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Fault analysis of a marine current vertical-axis turbine missing two blades

Minh Thao Nguyen, Johan Forslund, Karin Thomas, and Anders Goude

Abstract—**Analysis of a vertical-axis turbine operating with two blades missing was conducted to the rotational speed and blade normal forces. A comparison between the missing-bladed turbine and the initial five-bladed turbine during free-spin mode is presented in this paper. Experimental data of the fault turbine indicated, surprisingly, that the turbine average rotational speed was similar to that of the five-bladed turbine but the variance of rotational speed was significantly increased especially in high flow speeds. In addition, the maximum force on a single blade of the fault turbine seen by numerical simulations was 77% higher than that from the normal turbine operation. The main goal of the study is to present the effect of the losing two out of five blades on a vertical-axis turbine for marine current application.**

Keywords— **Blade forces, fault analysis, marine current turbine, vertical-axis turbine.**

I. Introduction

MARINE currents are renewable and predictable which makes it a promising resource for harvesting energy[1]. The operational principle of a marine current turbine is similar to that of a wind turbine. In wind, most turbines are horizontal-axis ones, mainly due to their higher efficiency, but in this application the use of vertical-axis turbines and their omnidirectional ability are attractive [2]. Additionally, the electrical generator of the vertical-axis turbine system can be placed at bottom of river or sea that has lower costs compared to the horizontal-axis turbine with the generator at the top of the tower. Despite their advantages, cross-flow hydrokinetic turbines have not received as much attention as horizontal-axis turbines. Certain drawback persists: most importantly the constantly changing angle of attack gives fatigue loads on the blades.

Research has been conducted on vertical-axis marine current turbines but most experimental tests have been performed in laboratories, so not the turbine interaction in natural water flows [3]. Therefore, there is a significant uncertainty in determining the turbine characteristics during operation due to the very complex flow structures and high cost to build the completed turbine system in a natural water channel. In addition, to the authors' knowledge, there is not much published on fault analysis of five-bladed vertical-axis turbines for marine current applications.

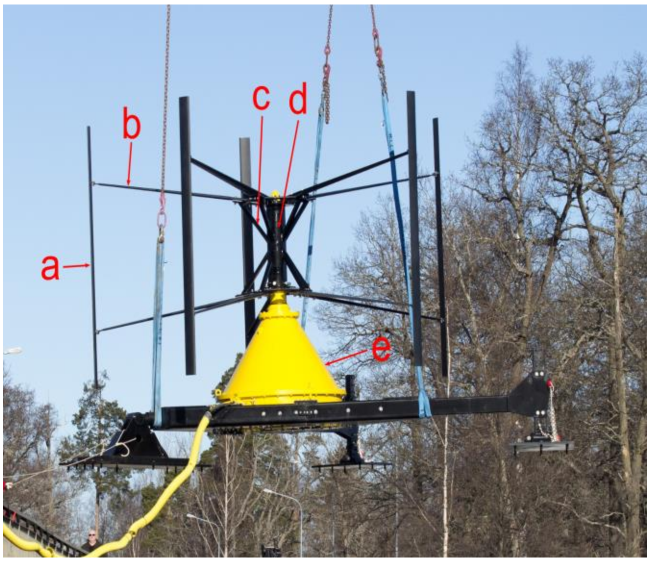

Fig. 1. Overview of a five-bladed vertical-axis turbine deployed in the river in 2013 [Uppsala university, marine current group].

The marine current energy research group at Uppsala University has developed a five-bladed fixed-pitch vertical-axis turbine system [4]. In 2013, the first prototype of the turbine, as seen in Fig. 1, with a rated power of 7.5 kW, was deployed in the river Dal in Söderfors, a distance of 70 km north of Uppsala, Sweden [5]. Two years after the deployment, two blades were detached during the start-up sequence in unusually high flow speeds. The fault turbine has geometry as seen in Fig. 2.

The aim of this study was to evaluate the operation of the turbine after the loss of the two blades by comparing it

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M. T. Nguyen , J. Forslund, K. Thomas , A. Goude are with the Department of Engineering Sciences, Uppsala University, 75121 Uppsala, Sweden.

