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A review on potential applications of carbon nanotubes in marine current turbines

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ABSTRACT

Marine current turbine is one of the promising marine renewable energy technologies that could provide clean and sustainable energy. This field has undergone rapid growth in both industry and academia during the last decade. However, there was no study being done in incorporating nanotechnology into marine current turbines. Carbon nanotubes, as one of the most studied nanomaterials, are a potential candidate to be incorporated into marine current turbines. This paper aims to review some of the researches done on carbon nanotubes to date, and proposed some potential applications in marine current turbines based on the review. The potential applications proposed are based on the need of marine current turbines. Apart from that, it also aims to act as a starting point to connect the two research areas (marine renewable energy and nanotechnology) together. The proposed applications include: structural reinforcement, fouling release coating, structural health monitoring, high performance wires/cables and lubrication.

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1. Introduction

Marine renewable energy as one of the renewable energy sources has gained attention from European countries and US since 1970s [1]. However, limited researches and studies were conducted in this field until the last decade [2]. Generally, types of marine renewable energy can be categorised into tidal, wave, current, ocean temperature gradient, salinity gradient and offshore wind. [1,2]. Offshore wind is a product of the interaction between the heat from the ocean surface and the atmosphere above it. This is the reason for categorising offshore wind as part of the marine renewable energy. These energy sources, especially tidal, wave and current, are said to possess greater potential in generating electricity compared with other renewable energies, as they are relatively consistent and predictable [3–6].

The rapid growth of marine renewable energy in the last decade, both in industry and academia, can be seen from the Annual Reports published by Ocean Energy Systems Implementing

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Agreement (OES-IA) of the International Energy Agency (IEA) [7–9], and review papers published by various researchers around the world [10–13]. Although most of the works are still in prototype testing phase, the commercialisation of some systems like tidal current and wave is already in progress [14–16]. Despite the rapid growth, to the best of authors' knowledge, no study has been carried out in incorporating nanotechnology into marine renewable energy technology. In fact, such an idea was mentioned a decade ago [17] and some possible applications of nanotechnology in marine renewable energy technology were suggested.

Nanotechnology, which utilises the special characteristics possessed by various nanomaterials, is well known in some renewable energy fields and environmental applications such as: photovoltaic cell, clean energy production and storage, catalyst for air treatment and wastewater treatment [18–20]. However, application of nanotechnology in marine renewable energy devices is rarely seen either in industry or academia. To date, there is only research in studying carbon nanotubes for wind turbine blade [21–24]. Viewing that the offshore wind is part of the marine renewable energy, these research works can be considered as pioneering study towards actual application of nanotechnology in marine renewable energy field.

As previously mentioned, the idea of using nanotechnology in marine renewable energy field is not new. However, detailed discussions and studies in integrating which nanotechnology with which marine renewable energy devices (exclude offshore wind) are limited or nearly zero. Hence, this paper aims to review and to propose possible applications of nanotechnology in marine renewable energy. Marine current turbine as one of the marine renewable energy technologies has undergone rapid growth in the last decade [25]. But to the best of authors' knowledge, no study has been done in incorporating nanotechnology into marine current turbines. Hence, marine current turbine is selected for this study. The selected nanotechnology is the carbon nanotubes, as it is one of the most studied nanomaterials and its applications cover a wide range of areas.

2. Characteristics of carbon nanotubes

The world has started to pay attention on carbon nanotubes since the report of multi-walled carbon nanotubes by Iijima in 1991 [26], and single-walled carbon nanotubes by Iijima et al. and Bethume et al. simultaneously in 1993 [27,28]. Carbon nanotube is a material consists of pure carbon atom which exists in tube shape. For single-walled carbon nanotubes, it is like rolling a monoatomic layer of carbon into a cylinder. Whereas multi-walled carbon nanotubes are made of more single-walled carbon nanotubes arranged concentrically. The average diameter of a single-walled carbon nanotube is about 1–2 nm, while a multi-walled carbon nanotube can be more than 50 nm [29,30]. Generally, the length of carbon nanotubes can be in the range of micrometre or even millimetre, and this gives carbon nanotubes a high aspect ratio.

