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Reliability analysis of rotor blades of tidal stream turbines

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ABSTRACT

Tidal stream turbines are used for converting kinetic energy of tidal currents into electricity. There are a number of uncertainties involved in the design of such devices and their components. To ensure safety of the turbines these uncertainties must be taken into account. The paper shows how this may be achieved for the design of rotor blades of horizontal-axis tidal stream turbines in the context of bending failure due to extreme loading. Initially, basic characteristics of such turbines in general and their blades in particular are briefly described. A probabilistic model of tidal current velocity fluctuations, which are the main source of load uncertainty, is then presented. This is followed by the description of reliability analysis of the blades, which takes into account uncertainties associated with tidal current speed, the blade resistance and the model used to calculate bending moments in the blades. Finally, the paper demonstrates how results of the reliability analysis can be applied to set values of the partial factors for the blade design.

1. Introduction

Tidal stream turbines are a relatively new technology for extracting kinetic energy from tidal currents, which is currently in transition from development stage to industrial implementation. A number of different concepts of such devices have been proposed so far and the most popular of them is a horizontal-axis turbine with propeller-type blades [1]. There are still no standards or other guidelines for the design of such devices in general and their rotor blades in particular. There are two types of limit states that may be of concern for the design of the rotor blades – ultimate and fatigue. However, it is expected that the design of rotor blades for tidal stream turbines will be controlled mainly by bending failure due to extreme loading as opposed to that for wind turbines where fatigue is the main cause of concern. This is supported, for example, by results presented by McCann et al. [2] who examined the influence of both extreme and fatigue loads on the design of blades for a generic tidal stream turbine. Of course, this does not mean that fatigue loading is completely unimportant for the design of such devices and there is no need to consider it.

The paper starts with a brief description of the main characteristics of tidal stream turbines with particular emphasis on horizontal-axis turbines with propeller-type blades. This is illustrated by an example of a generic horizontal-axis pitch controlled turbine, which is later employed to demonstrate the reliability assessment of the rotor blades. After that a probabilistic model of tidal current velocity fluctuations, which are the main source of load uncertainty, is presented. Since the rotor blades under consideration are pitch controlled it can be assumed that their overloading due to slow variations in the tidal current velocity is prevented by adjustment of the pitch angle. Thus, only variability of the tidal current velocity due to high frequency fluctuations caused by turbulence is modelled. The stochastic turbulence model is based on von Karman spectrum, which satisfies Kolmogorov's theory of turbulence and hence can be used to describe both sea [3] and wind turbulence [4].

Reliability analysis of the rotor blades in the context of bending failure due to extreme load during power production is then described. It should be noted that other ultimate limit states (e.g., local buckling) and design situations (e.g., fault conditions) may need to be considered in the rotor blade design; however, these are out of the scope of this paper. Uncertainties associated with tidal current speed, the blade resistance and the model used to calculate bending moments in the blades are taken into account. Only static behaviour of the blades is considered. Bending moments in the blades are calculated using the blade element-momentum theory. Finally, the paper shows how results of the reliability analysis can be applied to determine values of the partial factors for the design of tidal turbine rotor blades with respect to bending failure.

2. Tidal stream turbines

2.1. Basic classification

Tidal stream turbines can be classified according to:
rotor configuration – axial- or cross-flow, open or ducted;

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drive train configuration – indirect drive, when a rotor is connected to a generator via a gearbox, or direct drive, when a rotor is directly connected to a generator;

type of supporting structure – fixed to the seabed, gravity based or floating.

Additional classifications based on other parameters are also possible. A majority of the turbines currently under development are horizontal axis (i.e. axial-flow) devices with an open rotor [1]; thus, similar to a typical wind turbine. An important parameter for this type of turbines is the way their blades are connected to the rotor hub. The blades can be fixed (fixed-pitch) or being made rotatable about their axes (variable pitch). In the latter case the blades' orientation towards the current flow direction can be changed and by this the power take-off can be controlled (pitch controlled turbine).

2.2. Performance characteristics

Performance of tidal stream turbines is usually characterised in terms of dimensionless coefficients such as the power coefficient, C_P

$$C_P = \frac{P}{\frac{1}{2}\rho U^3 \pi R^2} \tag{1}$$

and the coefficient of thrust, C_T

$$C_T = \frac{T}{\frac{1}{2}\rho U^2 \pi R^2} \tag{2}$$

where P is the power, T is the thrust, R the radius of the rotor, U is the speed of tidal current and ρ is the density of seawater (≈ 1025 kg/m^3). The first coefficient represents the efficiency of a tidal turbine in converting kinetic tidal stream energy into mechanical energy. The second one represents the thrust acting on the turbine rotor and therefore is related to bending moments in the rotor blades; for the same U the higher the C_T the larger the bending moment at the root of the blade.

