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A NOVEL DESIGN AND PRELIMINARY INVESTIGATION OF COMPOSITE MATERIAL MARINE CURRENT TURBINE

A high performance and light-weight wound composite material wheel has been developed and is intended to be used for many purposes. One of these applications is marine current turbine (MCT). Traditionally, major problems influencing the design and operation of MCTs are fatigue, cavitation and corrosion due to the sea water. Considering these factors, implementation of composite materials, especially Kevlar fiber/epoxy matrix, in MCTs is explained in this paper. This novel design pattern of composite material marine current turbine (CMMCT) shows many advantages compared to conventional turbines. This paper investigated several factors which should be considered during this novel turbine design process such as the composite material selection, filament winding of composite wheel and turbine's structural and cavitation analysis. The power coefficient of CMMCT by using CFD is also obtained and the experimental facilities for testing CMMCT in a water towing tank are briefly described.

1. Introduction

1.1 Marine current turbine

The oceans offer a huge energy resource that has the potential of producing large amounts sustainable power [1]. Among several different oceanic energy forms, ocean-energy resources, wave and marine-current energy are the most promising options for massive ocean-energy generation in the near future. Marine currents are caused mainly by the rise and fall of the tides causing the whole sea to flow [2]. However, the marine environment is considerable more hostile than the low level atmospheric conditions experienced

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by wind turbines. The biggest difference between marine and wind turbine is related to the cavitation phenomenon. Cavitation is the formation of vapor bubbles of a flowing liquid in a region where the liquid pressure decreases to its vapor pressure [3]. Cavitation often causes performance degradation and structural damage to hydraulic devices. In addition, corrosion is another serious problem to be considered. Seawater is a saline solution so any metallic components will have to be protected from the water [4]. Thus, the operation of repairing turbines should be easily and low-costly.

1.2 Composite material marine current turbine (CMMCT)

Advanced composite materials are broadly used because of their high strength to weight ratios and high corrosion resistance. A novel manufacturing approach, similar to filament winding, was developed in the Turbomachinery Lab at Michigan State University (MSU), and is able to produce the composite wheels in a variety of possible patterns (Fig. 1). The advantage of using a filament winding method to manufacture high performance and lightweight composite wheels is that the production can be rapid, inexpensive and utilize commercially available winding machines [5].

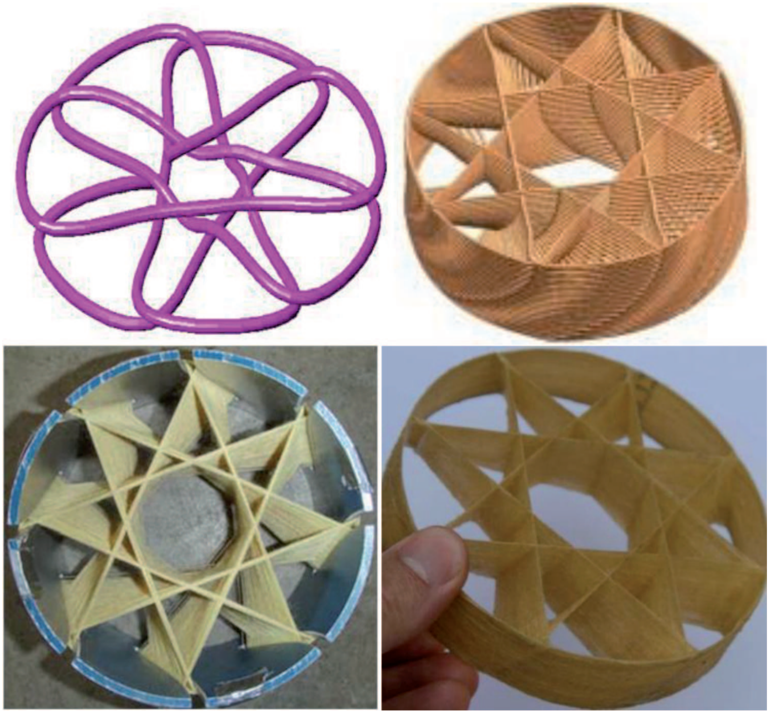


Fig. 1. CAD design of wound composite material wheel (upper)
Prototypes of composite material wheel (bottom)

A whole CMMCT test frame was designed to support the wheel taking into consideration that the frame would endure the maximum torque that the shaft transmits for different water flow speeds. Fig. 2 shows a schematic of CMMCT design in a water towing tank. The CMMCT with support structure in a water towing tank is shown in Fig. 3.

