

# **IMPROVEMENT OF HYDRODYNAMIC EFFICIENCY OF FULL-SCALE COMPOSITE MARINE PROPELLERS IN OFF-DESIGN CONDITIONS USING SMART MATERIAL ACTUATION**

HIMALAYA NIRJHAR DAS



DEPARTMENT OF APPLIED MECHANICS  
INDIAN INSTITUTE OF TECHNOLOGY DELHI  
MARCH 2019

©Indian Institute of Technology Delhi (IITD), New Delhi, 2019

# **IMPROVEMENT OF HYDRODYNAMIC EFFICIENCY OF FULL-SCALE COMPOSITE MARINE PROPELLERS IN OFF-DESIGN CONDITIONS USING SMART MATERIAL ACTUATION**

by

HIMALAYA NIRJHAR DAS  
Department of Applied Mechanics

*Submitted*

In fulfillment of the requirements of the degree of Doctor of Philosophy

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI  
MARCH 2019

# Certificate

This is to certify that the thesis entitled “**Improvement of Hydrodynamic Efficiency of Full-Scale Composite Marine Propellers in Off-Design Conditions Using Smart Material Actuation**” being submitted by **Mr. Himalaya Nirjhar Das** to the Indian Institute of Technology Delhi for the award of the degree of **Doctor of Philosophy** in Applied Mechanics is a record of original bona fide research work carried out by him under our supervision and guidance. The thesis work, in our opinion, has reached the requisite standard fulfilling the requirements for the degree of Doctor of Philosophy.

The results contained in this thesis have not been submitted in part or full to any other University or Institute for the award of any degree or diploma.

Dr. Ch. Suryanarayana  
Naval Science & Technological Laboratory  
Defence Research & Development Organisation  
Visakhapatnam 530027

Prof. Santosh Kapuria  
Department of Applied Mechanics  
Indian Institute of Technology Delhi  
New Delhi 110016

Prof. B. P. Patel  
Department of Applied Mechanics  
Indian Institute of Technology Delhi  
New Delhi 110016

# Acknowledgements

Many people have helped and inspired me to get into this work and move ahead to reach a reasonable conclusion. My parents had initially aspired that I would go for PhD study, which I continuously ignored in their lifetime. More than a decade after their demise, when I try to write this thesis I offer my respect to them posthumously.

Two more persons, my wife, Krishna, and son, Panchajanya, stood strongly beside me to continue this work, whereas I physically deserted them and stayed at the hostel of IIT, Delhi for completing the required course work. Every step of this thesis witnessed their solidarity towards me.

The biggest contribution in terms of research and guidance has come from my supervisor, friend and once fellow student Prof. Santosh Kapuria. Apart from educating me on structural behaviour of composite materials and shape memory alloys he taught me how to carry out a research and report the findings in scientific manner. He taught me to put the observations in right perspective and write meaningful compendium.

My co-supervisor Dr. Ch Suryanarayana, scientist of Naval Science & Technological Laboratory (NSTL) helped me to overcome many hurdles at my office at NSTL and provided continuous encouragement when going was getting tough. I also acknowledge Shri SV Rangarajan, the former Director of NSTL, who has permitted and encouraged me to carry out this study at IIT, Delhi.

Special thanks are due to my colleagues and students at NSTL. I have discussed many issues of this work with Shri VF Saji, Shri Manojit Gharai, Shri M Nageswar Rao, Smt. T Nagalaxmi, Shri P Veerabhadra Rao and Shri D Sridhar. These discussions might not yield results every time but definitely kept me encouraged and positive.

My friends at IIT Delhi, Dr. Jitendra Agrahari, Shri Vinod Pandey, Dr. Poonam Kumari, Dr. M Yaqoob Yasin, Shri Adnan Ahmed and others have helped me to settle down at IIT and encouraged to keep going when things were getting hopeless. I also acknowledge the teachings of Prof. RK Mittal and Prof. PK Sen and the encouragements from Prof. BP Patel and Prof. P Mahajan of IIT Delhi. Chairman and members of SRC committee, Prof. Suhail Ahmed, Dr. S Pradyumna, Prof. SR Kale and Dr. Amit Gupta have offered many valuable suggestions to my research, which have improved the quality of the thesis.