(E-mail: minh-thao.nguyen@angstrom.uu.se, johan.forslund@angstrom.uu.se, karin.thomas@angstrom.uu.se, anders.goude@angstrom.uu.se)

to the five-bladed turbine in free-spin operation (running without load). Results obtained from two water speeds were analysed in order to analyse the turbine angular speed and to estimate the force on the blades.

II. Methods

A. *Experimental research location*

The marine current station is located in the river Dal in Söderfors, where the water always flows only in one direction. River water speeds are in the interval of 0.4 - 1.5 m/s. The experimental site is located about 800 m downstream of a conventional hydro power plant that discharges water into the river to keep the flow constant.

B. *Experimental system*

The geometry information of the turbine connected to the permanent magnet generator can be seen Table I.

The experimental system comprises the vertical-axis turbine, a permanent magnet synchronous generator and an electrical control and measurement system. For the turbine, the symmetrical NACA 0021 turbine blade profile was chosen due to the availability of the measurement data. Therefore, the processes of theoretical predictions can be made faster and easier. The blades (a) as seen in Fig. 1 have a fixed pitching angle. The blades are installed with a 72° angle between them. Each blade is connected to the shaft (d) using two struts (b) and two connectors (c). In the broken turbine, two blades detached but the struts and connectors still remained, as seen in Fig. 2b. In total, there are ten connectors connected to ten struts. The shaft in the centre of the turbine is directly fixed to the generator (e).

Hall Effect sensors were mounted inside the generator in order to measure the turbine rotational speed. An Acoustic Doppler Current Profiler (ADCP) is installed upstream of the turbine at approximately two turbine diameters from the turbine, used for measuring water instantaneous speed.

C. *Free-spin sequence of marine current turbine system*

Free-spin mode is described as follows:

1. The turbine in stand-still condition was started by running the permanent generator synchronous as motor. In this stage, the required energy for start-up was supplied by the utility grid through the power converter.
2. As the rotational speed of the turbine increases, the power absorption of the turbine also increases until the turbine can establish a self-sustained operation. Then, at this stage the turbine has been started working in the free-spin mode.

No power was transmitted to loads externally connected at during free-spin operation. The rotational speed of the turbine was only controlled by the water flow. The forces on the blades during the free-spin operation is described in [6] for the five-bladed turbine. In section III, the broken turbine will be analyzed in terms of the turbine rotational speed and estimated the force on the blades during free-spin mode.

TABLE I
VERTICAL-AXIS TURBINE SYSTEM

Quantity	Unit
Turbine	
Number of blades	3
Blade profile	NACA0021
Chord length	0.18 m
Pitch angle	0°
Blade height	3.5 m
Turbine diameter	6.0
Generator	
Number of poles	112
Stator phase resistance	0.335 Ω
Armature inductance	1.5 mH

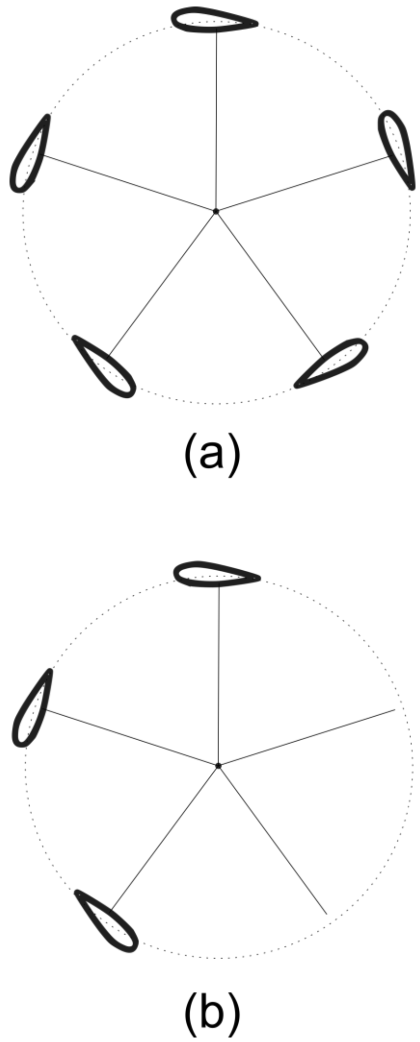

Fig. 2. Vertical projection of two turbines: (a) the fully operational turbine, (b) the turbine with two blades detached.