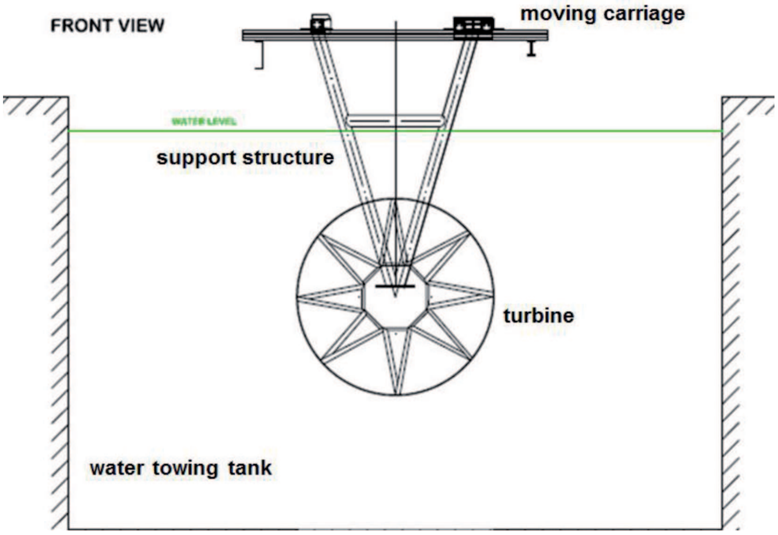


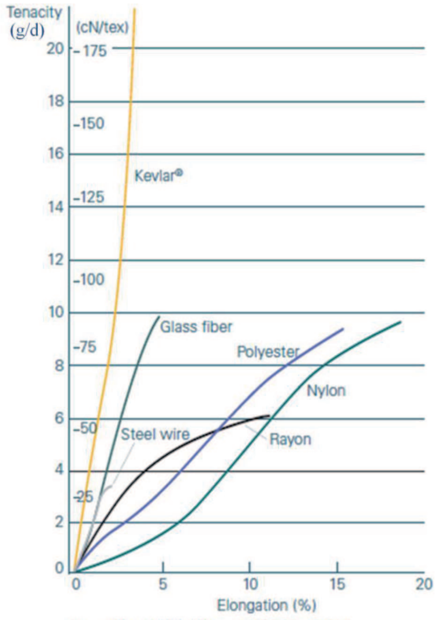
Fig. 2. Schematic of CMMCT design in a water towing tank

Fig. 3. CMMCT with support structure in a water towing tank

2. Selection of composite material

NOMENCLATURE
E_f Young's modulus of fiber, GPa
E_m Young's modulus of matrix, GPa
E_1 Modulus in direction longitudinal to fiber, GPa
E_2 Modulus in direction traverse to fiber, GPa
G_f Shear modulus of fiber, GPa
G_m Shear modulus of matrix, GPa
G_{12} In-plane shear modulus of material, GPa
V_f Volume fraction of fiber
V_m Volume fraction of matrix
v_f Poisson ratio of fiber
v_m Poisson ratio of matrix

Fig. 4 shows the comparison of stress-strain behavior of several commonly used materials [6]. It is seen that the Kevlar fiber has higher strength than other materials. In fact, Kevlar fiber in marine composites provides the ideal balance of strength, stiffness and light weight properties, which can be used in many marine applications. The density of Kevlar is about half that of glass fiber and its specific strength is among the highest of currently available fibers. Kevlar also has excellent toughness, ductility, and impact resistance, unlike brittle glass or graphite fibers [7].



Source from technical report KV-98-2 by Gallini.