**Himalaya Nirjhar Das**

# Abstract

Marine propellers are normally designed to operate at a particular advance ratio, where it exhibits the maximum hydrodynamic efficiency. However, many propellers require to operate at different off-design conditions, when the suboptimal angle of attack leads to a drop in its hydrodynamic efficiency. There has been an enormous interest among researchers for enhancing the hydrodynamic efficiency of marine propellers in off-design conditions, since it can lead to significant reduction in the operating cost due to fuel saving. With the objective of addressing this issue, the present work aims to study (i) the effect of deformation on hydrodynamic performance of metallic propeller; (ii) the effect of bend-twist coupling on the hydrodynamic performance of full-scale composite propellers; and (iii) the use of SMA actuation for improving hydrodynamic performance of full-scale composite propeller in off-design conditions.

A full-scale 4.2 m diameter five-blade Ni-Al bronze propeller of a naval ship is studied first, through numerical simulation, to ascertain the effect of deformation of the propeller blades under different operating conditions on its hydrodynamic performance. The open water performance is estimated using the finite volume method employing the pressure based Reynold's averaged Navier-Stokes (RANS) equation for the steady, incompressible, turbulent flow. The deformation analysis is done using the finite element method using shell elements based on the first order shear deformation theory. The fluid-structure interaction is incorporated in an iterative process validated against a benchmark solution. The grid independence study has been conducted to ascertain the optimal grid for the problem. The flow solution is validated for two pitch ratios of the propeller blades, for which experimental results

are available. The study reveals that the deformation of the full-scale metallic propeller does not cause any significant influence on its effective pitch and consequently its hydrodynamic performance.

The bend-twist coupling of anisotropic composite material is explored next for passively adapting the pitch of the propeller to different flow conditions in order to improve the hydrodynamic efficiency at off-design conditions. To understand the effect of bend-twist coupling, a full-scale propeller of diameter 4.2 m having a simplified blade geometry with constant chord and constant pitch angle has been considered for this study. Four different composite materials, namely, carbon fibre reinforced plastic, graphite epoxy, glass epoxy and high tension carbon epoxy composites, are used. The analysis accounts for the viscous turbulent flow, the shear deformation effect which is significant for composite structures, the geometric nonlinearity for large deformations and the material failure through Tsai-Hill criterion. The numerical study has revealed that, within the limits of material safety, the twist generated in the deformed propeller using the commonly used composite materials is inadequate to create any noticeable change in the hydrodynamic efficiency. When the material failure is ignored, however, it is possible to generate sufficient deformation and twist that can cause appreciable improvement in the hydrodynamic performance.

In the next step, a study is made to use of shape memory alloy (SMA) for inducing variable twist in composite propellers for achieving the same. Prestrained SMA fibres are embedded in the composite in the martensite phase. When SMA fibres are heated upto the austenite phase, a large recovery stress is developed due to the shape memory effect. This stress is used to create twist in the propeller blade through appropriate positioning of the SMA actuator elements. An idealised propeller with a simple geometry is studied first. The thermomechanical behaviour of the SMA fibres is predicted using the Brinson model, and the effective material properties of the SMA hybrid composite (SMAHC) are determined using the

strength of materials approach. The study establishes for the first time that using SMA composite actuator elements, it is possible to generate sufficient twist that can cause the desired improvement in the hydrodynamic performance of full-scale marine propellers at off-design conditions over a wide range of advance ratio. Finally, the efficacy of the SMA actuation for adaptive control of twist is established for a full-scale composite propeller with the actual blade geometry of a naval ship.

