their pitch, so maintaining optimum propulsive efficiency across a range of throttle settings. As a result, fuel consumption can be reduced by up to 15%. In addition, adaptive self-pitching propellers reach rated rpm faster than conventional props, so that the vessel has better acceleration. Cavitation is reduced because, as the blade adapts itself to different loads, the load over a given blade area tends to stay within the limits at which implosion of cavities against the blade is induced.

Blades are manufactured in closed moulds by a resin transfer moulding (RTM)-like process, to close tolerances so that their hydroelastic and other properties are matched. Contur propellers reduce the cost of propeller maintenance by having separate exchangeable blades, each blade possessing a thickened root that slots into a metallic hub. In a speed trial, the vessel with Contur propellers proved only 0.2 kts slower than when she was new with her metal propellers.

UK importer and distributor Fleetwater Marine reports growing interest in Contur composite propellers from professional charter/leisure craft and workboat operators. Before ordering these, tests of the composite propellers at sea against the normal bronze propellers were conducted. Results showed fuel reductions of almost 10% at full throttle and 17.5% at mid range. Acceleration was enhanced and noise in the wheelhouse was cut by up to 4%. When several sizeable underwater objects were struck unexpectedly, the composite blades continued to operate smoothly without damage whereas, in the opinion of the on-board crew, metal blades would probably have bent and started to vibrate.

The Contur blade tips are reported to be especially resistant to below-water impacts because they are fortified with drawn polyethylene fibres. It is said that the blades flatten out with load so that optimum pitch is maintained the whole time. This contrasts with the fixed pitch of conventional bronze blades which is normally set to absorb the full engine power at maximum throttle setting. This means that at the normal cruise settings at which vessels spend most of their time, they are operating away from peak efficiency. The largest prop Fleetwater has supplied to date is a 3m diameter unit fitted to a minesweeper. The possibility of fitting Contur props to fast patrol boats was being considered by Fleetwater.

2.2.5 European Community-Sponsored Composite Marine Propeller (COMARPROP) Project

In the late 1990s, the European Community-sponsored Composite Marine Propeller (Comarprop) project brought researchers from four countries together in an effort to define design and manufacturing technologies, confirm the propellers' commercial benefits and establish a basis for their acceptance by classification societies. Investigations ranged from composite materials evaluation to producing full-scale props by resin transfer moulding and trials at sea. Work on design methodologies involved finite element modelling and trying to adapt the hydrodynamic design process to allow for the non-isotropic properties of composites. Another focus was how best to incorporate hydroelasticity so as to secure adaptive blade pitching. Project collaborators included:

- The Norwegian Marine Technology Research Institute (Marintek);
- Dowty Aerospace Propellers and DERA (now QinetiQ), Haslar in the UK;
- The National Technical University of Athens; and
- The Registro Italiano Navale, shipbuilder Fincantieri, CETENA SpA and the Consorzio Armatori per la Ricerca Srl from Italy

The US Navy, intrigued by the adaptive blade pitching and other possibilities offered by the AIR Fertigung-Technologie composite propellers, initiated a three-year evaluation programme. The work was being funded by the US Department of Defense Comparative Testing Office.

Researchers at the Propulsion and Fluid Systems Division, West Bethesda, have evaluated blades designed by the division and built by the German company in a water tunnel, in a large cavitation channel and in extensive towing tanks at Carderock. Engineers used data from fibre optic strain gauges embedded in the blade laminates to validate prediction codes and estimate propeller service life. It is reported that large blades, including those for an 8m diameter propeller, were planned to be built and fatigue tested at the University of Rostock and the United States Naval Academy (Marsh, 2004).

2.2.6 QinetiQ Composite Propeller (UK)

In the UK, QinetiQ, in collaboration with Dowty Propellers and Wartsila Propulsion in the Netherlands, designed, built and carried out sea trials on a 2.9 m diameter, five-blade composite propeller assembled on a bronze hub (see Figure 7). The blades were designed and built to warship standards, using a hybrid glass/carbon composite construction. The propeller was fitted to QinetiQ's trimaran warship demonstrator, the RV Triton, in place of the latter's normal fixed-pitch bronze unit.

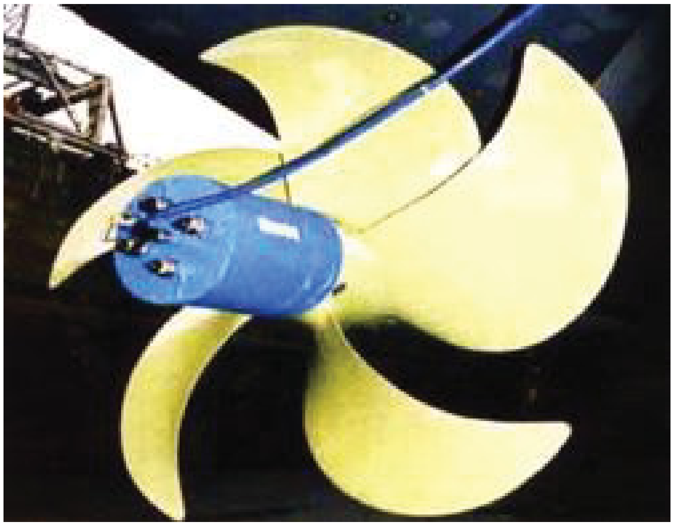


Figure 7: The 2.9 m diameter composite propeller on the RV Triton triple hull warship.

The QinetiQ design resulted in thicker blades that offer the potential for improved cavitation performance, while reducing vibration and underwater signatures. However, the propeller design provided weight savings of about 20% compared with normal bronze blades. It is reported that the weight savings could be as high as 30-40% if the hub was also made of composite. Marsh (2004) also reports that the QinetiQ composite propeller was also designed to eliminate certain problems, such as blade separation, that were encountered in earlier composites propeller developments. The propeller was approved by DNV.