Fig. 4. Comparison of stress-strain behavior of Kevlar fiber with other materials

According to the micromechanics model of composite materials, the composite material properties are determined from [8]:

$$E_1 = E_{f1}V_f + E_mV_m \tag{1}$$

$$E_2 = \left(\frac{V_f}{E_{f2}} + \frac{V_m}{E_m}\right)^{-1} \tag{2}$$

$$v_{12} = v_fV_f + v_mV_m \tag{3}$$

$$G_{12} = \left(\frac{V_f}{G_{f12}} + \frac{V_m}{EG_m}\right)^{-1} \tag{4}$$

where the indices 1 and 2 are referred to the direction longitudinal and perpendicular to the fibers. The mechanical properties of Kevlar fiber/epoxy matrix composite material are listed in Table 1.

Table 1.

Properties of Kevlar fiber/Epoxy matrix composite material

Density, ρ = 1380 kg/m^3

Longitudinal modulus, E_1 = 80 GPa

Transverse modulus, E_2 = 5.5 GPa

In-plane shear modulus, G_{12} = 2.2 GPa

Out-of- plane shear modulus, G_{23} = 1.8 GPa

Major Poisson's ratio, v_{12} = 0.34

Out-of- plane Poisson's ratio, v_{23}= 0.4

Longitudinal tensile strength, σ_1^T = 1.4 GPa

Longitudinal compressive strength, σ_1^C = 0.335 GPa

Transverse tensile strength, σ_2^T = 0.03 GPa

Transverse compressive strength, σ_2^C = 0.158 GPa

In-plane shear strength t_{12}^{ult} = 0.049 GPa

3. Filament winding of composite material wheels

MSU's invention can be realized by a low-cost flexible and fully automatic manufacturing method using commercially available CNC machines shown in Fig.5 for filament winding of the turbo-compressor wheels.

These machines, integrated conveniently into CAD/CAM systems, can be used for rapid-prototyping and mass-production. Depending on the size and sophistication, one wheel may cost even less than ten dollars. Fig.6

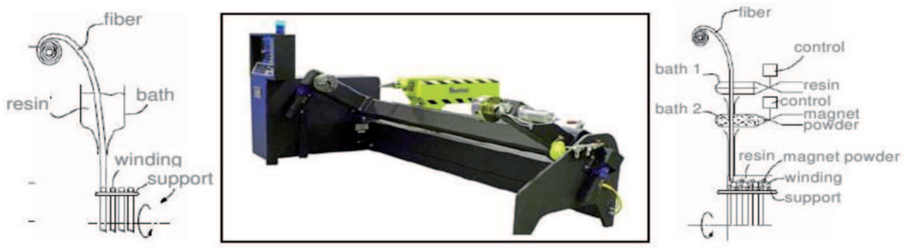


Fig. 5. Fiber wetting with one bath (left), example of multiple axis winding machine (center), controlled alternative fiber wetting with two baths (right)

shows a schematic of filament winding facility, where a two component epoxy syringes system acts the role of resin bath in a traditional filament winding machine. The disadvantage of a traditional resin bath is that it is not easy to control epoxy's properties during the winding process as epoxy crystallizes along with the time. Instead of using traditional resin bath, a two component syringe system is designed to mix resin and hardener. During the winding, when mixed epoxy at the tip of syringe system is run out, linear actuators, which are controlled by the computer, push syringe to inject desired amount (~0.1ml) into static mixer at the tip. In this way, the filament tow is always impregnated with fresh epoxy, which ensures the quality of the whole composite wheel [5].