## स्मार्ट सामग्री के प्रवर्तन द्वारा ऑफ डिजाइन परिस्थितियों में पूर्ण मापी मिश्रित समुद्री नोदकों की द्रवगतिकीय दक्षता में अभिवृद्धि

### सार

समुद्री नोदकें सामान्यतः एक विशेष अग्रसरण अनुपात प्रचालन हेतु डिजाइन किये जाते हैं, जहां यह सर्वाधिक द्रवगतिकीय दक्षता प्रदर्शित करता है। वैसे बहुत सारे नोदकों को विभिन्न ऑफ डिजाइन परिस्थितियों में चलना पड़ता है जब प्रवाह का उप इष्टतम कोण का आक्रमण, इसकी द्रवगतिकीय दक्षता में गिरावट लाता है। ऑफ डिजाइन परिस्थितियों में समुद्री नोदकों के द्रवगतिकीय दक्षता में वृद्धि लाने की दिशा में शोधकर्ताओं में बेहद उत्साह और ऊर्जा देख सकते हैं क्योंकि इससे ईंधन की बचत होगी एवं इसके प्रचालन व्यय में अवश्य ही कमी आयेगी। इस विषय पर विस्तार से चर्चा करने के लिए वर्तमान में इन बिंदुओं का पठन करना ज़रूरी है – क) धात्विक नोदकों के द्रवगतिकीय प्रदर्शन पर विकृति का प्रभाव । ख) पूर्ण मापी मिश्रित नोदकों के द्रवगतिकीय प्रदर्शन पर बेंड – मरोड़ युग्मन का प्रभाव । ग) ऑफ डिजाइन परिस्थितियों में पूर्ण मापी मिश्रित नोदकों के द्रवगतिकीय प्रदर्शन में उन्नति लाने हेतु एस.एम.ए. प्रवर्तन का प्रयोग ।

इस शोध में एक नौसेना जहाज़ के 4.2 मीटर व्यास वाले पूर्ण मापी निकेल-एल्युमिनियम पंच कांस्य ब्लेड नोदक पर संख्यात्मक अनुकार के माध्यम से पहला अध्ययन किया गया है जिसमें द्रवगतिकीय प्रदर्शन के आधार पर विविध प्रचालन स्थितियों के अधीन नोदक ब्लेडों के विकृति के प्रभाव को सुनिश्चित किया जा सकें। खुले जल के प्रदर्शन की गणना परिमित आयतन विधि से किया गया है। फिर स्थिर, असंपीड़्य, प्रक्षुब्ध प्रवाह हेतु दबाव आधारित रेनॉल्ड्स एवरेज़्ड नेवियर – स्टोक्स (आर.ए.एन.एस.) समीकरण को काम में लाया गया है। पहले क्रम के अपरूपण विकृति सिद्धांत पर आधारित शेल एलीमेंट के व्यवहार से परिमित एलीमेंट विधि का प्रयोग करते हुए विकृति विश्लेषण किया गया। एक आदर्श समाधान के रूप में पुनरावृत्ति प्रक्रिया को मान्यता दी गयी है जिसमें तरल संरचना की पारस्परिक क्रिया को समावेश किया गया। इष्टतम ग्रिड को सुनिश्चित करने के लिए ग्रिड स्वतंत्रता के अध्ययन की व्यवस्था की गयी है। नोदक ब्लेडों के द्वि पिच अनुपात के लिए प्रवाह समाधान को मान्यता दी गयी है जिसके लिए परीक्षण परिणाम मौजूद है। इस अध्ययन से पता चलता है कि कई पूर्ण मापी धातु नोदक की विकृति का इसके प्रभावशाली पिच और इसके द्रवगतिकीय प्रदर्शन पर कोई विशेष प्रभाव नहीं डाल पाता है।