The sea trials provided valuable load data that can now be used in refining hydrodynamic and structural design models. Knowledge was also gained about the acoustic performance of a rotating composite structure and its impact on the galvanic environment at the aft end of a vessel. The extensive development trials also included durability testing in the marine environment and water uptake and fouling tests. The effects of cavitation, impact and environmental fatigue were also studied. Overall the tests were regarded as successful, the propeller demonstrating a smooth take up of power and reduced vibration.

2.2.7 US Naval Academy Yard Patrol Craft Composite Propeller (USA)

Wozniak (2005) discusses the analysis, fabrication and testing of a composite bladed propeller for the US Naval Academy Yard Patrol (YP) craft, which is part of the Trident project. The objectives of the research were to: evaluate a hub design; perform a structural design of a YP craft composite bladed propeller; and finally, build and test a full-scale propeller using the composite materials. As the general concept used composite blades attached to a NAB hub, the first step was to develop a design for the hub-blade interaction. Afterwards, the loads were predicted using computational fluid dynamics. The pressure plot was then combined with the geometry in a finite element structural analysis program to determine fibre orientation and strength characteristics. A full-scale mould plug was created using stereo lithography. Finally, the carbon/epoxy blades were laid up in this mould. The YP craft was selected as the test platform because it: (a) has two propellers (in the event of failure); and (b) is used for many hours, often in harsh conditions. Figure 8 shows the 3-bladed composite propeller fitted on the YP craft, a model of the blade and hub, and the carbon fibre composites during the fabrication process.

Highlights of the composite propeller development are provided below:

<u>Blade Design</u>

- “Dovetail” (German) and “nub-blade” (British) designs were considered and the dovetail design was selected for more blade continuity
- The blade design was based heavily on the existing metallic propeller
- In the blade analysis, the elements were converted to five layer laminates with 80% 0-90 degree weaves; and 20% +/- 45 degree weaves
- The dovetail was constrained as an elastic foundation
- Blade stress analysis showed that the limiting stress was the through thickness stress of the epoxy

<u>Hub Design</u>

- The hub material was NAB, with the taper and key designed to the original propeller specifications.
- Stress analysis of the hub showed the worst case scenario was shear, but the ability of the hub to withstand the applied load was demonstrated.

<u>Fabrication</u>

- Blade was fabricated in two halves, using a fibre glass mould
- The carbon fibre layers were cut with a quilting wheel and templated to the mould.
- The fibres were laminated with ProSet 125 epoxy mould

- Each blade half was built up with a maximum of approximately 105 plies
- Edges and surfaces were ground smooth for minimal gap
- A thickened Cabosil/epoxy mixture was used to join the two halves
- The hub was manufactured using a rapid prototyping machine at the Naval Surface Warfare Center, Carderock Division (NSWCCD)

Figure 8: Composite Propeller Fitted on US Naval Academy Yard Patrol Craft.

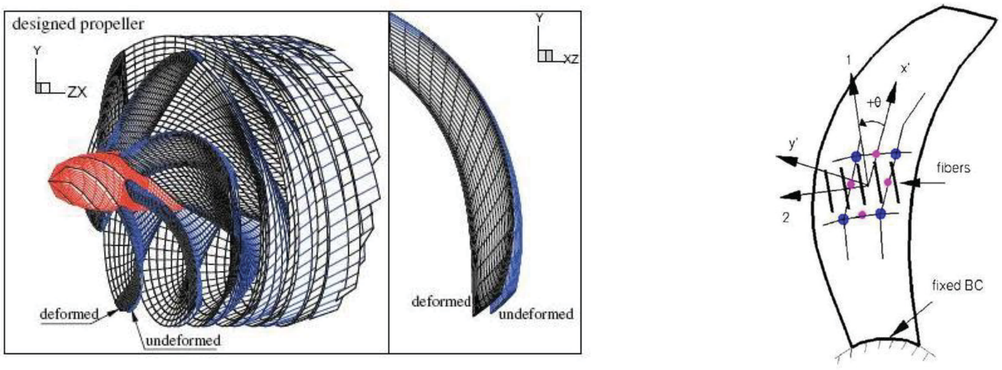
2.2.8 Other US Naval Composite Propeller Developments (USA)

It has also been reported that the US navy has installed several Contur propellers on their vessels (Contur Vendor website, 2010). Details of such studies were not available to this study. However, a number of US navy sponsored projects related to composite propeller development have been reported in the open literature. Some of these are summarized below.

Princeton University Studies

Motley et al (2009), Liu and Young (2009) and Young et al (2010) have presented composite propeller development studies that have been funded by the US Navy, involving researchers from Princeton University, NJ, Stanford University, CA, and the University of Michigan at Ann Arbor, MI. The studies involved the design, fabrication and testing of 0.6m diameter scale models of adapting composite marine propellers. The propeller design followed closely the German company AIR Fertigung-Technologie GmbH's Contur propeller design. The thrust of the studies was to utilize fluid-structure interaction effects to improve the performance of composite marine propellers (see Figure 9 (a)). This involved the utilization of the bend-twist coupling properties of anisotropic composites, and the load-dependent self-adaptation behaviour of composites to improve the performance of the composite propellers.

The material used for the propellers was Hexcel IM7-8552 carbon epoxy with an optimal stacking sequence of [30°/30°/90°/90°/30°]. The angles were measured with respect to the local radial direction, being positive in the counter clockwise direction (Figure 9(b)). The results of the studies showed that a properly designed flexible composite propeller can be more efficient, and cavitation inception in wake inflow can be significantly delayed compared to its rigid counterpart. The self-twisting composite propeller was designed (Motley et al, 2009) to passively control the propeller behaviour so that the self-twisting propeller performs the same as its rigid counterpart at design flow conditions; and the self-twisting propeller performs better than its rigid counterpart at off-design flow conditions.