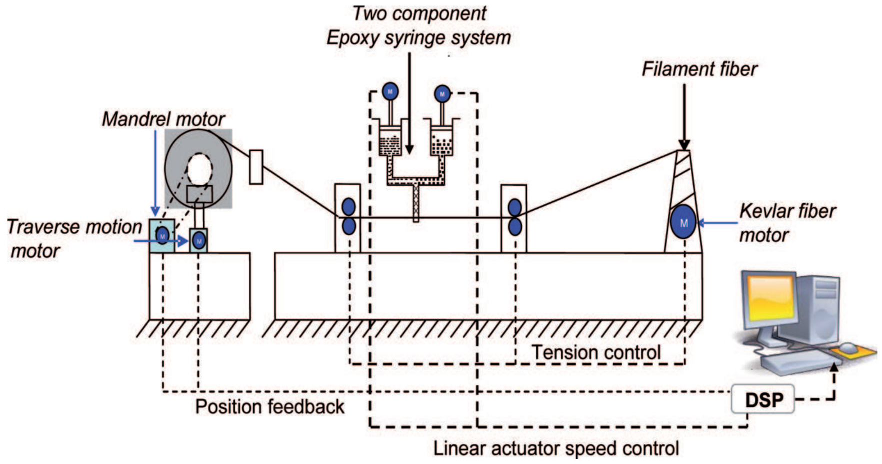


Fig. 6. Schematic of filament winding facility

4. Stress and cavitation analysis

The composite material wheel is intended to be used as axial compressor in a chiller system, and the previous studies show that the wheel can run at a high tip speed of 450m/s [8] and withstand the stresses associated with the high-speed operation. When the wheel works in a CMMCT system, its rotating speed is much lower than its application as a compressor. Considering the centrifugal and fluid forces applied on the wheel, by using Finite Element Analysis (FEA) and Computational Fluid Dynamics (CFD) method, the stress analysis was performed, and the result showed that the wheel was able to withstand the applied forces with a large safety factor. Fig. 7 shows the absolute pressure distribution on the wheel. The maximum pressure is found in the intersection of blades and shroud, where the blade imparts fluid's kinetic energy into pressure energy thus the highest absolute pressure. The stress distribution on the wheel in a CMMCT is shown in Fig. 8. It is seen that the maximum stress (0.236MPa) is much lower than the material's strength, which enables the CMMCT's high fatigue life.

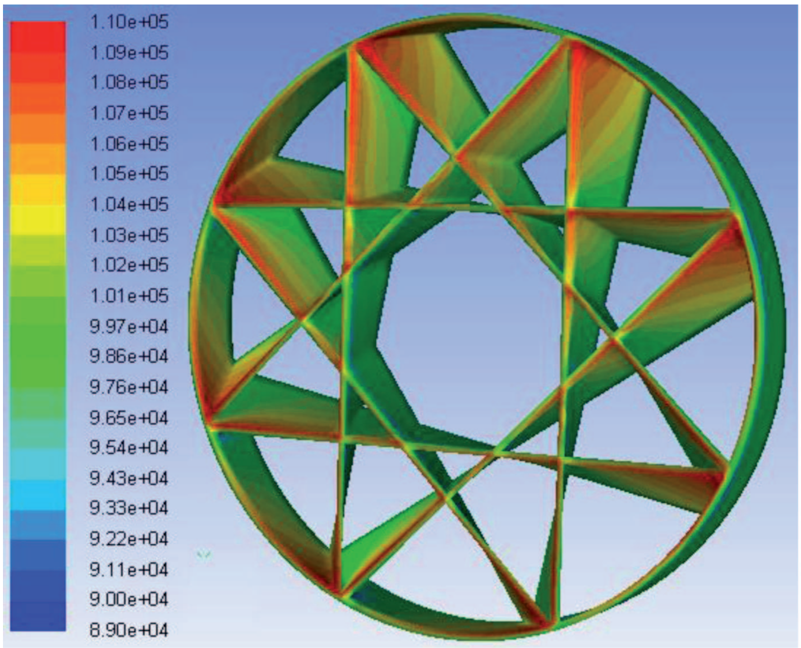


Fig. 7. Absolute pressure distribution on the wheel

Cavitation occurs when the absolute value of the local pressure coefficient on the airfoil, C_p, is greater than the cavitation number, σ_v. For this designed geometry of composite material wheel, the absolute value of pressure coefficient C_p is below 2. Marine current turbine is intended to work under the sea surface on the depth guaranteeing the minimal influence of the surface waves on the turbine operation. Assuming the minimal water depth 10 m and water flow speed 6.17 m/s, the cavitation number σ_v is