एनिसोट्रॉपिक मिश्र सामान की बेंड मरोड़ युग्मक का पता लगाया जाता है ताकि विविध प्रवाह स्थितियों में नोदक के पिच को अप्रत्यक्ष रूप से अनुकूल बनाया जा सकें जिससे ऑफ डिजाइन स्थितियों में द्रवगतिकीय दक्षता में उन्नति हो। बेंड मरोड़ युग्मक के प्रभाव को समझने के लिए एक पूर्ण मापी 4.2 मीटर व्यास युक्त नोदक ब्लेड का सरल आकार हो, साथ में निरंतर जीवा और पिच कोण हो, अध्ययन हेतु गृहित किया गया है। चार अलग अलग मिश्र सामग्री, यथा – कार्बन फाइबर प्रबलित प्लास्टिक, ग्राफाइट इपोक्सी, कांच इपोक्सी और उच्च तनाव कार्बन इपोक्सी मिश्रणों का उपयोग होता है। यह विश्लेषण प्रक्षुब्ध प्रवाह की श्यानता, मिश्र संरचनाओं के लिए महत्वपूर्ण अपरूपण विकृति प्रभाव, बड़े विकृति के लिए ज्यामितीय अरैखिकता एवं साइ-हिल मानदंड के आधार पर सामग्री असफलता की जानकारियों के लिए महत्वपूर्ण है। सांख्यिक अध्ययन से यह पता चलता है कि सामग्री संरक्षा की सीमा में सामान्य व्यवहृत मिश्र सामग्री के प्रयोग से विकृत नोदक में आयी मरोड़ द्रवगतिकीय दक्षता में किसी भी प्रकार के परिवर्तन लाने में असमर्थ है। जब

सामग्री असफलता को अलग रख दिया जाये तब आवश्यक विकृति और मरोड़ लाना सम्भव है जिसमें द्रवगतिकीय प्रदर्शन में काफी हद तक उन्नति देखी जा सकती है।

अगले कदम पर, मिश्र नोदकों में परिवर्ती मरोड़ प्रेरित करने के लिए आकार स्मृति पदार्थ (एस.एम.ए.) पर अध्ययन किया गया। मार्टेनसाइट फेज़ के मिश्रण में पूर्व तनाव युक्त एस.एम.ए. तन्तुएं अतः स्थापित हैं। जब एस.एम.ए. तंतुओं को ऑस्टेनाइट फेज़ तक गर्म किया गया तो आकार स्मृति प्रभाव के तहत एक बेहद बड़ा पुनराप्ति बल विकसित हुआ। इसी बल के आधार पर एस.एम.ए. प्रवर्तक ऐलीमेंटों की सही सही तैनाती के माध्यम से नोदक ब्लेड में मरोड़ बनाया जाता है। सबसे पहले एक आदर्श सरल ज्यामिती वाले नोदक का अध्ययन किया जाता है। ब्रिंसन मॉडल के उपयोग से एस.एम.ए. तंतुओं के ताप- यांत्रिक आचरण को पूर्वानुमानित किया जाता है और सामग्रियों के उपगमन शक्ति के प्रयोग द्वारा एस.एम.ए. हाइब्रिड मिश्रण के प्रभावशाली सामग्री गुणधर्म का निर्धारण किया जाता है। इस अध्ययन ने पहली बार यह स्थापित किया है कि एस.एम.ए. मिश्र प्रवर्तक ऐलीमेंटों को प्रयोग में लाते हुए व्यापक रेंज के अग्रिम अनुपात पर ऑफ डिजाइन स्थितियों में पूर्ण मापी समुद्री नोदकों की द्रवगतिकीय प्रदर्शन में आशानुरूप उन्नति लाना सम्भव है। अन्ततः एक नौसेना जहाज़ के असली ब्लेड ज्यामिती सहित पूर्ण मापी मिश्र नोदक में अनुकूल मरोड़ नियंत्रण हेतु एस.एम.ए. प्रवर्तन गुण की स्थापना की गयी है।

# Contents

<b>Certificate</b>	i
<b>Acknowledgements</b>	ii
<b>Abstract</b>	iv
<b>Contents</b>	vii
<b>List of Figures</b>	xi
<b>List of Tables</b>	xvi
<b>Nomenclature</b>	xviii
<b>1 Introduction</b>	1
1.1 Preface	1
1.2 Preliminaries on marine propellers	3
1.2.1 Evolvement of different types of propellers	3
1.2.2 Open water characteristics and optimal operation of propeller	6
1.2.3 Propeller at off-design operations	8
1.3 Review of literature	10
1.3.1 Use of composite marine propeller	10
1.3.2 Computational analysis of marine propellers	10
1.3.3 Use of flexibility of composite marine propellers	11
1.3.4 Shape memory alloy for composite marine propellers	17
1.4 Motivation	20