(a) Deformed and un-deformed propeller in design flow conditions

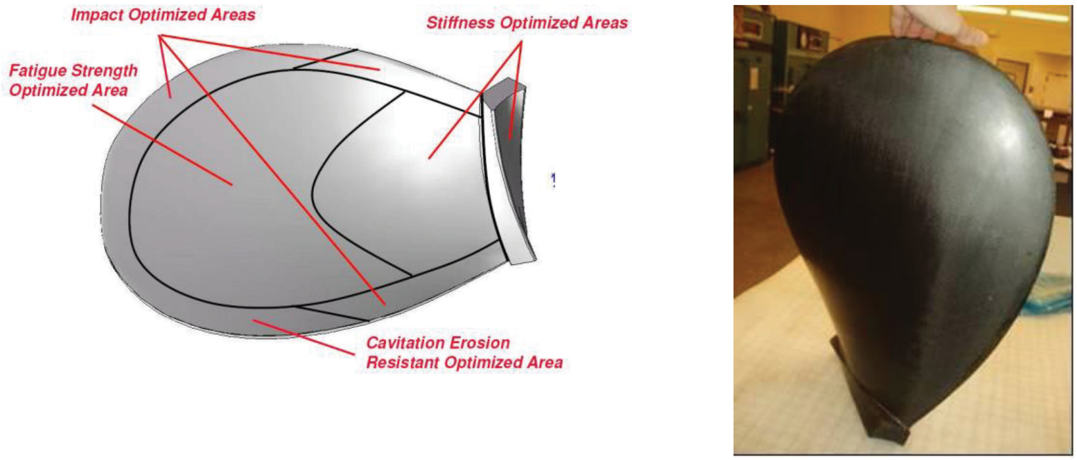
(b) Reference axes for fibre angles

Figure 9: Self-Twisting Composite Propeller (Motley et al, 2009).

Composite Technology Development (CTD) Studies

Composite Technology Development, Inc. (CTD), Lafayette, CO, was sponsored by the US Navy, under the small business innovation research (SBIR) program to develop advanced composite materials having performance that is optimized for the underwater propulsor environment (Hulse, 2007). CTD developed and tested composite materials that possess substantially higher cavitation erosion resistance in comparison to current commercially available materials. This has been done in partnership with the University of Maine (UMaine) and Dynaflow, Inc. to screen candidate materials for cavitation erosion resistance and identify key material parameters most affecting their cavitation erosion resistance. CTD also collaborated with Alion Science and Technology's Engineering Technology Center to identify methods for incorporating highly cavitation erosion resistant composite materials into a propeller blade composite construction to meet the high durability and hydrodynamic performance requirements of US Navy propellers.

Figure 10(a) shows a schematic of CTD composite propeller development, illustrating potential key areas where material selection and composite construction are optimized. In particular, cavitation-erosion resistance would be optimized in the blade's tip and in outer leading and trailing edges. Exposed blunt edges would be optimized for impact, the center section optimized for fatigue performance and the blade's root optimized for high stiffness and shock resistance. CTD claims that approximately an order of magnitude improvement in cavitation erosion resistance was obtained with their developed composite propeller shown in Figure 10(b).



(a) (b)

Figure 10: CTD Composite Propeller Development (Hulse, 2007).

2.2.9 Royal Dutch Navy Composite Propeller (Netherlands)

It has been reported that the Royal Dutch Navy has been investigating composite propellers for their vessels. The vendors of the Contur propellers claim that the Royal Dutch Navy has used the Contur propeller on their vessels, with diameters in the range of approximately 1.5m. Figure 2 11 shows a typical case in which the Contur carbon fibre propeller has been installed on a mine hunter of the Netherlands navy. Details of these developments were not available to this study. Efforts to obtain information directly from the researchers have not been successful at the time of preparation of this report.

Figure 11: Contur Carbon Fibre Propellers Fitted on a Mine Hunter of Netherlands Navy.

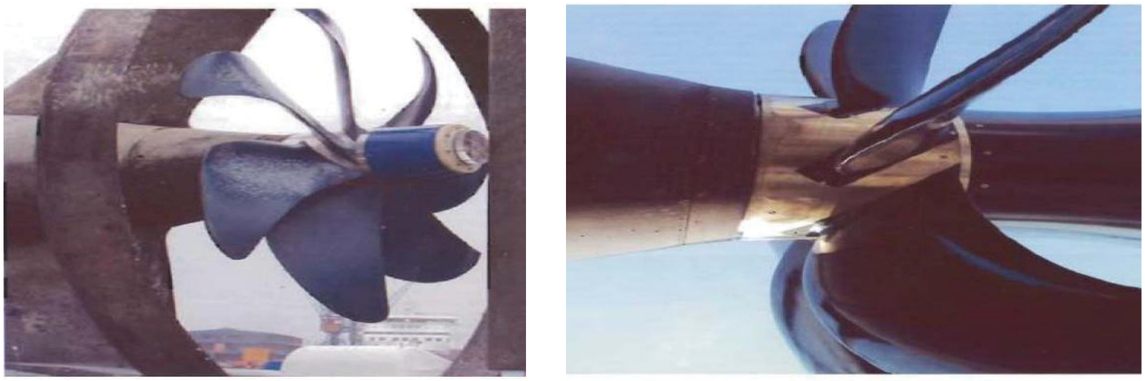
2.2.10 German Navy Submarine Composite Propeller

The Propulsion Committee (2008) of the International Towing Tank Conference (ITTC) discusses the German Navy's composite propeller developments. These include the studies by Büchler and Erdman (2006) on various composite propellers developed by AIR for surface ship applications; and Stauble (2007) on composite propellers for submarine applications (German 206A and 212A submarines).

