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A novel flexible foil vertical axis turbine for river, ocean, and tidal applications

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HIGHLIGHTS

- A novel flexible foil turbine with five wings was designed for hydrodynamic purposes.
- Flexible foils, pivots, and springs enabled passive pitching and limited RPM variations.
- Field tests achieved 0.37 peak power coefficient and self-starting capability above 0.5 m/s.

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ABSTRACT

Most hydrodynamic vertical axis turbine concepts use solid blades with active adjustable pitch. These turbines generally need external starting or active pitching mechanisms to overcome their limited starting performance. In this study, a simple and cost-effective vertical axis turbine with flexible foils was designed based on inspiration from hydrodynamic thrust characteristics of aquatic creatures. A full-scale turbine was tested in a controlled river environment in Norway. The turbine's high solidity, flexible foils with self-adjustable cambering, and pivot and spring arrangements on the blade and arm connections enabled the following: reduced turbine vibrations, dynamic foil adjustments, a passive blade pitch action, and limited variation in rotational speed versus incoming flow velocity. These novel aspects resulted in a high performance turbine that attained up to a 0.37 power coefficient in a confined channel and could self-start at low inflow water velocities.

1. Introduction

1.1. The advantages and limitations of Darrieus-type turbines

Development of renewable energy resources such as tidal energy is needed to achieve a carbon neutral future [1]. Renewable energy resources are essential for protecting our environment, and new innovative approaches are required to lower the cost of developing tidal energy. This study designed a novel type of vertical free flow turbine intended for ocean, river, and tidal current applications. The approach simulates natural flexible hydrodynamic thrust dynamics by introducing flexible foils and pivoting blades into a vertical Darrieus-type turbine. The concept of flopping blades with flexible foils is supported by the Knoller-Betz effect, which increases the general propulsive efficiency [2].

The straight-bladed H-Darrieus and squirrel-cage Darrieus turbines have good potential for wind and hydrodynamic applications [3,4], and are relatively simple and inexpensive to manufacture. Vertical axis designs are attractive because they respond to flow from any direction, which is important in tidal flow conditions. Their generating equipment can be placed at one end of the shaft, either above the water surface or close to the bottom. This enables the use of simple installation and retrieval techniques for bottom-fixed, floating, or near-surface mounting arrangements. Vertical axis turbines have reduced blade tip losses, and hence generally create less noise and turbulence than horizontal axis turbines, thus mitigating the impact on marine life and their habitat.

Most vertical axis turbines that are presently used for wind turbine applications, and a limited number of scale model water turbines, have inflexible and fixated blades. These turbines will generally pulsate during rotation when the blade angles change along their circular azimuth path, resulting in cyclic tangential forces that generate significant torque ripple in the output as well as high stress peaks in mechanical structural elements. This vibration can lead to early fatigue failure of the various turbine parts, unless the design minimizes such vibrations. To date, blade failures have been common in the tidal current turbine industry (reviewed

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in [5]). Designing robust turbines capable of enduring the challenging hydrodynamic environment will require, for example, optimizing turbine and blade design [5], and assessing the impact of variable current conditions within a given site on turbine performance [6,7].

Vertical axis turbines can experience cavitation at high RPM and typically have low starting torque. To overcome their limited starting performance, external electrical and/or mechanical starting mechanisms can be designed, or self-starting elements such as pitching can be introduced, although at increased cost and complexity. The tendency of the turbine to stall can be reduced by selecting (i) a higher tip speed ratio, (ii) a high blade chord Reynolds number to improve the blade stall angle, and (iii) blades inclined to the flow [8]. Fixed blade turbines often have low efficiency if the blades experience stall at <3–4 tip speed ratio [8].

There is interest in the use of flexible materials in the construction of both wind and hydrodynamic turbines. The use of 'morphing blade' concepts can potentially increase turbine efficiency, reduce turbine fatigue, and reduce operational costs compared to fixed blade concepts that require more complicated pitch and start-up strategies [9–13]. In the present study, the flexible foil hydrodynamic turbine showed high efficiency in tests within a confined channel. The design and results will be useful for optimizing future field development parameters such as intra-turbine spacing.