1.5	Objectives	21
1.6	Organization of the thesis	22
<b>2</b>	<b>Effect of deformation on hydrodynamic performance of metallic propeller</b>	
		25
2.1	Introduction	25
2.2	Analysis methodology	26
	2.2.1 Reynold’s averaged Navier Stokes (RANS) equations for flow solution	27
	2.2.2 Analysis for deformation of propeller blade	31
	2.2.3 Fluid-structure interaction (FSI)	32
2.3	Problem definition and modeling	32
2.4	Validation and grid independence study for propeller flow	36
2.5	Validation of fluid structure interaction	42
2.6	Results	44
	2.6.1 Performance of propeller with pitch ratio 1.547, before and after deformation	44
	2.6.2 Effect of pitch ratio on the hydrodynamic performance	48
2.7	Conclusions	49
<b>3</b>	<b>Improving hydrodynamic efficiency of full-scale composite propellers using bend-twist coupling</b>	
		50
3.1	Introduction	51
3.2	Analysis methodology	51
	3.2.1 Deformation analysis for composite laminate	51
	3.2.2 Failure criteria	55

---

3.3	Validation study	55
3.4	Analysis of composite propeller	58
3.4.1	Design of thickness	63
3.4.2	Hydrodynamic performance	63
3.4.3	Pre-pitched propeller	69
3.5	Effect of different turbulence models	73
3.6	Conclusions	77
<b>4</b>	<b>Enhancement of hydrodynamic efficiency of full-scale composite propellers using shape memory alloy actuation</b>	<b>79</b>
4.1	Introduction	79
4.2	Shape memory alloy modeling	80
4.2.1	Constitutive equation for SMA fibre	83
4.2.2	Recovery stress in lamina with SMA	84
4.2.3	Constitutive relations of a SMA hybrid composite lamina	87
4.2.4	Recovery stress at different temperatures	89
4.3	Analysis methodology	90
4.4	Validation study on a cantilever four-layer composite beam with prestress at top layer	92
4.5	Analysis and laminate thickness design	93
4.5.1	Propeller blade geometry	94
4.5.2	Flow modeling	94
4.5.3	Thickness design for the blade	99
4.5.4	Positioning of SMAHC actuator	102
4.6	Behaviour of smart composite propeller blades	108
4.6.1	Deformation behaviour under different operating	108



# List of Figures

1.1	Different types of propellers. (a) Contra-rotating, (b) Controllable pitch, (c) Supercavitating, (d) Surface piercing, (e) Hubless	4
1.2	Open water characteristic of a propeller ( Lewis, 1988)	7
1.3	Incidental flow to propeller blade section at different conditions (Lin et al., 2009 and Lewis, 1988)	7
1.4	Schematic diagrams for flow over propeller blade section	9
2.1	Geometry of propeller. (a) Engineering drawing, (b) Surface model	33
2.2	Extent of domain and boundary conditions for flow analysis	34
2.3	Grid over surface of blade for structural analysis	35
2.4	Boundary conditions with applied pressure for structural analysis	35
2.5	Grid over propeller for validation study	36
2.6	Open water characteristics compared with expt. (a) for $P/D=1.547$ (b) for $P/D=1.322$	37
2.7	Grid independence study: four different grids.(a) Grid-1, (b) Grid-2, (c) Grid-3, (d) Grid-4	38
2.8	Grid independence study: complete domain for four different grids.(a) Grid-1, (b) Grid-2 (c), Grid-3, (d) Grid-4	39
2.9	FSI benchmark problem	42
2.10	Grid and flow conditions for FSI benchmark problem	43