The study Büchler and Erdman (2006) involved three different kinds of composite propellers; including (a) propellers designed for passively adjusting pitch near the tip, (b) surface-piercing controllable pitch propellers, and (c) the rim-driven, hubless propellers shown in Figure 12. The passive pitch-adapting propellers showed improved low-speed manoeuvring. The hubless propellers eliminated the conventional tip-gap cavitation since the blades are attached to the outer ring. Although there is no hub, the blade tips are concentrated at the centre of the propeller that would potentially cause cavitation. The researchers pointed out that more research is required in the design and materials. One of the major issues with composite propellers is the cavitation erosion tendency that is much worse than metallic propellers, thus requiring proper protective coatings. It was stated that the propellers are coated with polyurethane coating materials, but details of the coating material were not given.

Figure 12: German Navy's Rim-Driven Hubless Composite Propeller (The Propulsion Committee, 2008).

The study by Stauble (2007) involved recent efforts in the German Navy to develop and test full-scale submarine composite propellers. Two 206A-Class submarines were fitted with composite propellers. The first composite propeller was installed in 2002 with the same geometry as a metallic propeller with 100% carbon fibre (see Figure 13(a)). The Propulsion Committee (2008) reported that at the time of their report, the composite propeller had been in operation for over 2 years and approximately 20,000 nautical miles without any damage or malfunction. The study also reported the installation of a highly damped composite propeller using aramid fibre (Kevlar). Acoustic trials "exceeded all expectation." In 2006, a new composite propeller program was initiated to design and install a much larger (3.9 m diameter) composite propeller on a 212A Class submarine (see Figure 13(b)) for a stringent acoustic evaluation. Sea trials indicated significant improvement in acoustic performance.



(a) Composite propeller installed on 206A Class submarines

(b) Composite propeller installed on 212A Class submarines

Figure 13: German Navy's Submarine Composite Propellers.

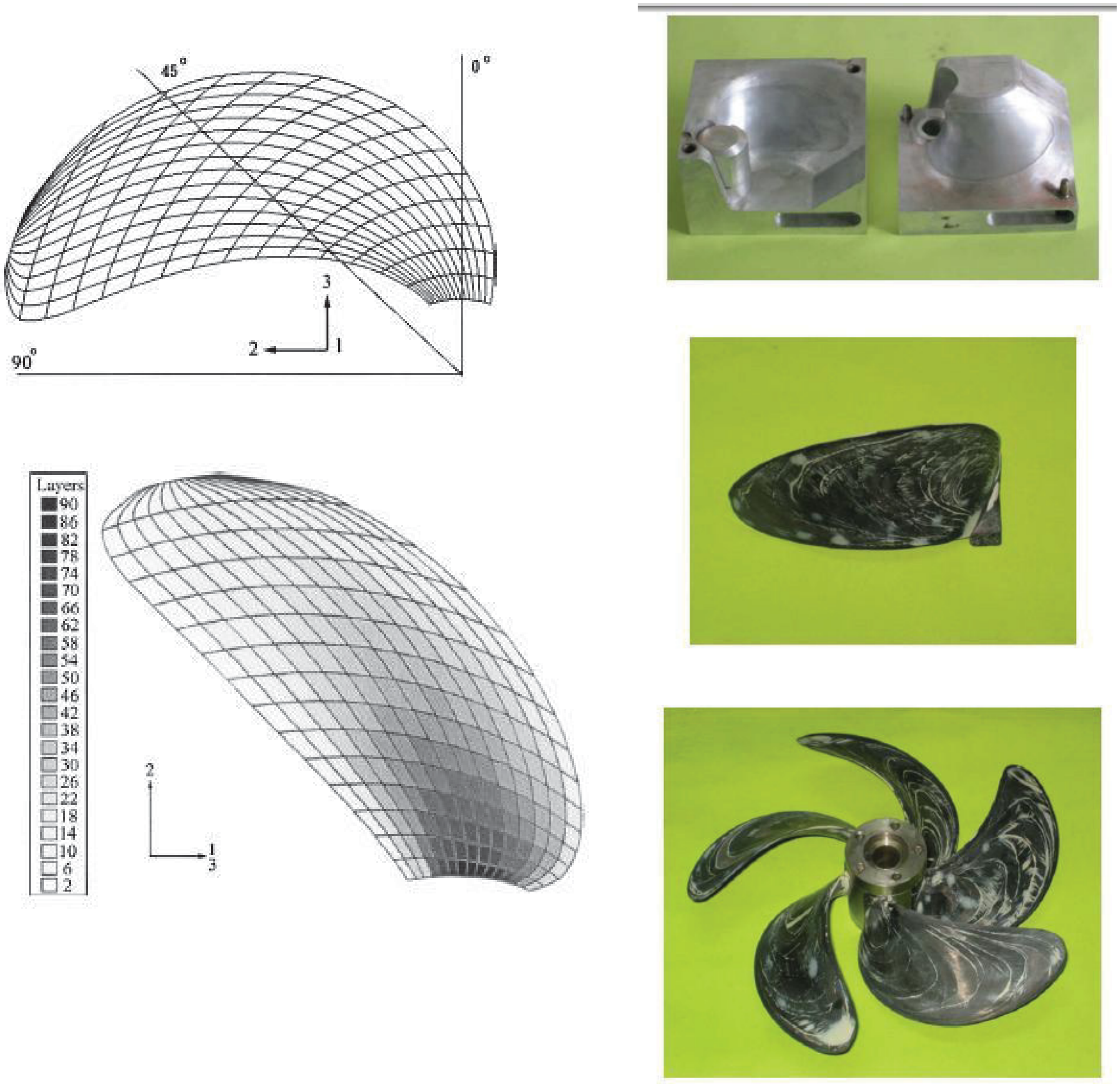
Efforts to obtain further details of these developments have not been successful at the time of preparing this report. However, these developments can be considered as some of the most advanced composite propeller developments, the results and lessons learned of which will be very valuable for the naval and submarine applications contemplated in this multi-phase effort. It would be worthwhile for DRDC to find means of collaborating with the German Navy on composite propeller development.

