Available online at www.sciencedirect.com
ScienceDirect
Comput. Methods Appl. Mech. Engrg. 284 (2015) 835–860
Computer methods in applied mechanics and engineering
www.elsevier.com/locate/cma

Isogeometric analysis and Genetic Algorithm for shape-adaptive composite marine propellers

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Available online 13 November 2014

Abstract

This paper presents a layup optimisation algorithm for composite marine propellers, including the hygrothermal effects, using Non-Uniform Rational B-Splines (NURBS) based FEM coupled with real-coded Genetic Algorithm (GA). The use of Iso-Geometric Analysis (IGA) enables accurate representation of complex marine propeller blades, coupled with GA for both continuous and mixed integer ply angle optimisation. The optimisation scheme was further investigated multi-objective, multi-material and multiple layer thickness optimisation scenarios. Furthermore, the IGA-FEM solver was constructed based on constitutive equations that take into account the hygrothermal effects that must be addressed to enable the optimisation of non-symmetric layups. Such non-symmetric layup patterns are proposed to be used to create extension-twist coupling to gain further control in layup optimisation. The optimisation technique is presented here as a method to widen the efficiency envelope of marine propellers. However, the same approach can potentially be adopted to cater many other practical applications such as composite wind turbine blades, aircraft propellers and other general composite ply angle optimisation scenarios. The paper discusses the proposed framework for optimisation of marine propeller, numerical tools used in the process and results under different conditions.

Keywords: Isogeometric analysis; Genetic Algorithm; Hygrothermal effects; Composite ply optimisation; Marine propeller

1. Introduction

The knowledge and technology behind design and manufacture of marine propellers has been in existence for several centuries. This is predominantly using alloys such as using Nickel Aluminium Bronze (NAB) and Manganese Nickel Aluminium Bronze (MAB). However, the increasing demand for high efficiency, high strength-to and high stiffness-to-weight ratio has led marine propeller research in a new direction towards engineered materials. Recently, the use of such engineered materials, especially laminated composites, to manufacture marine propellers has received considerable attention equally among researchers and industry. This is due to the favourable qualities of composites over metal alloys such as light weight, reduced corrosion, reduced noise generation, no magnetic signature and passive shape adaptability [1–3].

From a mechanical design and optimisation perspective, efficiency improvement through passive shape adaptability is one of the most attractive capabilities of a composite marine propeller. Passive shape adaptability refers to the

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http://dx.doi.org/10.1016/j.cma.2014.10.028
0045-7825/

capability of composites to deform, without the involvement of external mechanisms based on incoming flow conditions and rotational speeds. This can be achieved by exploiting the intrinsic extension-shear, bend-twist and bend-extension coupling effects of anisotropic composites [4]. Such deformations can potentially be used to enhance the efficiency of a marine propeller especially at off-design conditions. In this paper it is proposed to achieve this by optimising the fibre layup angles and layup materials of the composite, such that the propeller has an optimum bend-twist coupling performance.

The fundamental idea of layup optimisation of composite materials to cater certain requirements is not a novel concept. It has been demonstrated by many researchers in the past using simplified plate structures with classical boundary conditions or more complex geometries. Awad, et al. [5] presented a comprehensive review on using various optimisation algorithms for composite optimisation under various constraints to achieve certain objectives. The review covers the use of optimisation techniques such as the Genetic Algorithm, Simulated Annealing, Reliability based Design Optimisation, Particle Colony Optimisation, Ant Colony optimisation and Multi-Objective Genetic Algorithm. It is notable that all these works relied on optimisation schemes beyond classical gradient based methods due to the complexity and inherent non-convex nature of optimisation of composites. The review gave Genetic Algorithm based methods an overall 'High' ranking due to their multi-objective capability, low solution cost under parallel optimisation and the ability to converge to global solutions under appropriate parameter selection. Due to these favourable qualities, several authors in the past have used the Genetic Algorithm for layup optimisation of composite to great effect. Nagendra, et al. [6] used an improved Genetic Algorithm to design stiffen composite panels against buckling. Soremekun, et al. [7] further improved the work by introducing a variable elitist selection strategy for the GA. However, the structural domain was modelled as a simplified plate structure and the GA attempted to maximise the bend-twist performance by optimising the numerical values of laminate stiffness matrices (A, B, D matrices). Kemal Apalak, et al. [8] attempted to maximise the fundamental frequency of a composite plate under various boundary conditions using the GA. The fitness function was calculated using a well-trained Artificial Neural Network (ANN) due to the computational cost of using a coupled FE solver. Binary coded Genetic Algorithm was used with bit strings representing every possible integer angle in the interval $[-90^\circ, 90^\circ]$. Furthermore, Almeida and Awruch [9] used the multi-objective Genetic Algorithm for minimising the weight and the cost of a composite plate subjected to loading. The Tsai–Wu failure criterion was also used to evaluate the reliability of the layup. Discrete angle optimisation was used with ply angles limited to 0°, $\pm 45^\circ$ and 90°. Two different fabric materials (kevlar and carbon) were used for layup and the selection of material for each layer was a part of the GA chromosome. Structural quantities were solved using FEM using a triangular element with 18 DoFs known as the Discrete Kirchhoff Triangle. Beyond ply optimisation, Ghasemi, et al. [10] used NURBS based FEM coupled with GA to optimise the fibre distribution of short fibre composites such that the strain energy is minimised, which alternatively meant maximising structural stiffness of the material. Application of NURBS based FEM was seen as an ideal candidate for such problems as traditional FEM is limited by the mesh density when mapping the fibre distribution of the composite structure. With NURBS based FEM authors argued that it provided a much better distribution of fibre without being limited by the mesh density.

In addition to simple plate structures, various researchers in the past [1,2,4,11,12] have used flexibility and bend-twist coupling characteristics of composites to design marine propellers that have the capability of self-varying pitch (shape adaptable) based on out of plane bending moments caused by the incoming flow. The approach taken by Lin and Lee [11,13,14] was to minimise the change of torque coefficient of the propeller when moving from the design advance ratio to one other off-design advance ratio. The reason behind this strategy was maintaining the torque, thrust and efficiency the same as the design value when moving away from the design point. However, only one off-design point was considered. The optimisation process used by Liu and Young [4], Motley and Young [12], Pluciński, et al. [15] attempted to ensure that the ply configuration was chosen such that the blade can achieve the maximum possible pitch variation when moving from unloaded to loaded state. Essentially, the optimisation technique attempted to make the blade more flexible while maintaining strain and shape limitations. In addition, a previous work by Herath, et al. [16] employed an optimisation strategy similar to what is presented in this paper using Cell-Based Smoothed Finite Element Method (based on the work by Nguyen-Thoi, et al. [17]) coupled with the GA to optimise marine propeller blades. However, research that has been performed on marine propeller optimisation, thus far, are based on conventional Lagrange based FE techniques. Therefore, the optimisation is essentially based on an approximated shape for the structural domain. Furthermore, effects of non-symmetric layup patterns and especially the contribution of hygrothermal strains towards the change is twist and optimised layup are yet to be investigated.