2.11	Pressure distribution over face & back J = 0.6. (a) Face, (b) Back	44
2.12	Pressure distribution over face & back J = 1.2(a) Face, (b) Back	44
2.13	Velocity distribution around propeller (m/s), J = 0.6	45
2.14	Velocity distribution around propeller (m/s), J = 1.2	45
2.15	Von Mises stress(N/m <sup>2</sup> ) over propeller blade, J=0.6	46
2.16	Von Mises stress(N/m <sup>2</sup> ) over propeller blade, J= 1.2	46
2.17	Deformed shape at J=0.6	46
2.18	Deformed shape at J= 1.2	46
2.19	Open water characteristics for deformed and undeformed propeller (P/D =1.547)	47
2.20	Efficiencies of CPP at different pitch settings	47
2.21	Pitch angle for optimal efficiency with varying advanced ratio	48
3.1	Geometry of composite propeller	57
3.2	Surface grid over composite propeller	58
3.3	Pressure coefficient (Cp) for composite propeller at J=1.0	59
3.4	Open water characteristics of pre-pitched composite propeller (P/d=2.2)	60
3.5	Composition of composite blade with fibre layout	62
3.6	Mesh and boundary conditions with loading for structural analysis over composite propeller (Shell181 element) J=1.3	62
3.7	Open water characteristics for composite propeller (P/d=1.547)	68
3.8	Undeformed and deformed shape of blade at different operating conditions	72
3.9	Views of fine tetrahedral mesh over propeller	74

---

3.10	Distribution of $y^+$ over face and back of the propeller, $J = 1.5$	74
3.11	Pressure (coefficient) distribution over different radial sections of the propeller, $J = 1.5$ . (a) at $0.9R$ , (a) at $0.9R$ , (b) at $0.7R$ , (c) at $0.5R$	75
4.1	(a) Phase transformations in SMA under temperature and stress, and (b) Stress-strain behaviour before, during and after detwinning in low temperature martensite phase	81
4.2	Critical stress-temperature used in Brinson model	84
4.3	Representative volume element under stress along fibre and transverse direction, (a)Fibre direction, (b) Transverse direction	87
4.4	Variation of recovery stress and martensite volume fraction ( $\xi$ ) of SMA fibre with temperature for different values of prestrain in martensite phase	90
4.5	Four-layer composite $[0^0]_4$ beam subjected to (a) prestress on top layer, and (b) equivalent moment at the tip, having the same transverse deformation behaviour	93
4.6.	Geometry of the propeller	95
4.7	Views of propeller blade over hub showing one typical way (configuration 6 of Table 4.3) of placing SMAHC layer & aerofoil cross-section. (a) Isometric view , (b) Top view, (c) Aerofoil cross-section	96
4.8	Domain, grid and boundary conditions adopted for flow analysis around the propeller. (a) Extent of domain and boundary conditions for flow analysis, (b) Grid over propeller blade and domain	97

4.9	Variations of open water characteristics of smart propellers with SMAHC actuators with advance ratio without and with thermal actuation for two configurations. (a) Configuration 6, (b) Configuration 10	98
4.10	Contours of pressure coefficient over propeller for $J = 1.3$ .	99
4.11	Pressure (coefficient) distribution over different radial sections of the propeller, $J = 1.5$	100
4.12	Thickness distribution of propeller blade for structural analysis	101
4.13	Contours of axial stress ( $\sigma_y$ ) in 3 layers for blade with maximum and minimum thickness of 100 and 45 mm; hydrodynamic loading for $J = 1.2$	102
4.14	Maximum Tsai-Hill index at different locations and layers. Hydrodynamic load corresponding to $J=1.2$ , $v = 12.3$ m/s; recovery stress of 270 MPa applied along the trailing edge at the top layer. Figures in parenthesis indicate thickness (mm) of the respective segment	104
4.15	Different arrangements of location and fibre orientation of SMAHC elements considered for performance comparison	105
4.16	Deformed shapes of propeller blades without and with SMA actuation for two SMAHC configurations. (a) Config. 6: Austenite, (b) Config. 6: Martensite, (c) Config. 10: Austenite,(d) Config. 10: Martensite	109
4.17	Variation of twist in propeller blade with actuation temperature of Nitinol fibres at two off-design speeds, showing nonlinear increase in the twist with temperature	111