2.2.11 Taiwanese Composite Propeller Development

Lee and Lin (2004) and Lin et al (2009) have discussed composite propeller developments in Taiwan. Their studies involved analysis, design optimization, manufacturing and testing of changeable pitch composite propellers. As with the Princeton University studies, the bend twist coupling behaviour of composites is used to improve the performance of the composite propellers. The propellers were made of carbon epoxy composite material. Figures illustrating the design/analysis and manufacturing of the composite propeller are presented in Figure 14.

In composite propeller development, two stacking sequences are considered: The first one is a quasi isotropic sequence $[-45_2/90_2/45_2/0_2/-45_2/90_2/45_2/0_2/-45_2/90_2/45_2/0_2]s$; while the second one is an optimum sequence obtained using a genetic algorithm $[45_2/90_2/45_2/45_2/45_2/45_2/0_2/0_2/0_2/0_2/0_2/45_2]s$. Experiments were designed considering two original propellers manufactured by the first and the second stacking sequence, respectively, and a pre-deformed propeller with the second sequence. Experimental results corresponded to the same trend as the calculations and confirm the method of optimization.

The deformation of the composite material was controlled to yield satisfactory performance at various speeds. At first an attempt was made to optimize the propeller by arranging the stacking sequence but not changing the geometry of propeller; however, this was found to be unsatisfactory. A pre-deformed design was then used to improve the propeller. The optimum propeller satisfies the two requirements of optimization, reducing the range over which the torque varies and improving the cooperation between the propeller and the engine.



(a) Ply Angle Definition, and Thickness Distribution

(b) Mould, Composite Blade, and Assembled Composite Propeller

Figure 14: Taiwanese Composite Propellers.

3 Use of PVAST System for Modeling/Analysis of Composite Propellers

3.1 Analysis and Design of Propellers

The cantilever beam method is traditionally used for the design and analysis of propellers. The method relies on being able to represent the radial distribution of the thrust and torque force loading by equivalent loads FT and FQ at the center of action of these distributions (see Figure 15) (Carlton, 2007). The stress at a point of maximum thickness of a reference blade section is then given by the following expression:

$$\sigma = \sigma_T + \sigma_Q + \sigma_{CBM} + \sigma_{CF} \tag{1}$$

where σ_T is the stress component due to thrust action; σ_Q is the stress component due to torque action; σ_{CBM} is the stress component due to centrifugal bending; and σ_{CF} is the stress component due to direct centrifugal force. The maximum tensile stress exerted on a given section of the blade is given by:

$$\sigma = \frac{M}{Z} + \frac{FC}{A} \tag{2}$$

where M is the total bending moment due to the combined effects of hydrodynamic and centrifugal action (contributing to σ_T, σ_Q and σ_{CBM} stresses); Z is the blade section modulus; FC is the centrifugal force exerted by the blade on the section; and A is the blade section area.

With increasing computer power and the popularity, generality and ability of the finite element method (FEM) to model complex problems, the FEM is now generally used for the analysis and design of propellers. To assist propeller designers in developing blade designs based on composite materials, Lin (1991) performed an overview of composite material characteristics and available structural methods. Lin (1991) investigated a simplified stress/deflection calculation approach for a composite blade as well as 3-D FE approach using the ABAQUS FE program. The simplified method was an adaptation of the cantilever beam method. The composite propeller consisted of the following configuration:

1. The tip zone consisted of Type 4 NAB material for sections from $x_R = 0.8$ to the tip, where x_R is the radial fraction of radial position of the blade section.

2. The composite material zone (from the hub to $x_R = 0.8$), which consists of a sandwich composite, with outer thick-shell skin (0/+60/-60 E-Glass) and internal shear-web support made of +45/-45 braided E-Glass fibre-reinforced composites. The core is filled with anisotropic polyurethane foam material. A combined total of approximately 20% of the chord

length is formed of low-modulus materials streamlined for hydrodynamic purposes at the leading and trailing edges (see Figure 16).