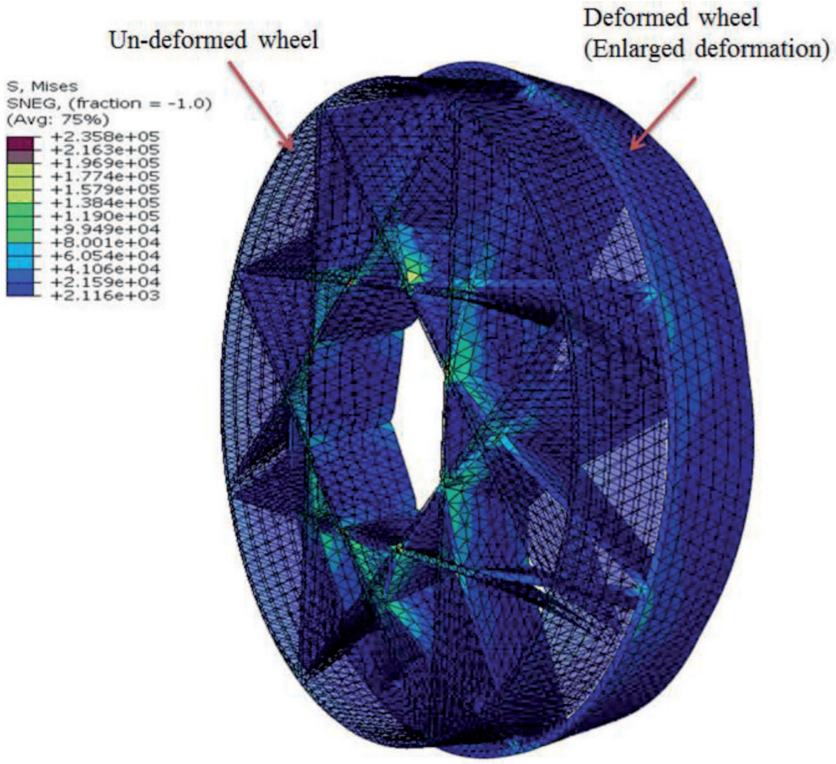


Fig. 8. Stress distribution on a composite wheel

estimated to be not lower than 4.6. Operation at such high cavitation number prevents existence of sheet cavitation and danger effects of cloud and bubble cavitation. Additionally, the external shroud protects generation of vortex cavitation characteristic to the free blades tips. During the water towing tank test at the depth of only 0.5 m no cavitation effects have been observed.

5. Power coefficient calculation

The Computational Fluid Dynamics (CFD) simulation results for the power coefficient of CMMCT in various hydrodynamic flow conditions are shown in Fig.9. Several water flow speeds were simulated based on the capability of the experimental system. This figure states that for a specific water flow speed, the coefficient increases with rotating speed until obtaining a maximum value, where further increases in rotating speed will reduce this coefficient. Therefore, the CMMCT should be working in a suitable rotating speed in order to obtain the maximum power coefficient. In addition, for a specific rotating condition, this coefficient is dependent on the water flow speed. It is observed that the maximum power coefficient is 0.2 with the inlet flow speed of 2.57m/s and the average coefficient is about 0.19.