---

4.18	Percent change in propeller efficiency after deformation with and without actuation for two SMAHC configurations. Martensite and austenite states correspond to actuation and no-actuation cases	112
5.1	Extent of domain and boundary conditions for flow analysis	117
5.2	Surface grid over propeller	117
5.3	Grid over surface of blade for structural analysis	118
5.4	Placement of SMAHC patches with fibre orientation (a) Configuration 1, (b) Configuration 2	119
5.5	Deformed shapes and rotation in the blade for two configurations of placement of SMA fibres in austenite phase under operating condition, $J = 1.0$ . (a) Views of deformed shapes showing twist, (b) Contours of sum of rotation vectors (radian) in the blade	123
5.6	Open water characteristics of propeller, before and after deformation (SMA fibres placed as configuration 1)	124
5.7	Open water characteristics of propeller, before and after deformation (SMA fibres placed as configuration 2)	125
5.8	Variation of thrust, torque and efficiency with temperature (Configuration 1, Nitinol actuated at first layer, $J = 0.8$ )	127

# List of Tables

2.1	Grid convergence study	41
2.2	Force and deformation for the FSI benchmark problem	43
3.1	Validation study for deformation of composite plates	56
3.2	Material properties	61
3.3	Deflection and stresses in composite propeller blades of different thicknesses [propeller rpm=200; velocity = 15.4 m/s; material: graphite epoxy]	64
3.4	Deflection and stresses in composite propeller blades with different ply orientations [thickness = 80 mm; propeller rpm = 200; velocity = 15.4 m/s]	65
3.5	Operating conditions of the propeller	66
3.6	Deflection and stresses in a composite propeller blade under different operating conditions [thickness = 80 mm; laminate (90°/0°/0°/90°/90°); material: graphite epoxy]	66
3.7	Open water characteristics: before and after deformation under different operating conditions [thickness = 80 mm, material: graphite epoxy, laminate (90°/0°/0°/90°/90°)]	67
3.8	Deflection and stresses in a composite propeller blade of graphite-epoxy laminate (90°/60°/45°/-60°/45°/60°/90°/90°/ 90°/90°) [thickness = 80 mm, J =0.8, propeller rpm 220, velocity 12.3 m/s]	68

3.9	Effect of ply angle on twist in an angle-ply composite blade [material: graphite epoxy ( $v_f = 0.3$ )]	70
3.10	Maximum deflection and twist in propeller blades of different laminate configurations	71
3.11	Open water characteristics of original undeformed propeller, using four different turbulence models	76
4.1	Mechanical properties of different materials	89
4.2	Maximum Tsai-Hill index in the laminate for different thickness conditions	103
4.3	Twist and deflection in blade with different arrangements of SMAHC layer	106
4.4	Twist and deflection of blade at different operating conditions	110
5.1	Deflection and twist in propeller blade	122
5.2	Failure analysis: maximum Tsai-Hill index for different operating conditions	122
5.3	Recovery stress in Nitinol fibres at different temperatures ( $\epsilon_P = 2\%$ )	126
5.4	Deformation of propeller blade of configuration 1 with SMA actuated at first layer ( $J = 0.8$ )	128

# Nomenclature

$A_1, A_s, A_m$  cross-sectional area of element, fibre, matrix

$A_f$  austenite finish temperature

$A_f^m$  modified austenite finish temperature

$A_{ij}$  extensional stiffness matrix

$A_s$  austenite start temperature

$A_s^m$  modified austenite start temperature

$a$  length of plate

$B_{ij}$  coupling stiffness matrix

$C$  chord length of propeller section

$[C]$  damping coefficient

$C_A$  stress influence coefficient

$C_p$  pressure coefficient

$C_{\epsilon 1}, C_{\epsilon 2}, C_{\mu}$  constant of  $k\epsilon$  turbulence model