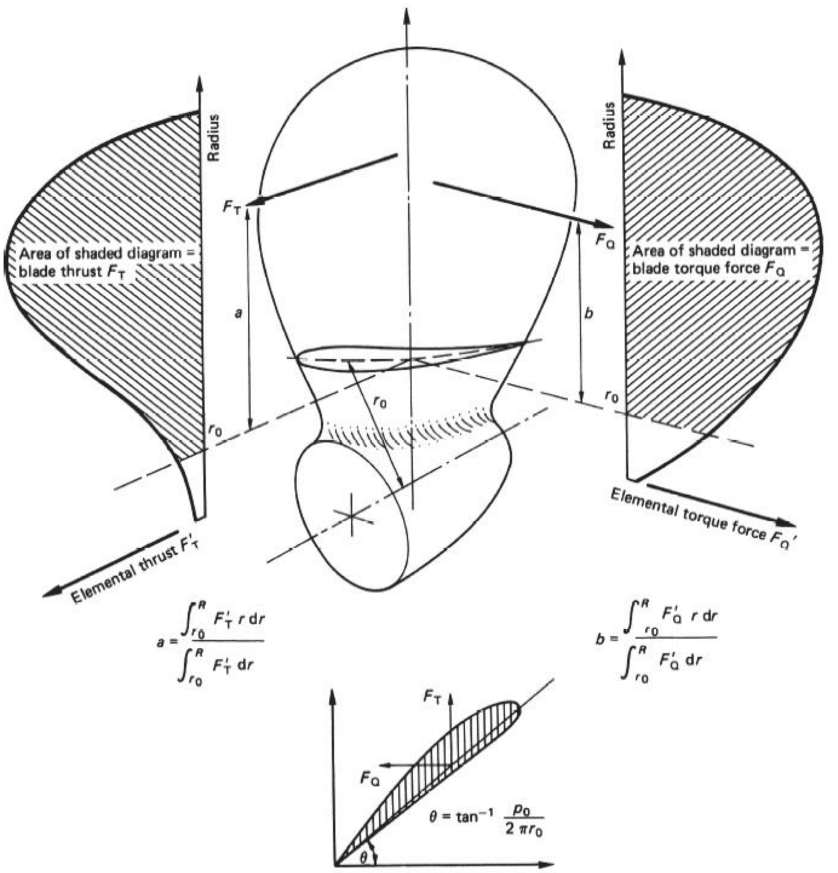


Figure 15: Basis for Cantilever Beam Method for Blasé Stress Analysis (Carlton, 2007).

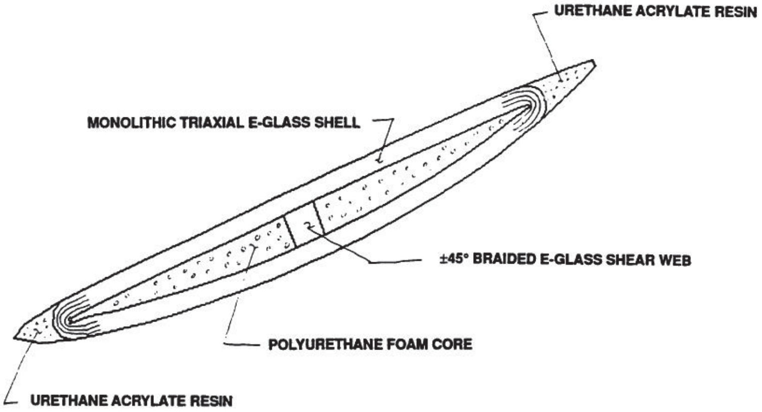


Figure 16: Material Arrangement in Composite Zone (Lin, 1991).

It was shown that compared to the 3-D finite element methodology, the simplified method provided conservative results for solid isotropic blade, whereas it provided un-conservative results for the composite blade, due to the inherent assumptions made in the simplified method for the composite blade. As a result, Lin (1991) suggested that in order to capture the complexities involved in the analysis of the composite propeller, 3-D finite element analysis be used for composite blade design and analysis.

3.2 Overview of PVAST Software

PVAST is a special purpose finite element analysis program for the vibration and strength analysis of marine propellers. Part of the Trident suite, PVAST is designed to automatically generate finite element models for a variety of propeller geometries. It is supported by advanced graphics capabilities for displaying/checking geometric and finite element models as well as displacements, eigenmodes, stresses and strains resulting from finite element analyses. Key features of PVAST include the following:

- Integrated modeller, pre/post-processor and solver
- The PVAST blade geometry definition capability provides a means of converting 2-D data into 3-D coordinates defining the blade geometry. The blade data can be supplied interactively or through predefined external data sets. The geometry is based on blade equations and a choice of blade data formats, such as NACA section thickness and camberline data or individual section coordinates are provided. Graphical verification input data (pitch angle, camber, skew, rake, chord, thickness); individual section plots; and 3-D plots of single or multiple blades can also be performed.
- The PVAST pre-processing capability enables the automatic generation of finite element models of the propeller blade, fillet, palm, and hub structures. The pre-processing features include blade only; blade with fillet; substructured model of blade, fillet, palm with or without bolts; hub model with keyway. A large number of element types, including shell, 3-D brick, tetrahedral, wedge, rod, membrane and gap elements for structural modelling; 3-D fluid, interface or surface panels for fluid modelling are provided.
- Analysis of propeller blade structures is performed using the Trident FEA solver. The analysis capabilities include: static displacements and stresses due to distributed or concentrated loads and/or prescribed displacements; time history response (direct integration or modal super-position); natural frequency analysis in air or in water; and centrifugal stiffening.

PVAST provides a menu driven interactive colour graphics capability for plotting analysis results. The post-processing features include general and propeller specific plots of displacements and stresses and eigenmodes (Martec, 2000).

3.3 Use of PVAST for Modeling Composite Propellers

The modeling of the composite propeller is complicated by the fact that the blade thickness varies continuously with radial and chordwise position. It is therefore difficult to define layup sequences that are universally applicable to a number of elements, as in the case of flat prismatic sections.

In fact, in the most rigorous situation, each element of a composite propeller blade will require its own layup sequence definition in order to define the element thickness. Unfortunately, the finite element mesh configuration is not known *apriori* and besides, it would be extremely tedious to require the analyst to define layup sequences for each element. To this end, the following procedure will be used to model the composite propeller blade configurations.

- Partition the propeller blade geometry into a number of manageable segments
- Define master layup sequences for each of these segments
- Check element position, apply the appropriate layup sequence for the segment to which the element belongs
- Using the layup sequence for the segment and the element thickness, determine the element layup sequence (some trimming of layers/thicknesses may be required).
- Subdivide element into a number of elements in the thickness direction, if required. Adjust refined element layup sequences using the coarse element layup sequence information.