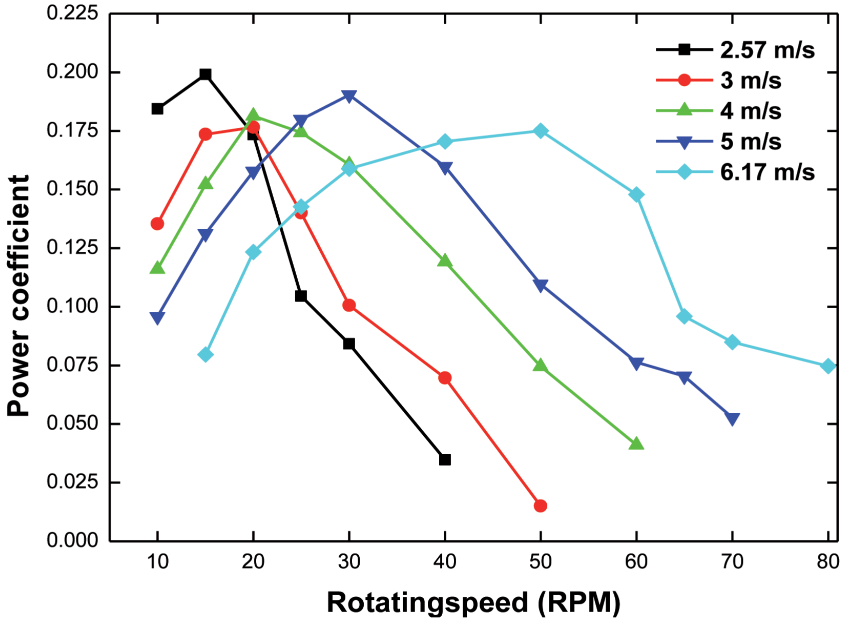


Fig. 9. Power coefficient variation with inlet flow speed and rotating speed

Compared the coefficient between CMMCT and different types of conventional water turbines in Table 2 [9], it is seen that the CMMCT is comparable to the axial current turbine with the highest power coefficient 0.2. Even though cross-flow turbines have higher coefficient, they are not self-starting in most cases and they develop strong pulsation [9]. In addition, propeller turbines with fixed blade cannot be used directly in reversible tidal flow as well as shallow water sites. On the contrary, CMMCT does not show these problems due to its specific pattern design.

Table 2.

Power coefficient of conventional turbines

Type of Turbines	Name of Turbines	Power coefficient
Propeller turbines	Tyson Turbine Garman Turbine IT-Power, Ltd,Marine Turbine	0.16 0.15- 0.18 0.20
Cross-flow turbines	Darrieus Turbine Gorlow (Helical) Turbine	0.235 0.35

The CMMCT is tested by mounting it in a moving carriage and driving it at a steady speed, as far as possible, in still water (Fig. 10). This is equivalent to mounting the turbine under a fixed pontoon in moving water, but it has the advantage that the relative velocity between the water and the turbine can be controlled. As mentioned before, the water flow speeds of 2.57m/s, 3m/s, 4m/s, 5m/s and 6.17m/s can be controlled and the extracted torque and power are measured to validate the CFD results.

Fig. 10. Test frame of CMMCT in a water towing tank

6. Conclusion

Using a filament winding method to manufacture high performance and light weight composite marine current turbine can be rapid, inexpensive, and can utilize commercially available winding machines. This novel design shows many advantages compared to traditional turbines from the aspect of fluid dynamics and structural requirement. Through the novel design, the cavitation is not observed during the test and the wheel shows a good strength property by using FEA. The CFD simulation results show that the maximum power coefficient of CMMCT is 0.2 and the average coefficient is about 0.19, which are comparable to traditional turbines. CMMCT is self-starting and can be used in revisable current flow, which is not obtained in traditional turbines. The CMMCT that has undergone testing in a water towing tank, where the water speed can be controlled to determine different extracted powers to validate the numerical turbine design, is a scaled down version of the turbines that will be used to harness tidal energy from the world's oceans. When these tidal farms are operational, little to no maintenance will be required to keep the wheels functioning properly.

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Nowatorski projekt i wstępna analiza turbiny wykorzystującej prądy morskie wykonanej z materiału kompozytowego

Streszczenie

Wysokiej wydajności wirnik wykonany z materiału będącego tkanym, lekkim kompozytem został opracowany i jest przeznaczony do stosowania do wielu celów. Jedną z tych aplikacji są turbiny wykorzystujące prądy morskie (MCT). Tradycyjnie, główne problemy wpływające na budowę i działanie MCT to problemy zmęczeniowe, związane z kawitacją i korozją w wodzie morskiej. Wyjaśniono w tym artykule dlaczego biorąc pod uwagę powyższe czynniki, wykonano rotor z materiałów kompozytowych, zwłaszcza włókna Kevlar w epoksydowej matrycy. Ten nowy sposób wykonania elementów turbin wykorzystujących prądy morskie z materiałów kompozytowych pokazuje wiele zalet w porównaniu do stosowanych w konwencjonalnych turbinach.

W artykule przedstawiono badania kilku czynników, które należy rozważyć w procesie projektowania turbin, takich jak dobór materiałów kompozytowych, sposobu tkania włókien kompozytowych wirnika oraz analizy strukturalnej turbiny i zjawisk kawitacji. Przedstawiono wartość współczynnika mocy turbiny uzyskany za pomocą CFD oraz przedstawiono krótko podstawowe informacje o stanowisku do badań doświadczalnych turbiny holowanej w basenie.