$D$  diameter of propeller

$D^e$  material constitutive matrix for element

$D_{ij}$  bending stiffness matrix

$d$  diameter at any particular radial section of propeller

$E_i$  Young's modulus along  $i^{\text{th}}$  direction

$E_A$  Young's modulus at austenite state

$E_M$  Young's modulus at martensite state

$F_x, F_y$  components of forces

## Nomenclature

---

$F_{co}, F_{ce}, F_h$	Coriolis, centrifugal, hydrodynamic force
$G_{ij}$	shear modulus
$h$	thickness of plate
$J$	advance ratio
$K$	global stiffness matrix
$K_g$	geometrical stiffness matrix
$K_t$	coefficients of thrust
$K_q$	coefficients of torque
$k$	kinetic energy of turbulence
$L$	number of lamina in composite laminate
$M_i$	component of moment/ twist per unit length
$[M]$	mass matrix
$N_i$	components of force resultants per unit length
$[\tilde{N}]$	shape function
$n$	revolution per second for propeller
$P$	pitch of propeller blade
$p$	pressure
$p_0$	uniformly distributed load
$p_{ref}$	reference pressure
$\bar{p}$	time averaged pressure
$Q$	stiffness
$Q'$	torque of propeller
$\bar{Q}$	stiffness for generally orthotropic condition
$Q^e$	element stiffness matrix
$Q_g^e$	element geometrical stiffness

---

$R$	radius of propeller
$r$	position vector
$S_{Ui}$	source term in transport equation
$S$	shear strength of composite lamina
$T$	temperature
$T'$	thrust of propeller
$T_0$	initial temperature
$t$	time
$U_{i1}^{\text{th}}$	component of velocity
$U_\infty$	free-stream velocity
$\bar{U}$	time-averaged velocity vector
$U^+$	nondimensionalised velocity
$u_x, u_y, u_z$	displacements
$u'$	fluctuating component of velocity
$\hat{u}_z$	nondimensionalised deflection
$u_\tau$	friction velocity of flow
$\{u\}, \{\dot{u}\}, \{\ddot{u}\}$	nodal displacement, velocity, acceleration
$V$	volume of element
$v_m$	volume fraction of composite matrix
$v_f$	volume fraction of fibre
$v_s$	volume fraction of SMA element
$X_T$	tensile strength in fibre direction for composite lamina
$Y_T$	tensile strength in normal to fibre direction for composite lamina
$y^+$	nondimensionalised distance from wall
$\alpha$	angle of attack

## Nomenclature

---

$\beta$	angle of resultant flow with propeller plane
$\gamma_{ij}$	shear strain
$\delta_{ij}$	Kronekar delta
$\varepsilon$	rate of dissipation of turbulent kinetic energy
$\varepsilon_0$	initial strain
$\varepsilon_i$	normal strain
$\varepsilon_L$	maximum recoverable strain
$\acute{\kappa}$	Von Kármán constant = 0.4187
$\kappa_i$	curvature in i direction
$\kappa_{ij}$	twisting curvature
$\Theta$	thermoelastic coefficient
$\Theta_A, \Theta_M$	thermoelastic coefficient at austenite and martensite phase
$\theta$	angle of orientation of fibre for composite
$\eta$	efficiency of propeller
$\mu$	coefficient of viscosity
$\mu_t$	coefficient of eddy viscosity
$\vartheta_{ij}$	Poisson's ratio
$\Omega$	rotational velocity vector
$\varphi_i$	rotational displacement in $i^{\text{th}}$ direction for plate
$\xi$	martensite volume fraction
$\xi_S$	stress induced martensite volume fraction
$\xi_T$	temperature induced martensite volume fraction
$\rho$	density of medium
$\psi$	pitch angle
$\sigma$	stress

---

$\sigma_0$	initial stress
$\sigma_1, \sigma_2$	normal stress in material direction in a composite lamina
$\sigma^r$	recovery stress
$\sigma_x, \sigma_y$	normal stress in respective direction
$\sigma_k, \sigma_\epsilon$	constant of $k\epsilon$ turbulence model
$\tau_{12}$	shear stress in material direction in a composite lamina
$\tau_w$	wall shear stress
$\tau_{xy}$	shear stress component