In order to facilitate the above modeling process, it would be prudent to implement suitable modifications to the PVAST/Trident FEA modeling capability to automate as much of the process as possible. The analysis will be based on the VAST solver, which has the following relevant capabilities that are suitable for the composite propeller analysis/design:

- Classical laminate theory for computing composite stresses and strains
- Higher order theories for thick shell structures
- Composite failure criteria including Tsai-Hill, Tsai-Wu
- Nonlinear geometric modeling for large deflections

4 Summary, Conclusions and Recommendations

4.1 Summary and Conclusions

A number of issues have been identified with the current Nickel Aluminum Bronze (NAB) submarine propellers, including vibration, electric signature, and possibly excess weight. A possible solution to all of these is to fabricate the entire propeller (or a significant portion) out of composite materials, because of the advantages these materials offer, such as corrosion resistance, light weight, tailoring of material properties, low electric signature and acoustic properties. This study represents the first of proposed multi-phase efforts to investigate the development of a Canadian Navy composite propeller technology in order to exploit the potential benefits that composite materials offer. The objectives of the present study include (a) reviewing worldwide developments of composite propellers; and (b) developing a strategy for modeling composite propeller blades in the PVAST/Trident FEA software. Highlights of the review are provided below.

Small Composite Propellers

Several successful small unit composite propeller applications have been developed worldwide. These composite propellers are said to be stronger, lighter, and have superior chemical and corrosion resistance than traditional aluminum propellers. These include

- The modular composite propeller developed by the Swedish company ProPulse AB. This propeller comprises a metal hub with replaceable ‘high quality composite’ blades whose pitch can jointly be adjusted (at blade installation) to one of five settings, and is suitable for motors of 20-300 hp. The propellers are 40% lighter than traditional aluminum propellers.
- The Pirhana (US) composite propellers made by injection moulding of LNG Engineering Plastics’ Verton long glass fibre reinforced polyamide thermoplastic. The hubs have a core of high strength aluminum over moulded with Verton. The site propellers are generally suitable for motors of 120 – 290 hp, and are also reported to resist abrasion better than metals. The propellers are said to be 10-15% stronger than traditional aluminum propellers
- The Comprop composite propellers developed by the US company Composite Marine Propellers. These are single-piece four-blade props, up to 55 cm in diameter, which are offered as original equipment on Regal, Wellcraft, Glastron and Corona boats, as well as being recommended for spares or replacements on a variety of craft powered by engines up to 225 hp. The blades that are designed to flex slightly or break off should they hit an obstruction, so that drive shafts and bearings remain undamaged.

Larger Composite Propellers

For larger scale applications, the Contur® composite propellers developed by the German company AIR Fertigung-Technologie GmbH appear to be the most successful composite propeller development. These are carbon fibre based composite blades manufactured by a resin transfer moulding (RTM)-like process that are fitted on metallic hubs, that are intended for super yachts and ships. It is stated that hundreds of ship sets of Contur advanced composite propellers have been sold, ranging in diameter from 50 cm to 5 m. AIR states that the Contur propellers weigh only a third as much as conventional NAB equivalents, and the composite blades can be thinner at the tips than metal, reducing propeller noise typically by 5 dB. The tips of the blade are fortified with drawn polyethylene fibres, which make them especially resistant to below-water impacts.

Naval Applications of Composite Propellers

Several navies have undertaken composite propeller technology demonstration projects involving the design, analysis and manufacturing of composite propeller for surface ships and submarines. These include the following:

- The UK navy, in collaboration with QinetiQ, Dowty Propellers and Wartsila Propulsion, Netherlands, designed, built and carried out sea trials on a 2.9 m diameter, five-blade composite propeller assembled on a bronze hub. The blades were designed and built using a hybrid glass/carbon composite construction, and was fitted QinetiQ's trimaran warship demonstrator, the RV Triton, in place of the latter's normal fixed-pitch bronze unit. The design resulted in thicker blades that offer the potential for improved cavitation performance, while also reducing vibration and underwater signatures. The composite propellers provided 20% weight savings compared with normal bronze blades. Sea trials were regarded as successful, the propeller demonstrating a smooth take up of power and reduced vibration.
- The Royal Dutch Navy has used applied the Contur propeller on their mine hunter vessels, with diameter in the range of approximately 1.5 m. Details of these developments were not available to this study.
- The German Navy has developed composite propellers based on AIR technology for surface ships. This involved three different kinds of composite propellers; including (a) propellers designed for passively adjusting pitch near the tip, (b) surface-piercing controllable pitch propellers, and (c) the rim-driven, hubless propellers. It was stated that the propellers are coated with polyurethane coating materials to reduce cavitation erosion damage, but details of the coating material were not given.
- The German Navy has also developed composite propellers for their submarines, based on AIR propellers. Two 206A Class submarines were installed with composite propellers. The first composite propeller was made of 100% carbon fibre material and had the same geometry as a metallic propeller. It was reported that the composite propeller had been in operation for over 2 years and approximately 20,000 nautical miles without any damage or malfunction. The second composite propeller was a highly damped composite propeller using aramid fibre (Kevlar). Another composite propeller program was performed to design and install a much larger (3.9 m diameter) composite propeller on a 212A Class submarine. Sea trials indicated significant improvement in acoustic performance.
- The US Navy has investigated the analysis, fabrication and testing of a composite bladed propeller for the US Naval Academy Yard Patrol (YP) craft, which is part of the Trident project. The YP craft was selected as the test platform because it: (a) has two propellers (in the event of failure); and (b) is used for many hours, often in harsh conditions. The blade was made from 100% carbon epoxy material that was attached to a NAB hub. The blade design was based heavily on the existing metallic propeller. A "dovetail" design was used. Sea trials were considered to be very successful.