1.2. A novel flexible-foil turbine designed for hydrodynamic purposes

This study created a novel vertical axis turbine with flexible foils and passive spring loaded pitching between the arm and blade that reduced torque ripple during rotation and enabled self-starting. The flexible foil concept was based on inspiration from dynamic characteristics of aquatic animal bodies and fins. Fish fins and cetacean flippers deform during locomotion, creating complex lift and drag properties that enable the redistribution of hydrodynamic loading. This generates a continuous thrust that smoothens out oscillations during stroke transitions [14,15]. Man-made flexible hydrofoils and airfoils have attempted to mimic the dynamic deformation patterns of various aquatic creatures [14–17]. Structural flexibility proves beneficial in the generation of lift, often increasing propulsion efficiency and energy exchange compared to steady fluid dynamic aero- and hydrofoils. Compared to rigid or fixed foils, propulsion efficiency increases in semi-flexible flapping foils [18], and in oscillating or moving rigid [19,20] or flexible [21–24] foils. Water wheels with flexible rubber blades have also been used to improve interaction between the blade edges and the surrounding environment [25].

The flexible foil turbine in this study had (i) a simple and robust design that minimized mechanical fatigue, (ii) inexpensive manufacturing and operating costs, (iii) low weight, (iv) simple installation and maintenance methods, and (v) a relatively high efficiency. The final turbine design incorporated five wings to improve rotational consistency. The turbine's on site performance in a controlled river channel showed autonomous self-starting capacity at low water speeds, high efficiency, and reduced torque vibration resulting in good mechanical fatigue characteristics. Previous studies performed on three-winged 1.5 m or full-scale models demonstrated that the introduction of blade pivoting springs and a five-winged design significantly improved the rotational torque variations (data not shown).

2. Materials and methods

2.1. Overall turbine design

The turbine design focused on simple function and self-regulation without active pitch control, which generally require complex control/mechanical systems. The turbine (9 m diameter) had five wings (5 m tall) composed of three horizontal sets of arms connecting the central main shaft (7 m tall) to the five sets of blades (Fig. 1A and B). The turbine was anchored to the river bottom with solid crossbeams bolted onto a concrete foundation, with a bearing assembly connecting the main axis to the bottom support frame. A special protective box with several integrated oil lock chambers and leap seals was used to ensure that the main thrust bearing, located at the interface to the bottom structure, was submerged in raps oil. The top of the turbine was further supported with four pre-tensioned support rods (top bearing rods) to prevent high bending moment into the foundation, and six arm support rods connecting the shaft to each arm. A bridge construction crossed the channel and (i) provided an integrated torque reaction point for the efficiency-measuring hydraulic motor, as well as (ii) routed all hydraulic hoses and signal wires to the hydraulic choke assembly station used for the efficiency measurements. All turbine

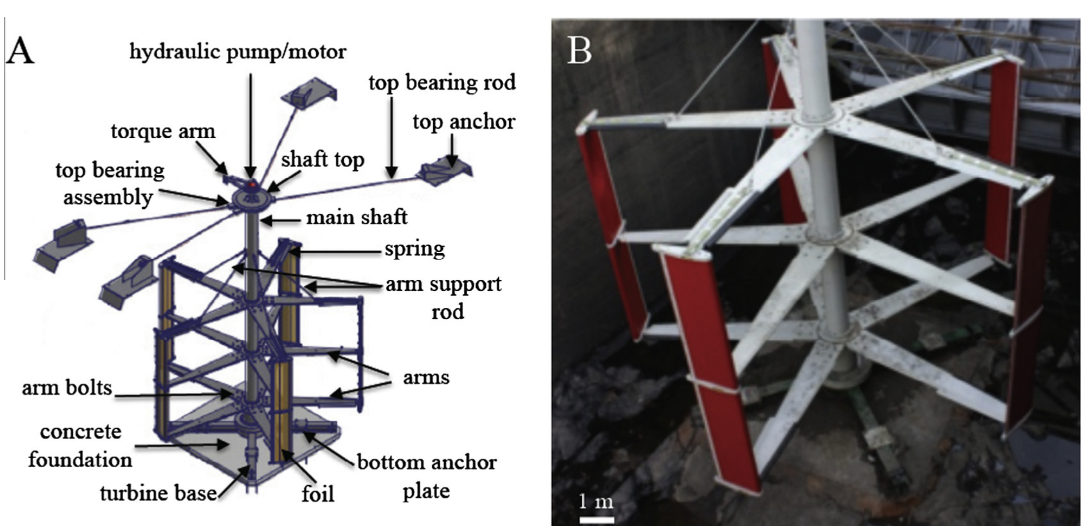

Fig. 1. Flexible foil turbine design. (A) A schematic showing the main design components of the flexible foil turbine. (B) The installed turbine as the water was released into the Glomma River channel at the Sarpefossen power station.