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Application of bend-twist coupled blades for horizontal axis tidal turbines

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ABSTRACT

The blades of a horizontal axis tidal turbine are required to operate in a harsh subsea environment over a long life cycle with minimal need for maintenance. The concept of using passively adaptive, bend-twist coupled spars for horizontal axis tidal turbine blades has been identified as a potential method of improving energy capture. In this work a structural analysis is coupled with a fluid dynamic model to perform a full fluid-structure interaction analysis of a range of composite, bend-twist coupled blades. Blade element momentum theory is used to assess the presence of stall and corroborate the performance data attained from the fluid analysis. This paper discusses the individual analyses and the manner in which they are coupled. Several example problems were analysed using the design tool. The results compare well to the preliminary studies and indicate that a decrease of up to 12% in thrust and an increase of up to 5% in power capture could be achieved through the use of properly designed, bend-twist coupled blades.

1. Introduction

The oceans are a large, renewable, resource of untapped energy. There are many marine renewable energy sources however tidal energy has the advantage of being highly predictable and less susceptible to climate change than most [1–7]. Due to environmental concerns regarding potential devices it is thought that a breakthrough will occur in the area of kinetic energy devices; however, technology is at an early stage of development and further research into the field is required to advance the concepts, improve the feasibility of maintenance and make devices more efficient and economic.

The blades of a Horizontal Axis Tidal Turbine (HATT) are the only means of extracting energy from the tidal flow and therefore the efficiency, and consequently annual energy capture, of a device could be increased by improving the blade design. With design for through-life performance and decommissioning becoming ever more prevalent, turbines are required to withstand the aggressive subsea environment for many years whilst being environmentally disposable come the end of their life. This has a large impact on fatigue loading, with an HATT typically experiencing in the order of 1×10^8 rotational cycles over a 20 year life span. Offshore maintenance is already a costly procedure and this, coupled with the fact that tidal arrays are typically located in remote regions at sea in areas of high flow velocity, promotes a need for minimal maintenance over long periods. Optimisation of the blade design could increase the amount of energy capture, reduce structural loading and also minimise the need for maintenance.

Composites offer several advantages over metals such as superior fatigue characteristics, high stiffness to weight ratio, ease of manufacture of structures with complex curvature and a reduction in inertial loading. The fundamental assumption is that the design methodology for a composite lifting surface, such as a turbine blade, should in general follow that for conventional isotropic materials that use sufficient stiffness to maintain a given optimum design shape. This conventional approach to lifting surface design relies on their being a fixed optimum shape. As the flow regime experienced is rarely steady, however, every shape will deflect under a given load condition and will dynamically respond to the transient fluid load fluctuations. Composites, however, offer the potential for hydroelastic tailoring; with the use of adaptive composites having been identified as a potential method for load reduction, increased efficiency and enhanced control of wind turbine blades [8–16] and propellers [17–20].

The concept of using adaptive, bend-twist coupled, composite blades in order to improve energy capture but also decrease design complexity has been considered. Preliminary analysis suggests that a 2.5% increase in annual energy capture and a 10% decrease in thrust loading could be expected through the use of a bend-twist coupled adaptive HATT blade [21–25]. There are many parameters that require optimisation in isotropic HATT blade design; not least diameter, section shape, thickness/chord ratio, pitch, skew, rake. Integrating adaptive composite materials into the blade also

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requires that other variables are optimised such as the material properties, number of plies and the ply angle. Ultimately the blade analysis becomes complex and involves many time consuming iterations of Blade Element Momentum Theory (BEMT), Finite Element Analysis (FEA) and Computational Fluid Dynamics (CFD) so as to produce an optimal design.

Following on from the preliminary investigations, the aim of this work is to gain a more detailed knowledge of the performance of a composite, bend-twist coupled HATT blade by performing a full fluid-structural interaction analysis. This includes the development of a design tool for adaptive HATT blades incorporating fluid and structural analyses and BEMT in a full Fluid Structural Interaction (FSI) analysis.

2. Adaptive composites

An adaptive textile composite is a structure tailored to exhibit desirable elastic deformation behaviour not necessarily proportional to the imposed load. An example of such a structure would be a box beam so tailored that an imposed cantilever load results in twisting as well as bending, although no torsional load was imposed. Such a structure is said to exhibit bend-twist coupling. Composite blade elastic coupling can not only be tightly controlled but also varied over the span by appropriate selection of ply angles, thicknesses and spanwise layup. A 60–70% reduction in production costs was seen in the marine propeller industry after research into coupled composite propeller blades, along with smoother power take up, reduced blade vibration, reduced noise, and better fatigue performance [26].