- The vendors of Contur propellers state that the US navy has installed several Contur propellers on their vessels. However, details of such studies were not available to this study.
- A number of US navy sponsored projects related to composite propeller development have been reported in the open literature. The significant studies involved the design, fabrication and testing of 0.6 m diameter scale models of adapting Hexcel IM7-8552 carbon epoxy composite marine propellers, whose design followed closely the German company AIR Fertigung-Technologie GmbH's Contur propeller design. The thrust of the studies was to utilize fluid-structure interaction effects to improve the performance of composite marine propellers. This involved the utilization of the bend-twist coupling properties of anisotropic composites, and the load-dependent self-adaptation behaviour of composites to improve the performance of the composite propellers. The results of the studies showed that a properly designed flexible composite propeller can be more efficient, a cavitation inception in wake inflow can be significantly delayed compared to its rigid counterpart.

Based on the successful applications of composite propellers for small craft and naval surface ships and submarines presented above it concluded that the Canadian Navy will benefit from the development of a composite propeller technology. The development of such technology will enable the Canadian Navy to keep pace with technological developments and other modern navies.

4.2 Recommendations

The next step should involve the conceptual design of a composite propeller to meet or exceed Canadian Navy requirements. The PVAST/Trident FEA system can be used to facilitate the design analysis process. With small enhancements to its composite modeling capabilities, the PVAST/Trident FEA system can be used to automatically generate composite propeller models, which would allow several design iterations to be assessed. The following tasks are recommended for the next phase of the composite propeller development:

- <u>Modify PVAST/Trident FEA for Automated Development of Composite Propeller Models.</u> This involves the implementation of modifications to DRDC's propeller modelling platform, namely the PVAST/Trident FEA software, to facilitate the automated modeling of composite propeller blade configurations. The modifications shall be in accordance with the methodology developed in Section 3.3.
- <u>Conceptual Composite Propeller to Meet Defence Requirements.</u> This involves the performance of preliminary design studies to investigate composite propeller design concepts and demonstrate their potential to meet Canadian navy requirements. A typical propeller blade such as the Quest propeller will be used for this study. This study will focus on the strength, vibration, damping, and implementation issues but will not change the hydrodynamic design. Comparisons shall be made to the existing NAB design. Different blade attachment methods shall be investigated.
- <u>Develop Composite Propeller Development Plan.</u> This involves the development of a plan to complete the composite propeller development study. This will cover aspects including detailed design/analysis including hydrodynamic design (if necessary), fabrication, testing, certification and guidelines for the life cycle management of the composite propellers.

- Collaboration with Other Navies. It is recommended that DRDC seek means of collaborating with other navies, such as the German, UK, Royal Dutch and US navies. This will provide avenues for lessons learned and reduce development costs to the Canadian Navy.

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A number of issues have been identified with the current Nickel Aluminum Bronze (NAB) submarine propellers, including vibration, electric signature, and possibly excess weight. A possible solution to all of these is to fabricate the entire propeller (or a significant portion) out of composite materials, because of the advantages these materials offer, such as corrosion resistance, light weight, tailoring of material properties, low electric signature and acoustic properties. This study represents the first of proposed multi-phase efforts to investigate the development of a Canadian Navy composite propeller technology in order to exploit the potential benefits that composite materials offer. Several successful small composite propeller applications have been developed worldwide. These include a modular composite propeller developed by the Swedish company ProPulse AB; composite propellers made by injection moulding by Pirhana (USA); and Comprop composite propellers developed by Composite Marine Propellers (USA). For larger scale applications, the Contur® composite propellers developed by the German company AIR Fertigung-Technologie GmbH appear to be the most successful composite propeller development and consist of carbon fibre-based composite blades fitted on metallic hubs. Several navies, including those of the UK, USA, Dutch, and Germany have undertaken composite propeller technology demonstration projects involving the design, analysis and manufacturing of composite propellers for surface ships and submarines. Based on the successful applications of composite propellers for small craft, naval surface ships and submarines presented above, it is concluded that the Canadian Navy will benefit from the development of a composite propeller technology.

Les hélices actuelles de sous-marins faites de bronze d’aluminium-nickel (NAB) présentent de nombreux problèmes; elles génèrent, notamment, des vibrations, une signature électrique, et peuvent être plus lourdes que d’autres types d’hélices. Pour remédier à ces problèmes, on pourrait fabriquer une hélice entière (ou une partie significative de celle-ci) avec des matériaux composites, car ceux-ci offrent des avantages. En effet, ces matériaux sont résistants à la corrosion, légers, personnalisables, et possèdent des caractéristiques acoustiques tout en ayant une faible signature électrique. La présente étude constitue la première étape d’un projet à phases multiples de la marine canadienne qui permet d’enquêter sur l’élaboration d’une technologie qui utilise et maximise les matériaux composites lors de la fabrication d’hélices. Plusieurs petites applications d’hélices en matériaux composites gagnantes ont été développées dans le monde, comme l’hélice modulaire en matériaux composites conçue par l’entreprise suédoise Pulse AB, l’hélice en matériaux composites fabriquée par moulage par injection de Pirhana (États-Unis) et l’hélice en matériaux composites Comprop de Composite Marine Propellers (États-Unis). Pour les applications à grande échelle, l’hélice en matériaux composites Contur® créée par l’entreprise allemande AIR Fertigung-Technologie GmbH semble être la plus populaire; elle est faite de pales en fibres de carbone installées sur des moyeux en métal. Plusieurs marines, y compris celle du Royaume-Uni, des États-Unis, des Pays-Bas et de l’Allemagne, ont des projets qui démontrent leur technologie, soit la conception, l’analyse et la fabrication d’hélices en matériaux composites destinées à des navires de surface et à des sous-marins. En se fondant sur le succès de l’utilisation d’hélices en matériaux composites pour les petits navires, les navires de surface et les sous-marins mentionné ci-dessus, il a été conclu que la marine canadienne bénéficierait de l’élaboration d’une technologie d’hélices en matériaux composites.

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