Based on the configuration of the carbon, carbon nanotubes can be further categorised into three structures, namely armchair, zigzag and helical. The properties of carbon nanotubes vary depending on these structures [30]. There are many methods used to synthesise carbon nanotubes such as: laser ablation, electric arc method and catalytic chemical vapour deposition (CVD). But, it is still difficult to specifically synthesise any of these structures alone through a controllable way at the moment [31]. Therefore, it is usual to get a bundle of carbon nanotubes comprise of all these structures in bulk production. Nevertheless, the orientation of the carbon nanotubes can be controlled to form vertically aligned array [29]. This type of highly ordered orientation also has effect on the final properties of the carbon nanotubes.

2.1. Mechanical properties

One of the most spectacular properties of carbon nanotubes is its mechanical properties. Theoretically, it was calculated that the tensile strength can be as high as 45 GPa for single-walled carbon nanotube [32] and 150 GPa for perfect multi-walled carbon nanotube [33]. But, the direct measured tensile strength reported was far lower than these values. Li and co-workers reported that the tensile strength for one single-walled carbon nanotube is around 22 GPa [34]. The tensile strength of a single-walled carbon nanotube bundle was estimated to be around 14 GPa and lower. In another work reported by Yu and co-workers, the measured tensile strength for multi-walled carbon nanotube is within the range of 11–63 GPa only [35]. This suggests that the bulk production produced carbon nanotubes would have a tensile strength of about 10–20 GPa.

As a comparison, the tensile strength of high strength steel is about 1–2 GPa [33]. This means that carbon nanotube is at least 5 times stronger than high strength steel. Yet, the density of single-walled carbon nanotube reported is about 1.33–1.40 g/cm^3, which is almost only half the density of aluminium [36]. Owing to the strong and lightweight properties, carbon nanotube can be used as reinforcing agent to create high strength composite materials without significant effect towards the final weight of the product [30,37,38]. A worth noticing thing is that different structure can give different strength properties (armchair has better tensile strength compared with zigzag and helical [39]). When the synthetic methods become more mature, it is possible to produce carbon nanotubes with higher strength, which comprised mainly or wholly of armchair structure.

2.2. Chemical properties

The nature of the carbon nanotubes' seamless cylindrical wall makes it chemically stable under room temperature. Generally, the chemical reactivity on the open end of carbon nanotube is higher than the side wall [40–42]. It is possible to functionalise carbon nanotubes for various desired applications by attaching functional groups to nanotubes through appropriate treatment [43,44]. In fact, such functionalisation is essential to improve the processability of carbon nanotubes, in order to couple its properties with other materials [45]. The chemical stability, coupled with the high surface area (given by the outer wall and the inner wall of the tube) also makes carbon nanotube a potential candidate for adsorption and storage application [46,47]. Specifically, research community is keen to utilise carbon nanotube for hydrogen storage purpose.

Pure single-walled carbon nanotubes do not disperse in water or organic solvent due to the strong Van der Waals force between individual carbon nanotubes [48], hence, making carbon nanotubes to be hydrophobic. The hydrophobicity of carbon nanotubes can be further enhanced by creating highly ordered vertically aligned carbon nanotubes. For such carbon nanotubes array or forest, their hydrophobicity is a result of the micro- or nano-scale hierarchical roughness [49]. When the water touches the surface of carbon nanotubes array, it will be supported by the nano-air bubbles entrapped within the array, hence resulting in the hydrophobic phenomenon. Since such mechanism depends on the surface structure, other nanomaterials (capable of forming aligned arrays) can also be utilised to create this type of hydrophobic surface.

2.3. Electrical properties

Carbon nanotubes as a one-dimensional system also possess unique electrical properties. Generally, single-walled carbon nanotubes