Both C_P and C_T are usually presented as a function of the tip speed ratio, λ, i.e. the ratio between the speed of the rotor blade tip and the current speed

$$\lambda = \frac{\Omega R}{U} = \frac{2\pi N_r R}{60U} \tag{3}$$

where Ω is the rotational speed of the rotor (rad/s) and N_r the number of the rotor rotations per minute (rpm).

In this paper a horizontal axis pitch-controlled turbine with a three-bladed rotor of 18-m diameter (i.e. $R = 9$ m) is considered. The turbine has a fixed rotational speed. The total water depth at the turbine location is 45 m and the height of the hub above the seabed is 21 m. The NREL S814 foil [5] is adopted for the blade section. Details of the blade geometry are given in Table 1, where r is the distance from the rotor axis and c is the blade chord. Fig. 1 shows C_P and C_T versus λ for the turbine. As can be seen, the turbine's performance is efficient when λ is in the range of 4–8 ($C_P > 0.4$). At the same time, lower values of C_T correspond to lower bending moments in the blades, hence, from this point of view the lower the λ the better. It is necessary to note that this turbine (including the blade geometry) has been developed with the only purpose to illustrate a method for reliability analysis of rotor blades presented further in the paper. The design is not optimal and not intended for the use in real devices.

The results in Fig. 1 are calculated using the NWTC Subroutine Library [6], which is based on the blade element momentum theory. The Prandtl tip-loss factor is used to account for tip and hub losses. The drag, C_d, and lift, C_l, coefficients for the blade elements are derived using the two-dimensional (2-D) vortex panel code XFoil [7]. Since XFoil is capable to calculate values of C_d and C_l only up to stall, their post stall values are estimated by the Viterna method [8]. To account for the effects of rotation on increasing lift and delaying stall the so-called 3-D correction method proposed by Snel et al. [9] is employed for each blade segment. It has been shown that loads on the rotor blades of tidal stream turbines predicted by this approach are in good agreement with experimental results [10], including cases when turbulence occurs [11]. The analysis also takes into account variation of the tidal current speed over the water column, which is described by the 1/7th power law (e.g. [12]).

Another important issue is cavitation, which can cause significant wearing of turbine blades due to local continuous cyclic stressing of the blade surface. Cavitation occurs when the local pressure, p_L, on the blade surface falls below vapour pressure of the sea water [13]. Consequently, cavitation inception can be predicted from the distribution of pressure around the blade foil by comparing the minimum negative pressure coefficient

$$C_p = \frac{p_L - (p_{AT} + \rho g h)}{0.5\rho U^2} \tag{4}$$

with the cavitation number

$$Ca = \frac{p_{AT} + \rho g h - p_V}{0.5\rho U^2} \tag{5}$$

where p_{AT} is the atmospheric pressure and p_V is the vapour pressure of sea water; cavitation occurs when $-C_P > Ca$. It has been ensured that there will be no cavitation at the turbine blade tips by checking that $-C_p$ remains below Ca for the range of U

Table 1
Details of the blade geometry.

r/R	c/R	Twist (°)
0.225	0.20	21.5
0.275	0.18	18.0
0.325	0.14	13.0
0.375	0.13	11.0
0.425	0.12	9.0
0.475	0.12	9.0
0.525	0.12	8.0
0.575	0.12	8.0
0.625	0.12	7.0
0.675	0.12	7.0
0.725	0.11	6.0
0.775	0.11	6.0
0.825	0.11	6.0
0.875	0.11	6.0
0.925	0.08	5.0
0.975	0.05	4.0

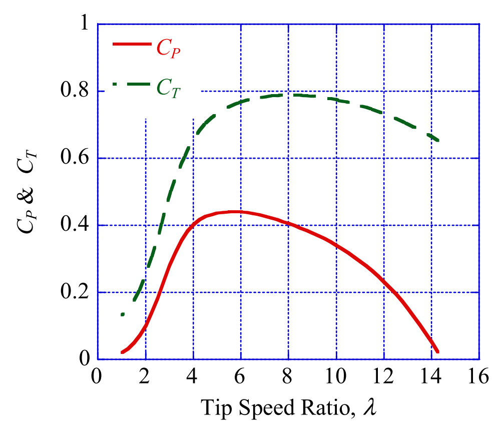

Fig. 1. Power and thrust coefficients for the turbine.