Much research has been undertaken in this field in the wind industry [8–16,27–29]. Wind turbines carry loads primarily by twisting and bending, much like tidal turbines. The level of load reduction depends on the twist distributed along the blade length, which is controlled by the amount of bend-twist coupling. This, in turn, depends on the blade cross sectional geometry, the level of anisotropy in the structural material, and the material distribution [27].

For conventional laminated composites constructed of orthotropic layers, the level of anisotropy is determined by the fibre orientation with respect to the primary loading direction. Kooijman [28] found that the mirror layup, Fig. 1, is required for bend-twist coupling to be exhibited; with a 20° fibre angle orientation achieving a maximum level of coupling [30].

3. Fluid structure interactions

Fluid-structure interactions (FSI) occur when a fluid interacts with a solid structure, exerting pressure that causes deformation in the structure subsequently altering the flow of the fluid itself. If a situation involving structure flexure is to be analysed it is highly beneficial to couple both the fluid dynamics and the structural analysis programs to produce iterative solutions for complex problems.

In operation an HATT is subjected to hydrostatic pressure, and as it is a lifting body with rotational motion it is subjected to further hydrodynamic forces – thrust, torque, cavitation etc. Due to the complex loading scenario experienced by a tidal turbine, knowledge of the hydroelastic behaviour of the blades, hub, nacelle, and also the support structure under this regime could lead to a more thorough understanding of structural constraints and how performance of the turbine could be improved. Whilst being a highly informative technique for the design analysis of a standard fixed blade device (assumed to be stiff), FSI is essential when considering adaptive composite blades as the pressure loading alters the shape more significantly when compared to standard blades.

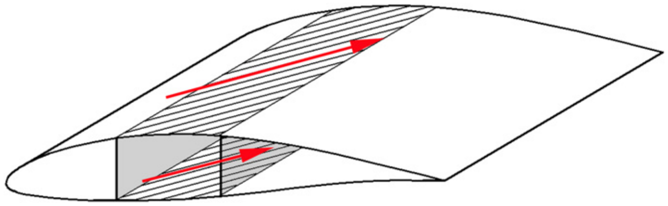

Fig. 1. Layup for bend-twist coupling illustrating that the composite plies in the top and bottom surface of the central area of the blade must mirror each other for coupling to occur.

There are three methods of joint fluid structural modelling in the time domain which involve solving the governing equations in a coupled, uncoupled or integrated manner [31–35]. In this work, a loosely coupled, modular approach is used; the flow problem and structural problem are solved successively until the change is smaller than the convergence criterion. This method has the benefit that the two domains are discretised to better suit the problem; as the mesh for the fluid analysis will tend to require greater refinement in different areas of the geometry than that for the structural analysis, and vice versa. The program alternately manipulates both the surface pressure distribution yielded from the fluid dynamics program and the displacement data output from the structural analysis, and feeds them back into the next relevant stage of the process. This is illustrated schematically by the flow chart in Fig. 2. Similar methods to this have been shown to be successful by Turnock and Wright [31] for the analysis of rudder propeller interactions.

3.1. Fluid dynamics analysis

The surface panel code used in this work was PALISUPAN (PArallel LIfting SUrface PANel) [36]. This code has previously been used to model the behaviour of a representative tidal turbine and good comparisons were obtained with published data, although problems were experienced in getting low twist sections to work due to the low pitch of the wake sheet [37,38]. Previous studies indicated that an optimum panel distribution can be achieved that maintains the accuracy of the result obtained with a finer distribution, but reduces the calculation time to around 15 min when using a standard desktop PC with one quad core Intel Xeon processor and 12 GB of RAM [37]. In comparison a full Reynolds Averaged Navier Stokes simulation of a similar tidal device carried out over 128 quad core Intel Nehalem processors on the 152 node Redrock computer cluster at the National Renewable Energy Laboratory would take up to 24 h depending on the mesh density [39].

Parameterisation and optimisation of surface panel codes is relatively simple, due to the low process times when implementing multiple runs – over 30 at a time – being highly feasible. Using a frozen wake model it is possible to reproduce the helical wake characteristic of tidal turbines. The number and distribution of panels in the wake is also very important for accurate modelling of device performance. Codes have been developed that generate panel distributions over complex shapes, such as a propeller or tidal turbine, and the associated wake panel arrangement. Such a code, Propgen [40] was used in this case to create the input blade geometry. Blade section data, section offsets, panel number and distribution for both blade and wake were input and the geometry is constructed from a set of section curves. The 2-D section is then mapped onto a cylindrical surface according to the specified variables using a transformation matrix. The appropriate pitch of the wake can be found through consideration of the axial and radial momentum changes in the flow due to the tidal turbine.

Once the blade geometry was generated it is then exported to Adaptflexi [41], a program which enables geometry manipulation and definition of the fluid analysis domain and flow variables, in which a surface is lofted through the sections to generate the blade. Additional variables are now defined for the HATT scenario such as