D. *Numerical simulations*

A two-dimensional vortex method model was performed used in this work. The method is a vortex particle method, where one vortex is released from each blade at each time-step. The flow velocities can be reconstructed from the vortices by solving Biot-Savat's law. The blade forces are calculated through a parameter based force model, which uses the calculated flow velocity at the blade position as input. This parameter model is based on measured force coefficients for the selected airfoil, combined with a dynamic stall model. The detailed method is described at reference [7, 8]. As the vortex method used is two-dimensional, support arms and tip vortex effects cannot be resolved by the model. This approximation is motivated by the large aspect ratio of the individual blades. The accuracy of the force predictions have been validated in [8]. The model calculates the rotational speed of the turbine from the turbine torque and the inertia. To compensate for the missing drag terms from support arms, attachments etc., the model adds an additional braking torque on the form

$$T = C\Omega^2 + K \tag{1}$$

where the constant C represents the drag terms, which are assumed to be proportional to the square of the blade speed, and a constant term, representing iron core losses in the generator, bearing losses and losses in the seals. The constant K is set to 350 Nm from measurements on shore, and the constant C is calibrated to 1100 Nms²/rad². This calibration was done for the original five-bladed turbine at 1.35 m/s, and the condition was that the free-spin rotational velocity should match. As all support arms are attached in both cases, the same constant is used for the fault turbine as well. The model has the estimated moment of inertia 3000 kgm². Those parameters is found in the Refs. [9]. The model has shown good agreement in predicting the variations in rotational speed for the original turbine during start-up sequences in Ref. [6].

All simulations used a time-step of 0.01 and simulated a total time of 120 s in order to reach convergence, which was checked upon comparison of the angular speeds between two subsequent revolutions.

III. Results and Discussion

Two experiments were carried out to investigate the operation of the fault turbine during free-spin operation. For the experiments, the upstream water speed was 1.34 m/s and 1.47 m/s, and the turbine was let to operate for 30 minutes of free-spin operation. The lower water speed is close to the rated speed for the turbine, 1.35 m/s.

The measured water speed for the first experiment can be seen in Fig. 3. The measured rotational speeds for both turbines in the two water flows can be seen in Figures 4 and 5. The calculated average rotational speed and variance are listed in Tables II and III.

All measurements were conducted during non-running load conditions in which the rotor was subjected to inertia and bearing friction.

E. *Experimental results*

By analysing the operation between the fault turbine and the five-bladed turbine one can see effect of the number and position of blade on the vertical-axis turbine.

Figure 4 shows 50 s of rotational speed of the three-bladed and the five-bladed turbine during 30 minutes of operation in free-spin at 1.34 m/s. From Table II, the variance of the fault turbine velocity is 3 times higher than that of the five-bladed turbine. On the other hand, the broken turbines average angular speed of 1.85 rad/s is only 7% lower compared to the five-bladed turbine, see Table III.

Experimental data at 1.47 m/s demonstrate that the velocity variance of three-bladed turbine is 6 times higher than that of the five-bladed one (see Table II).

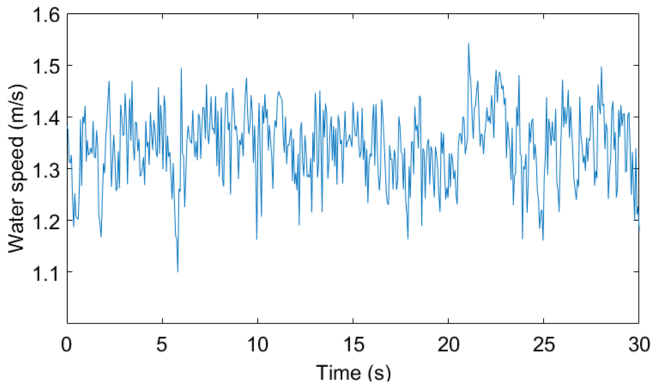

Fig. 3. Measured water velocity at 1.34 m/s average speed.

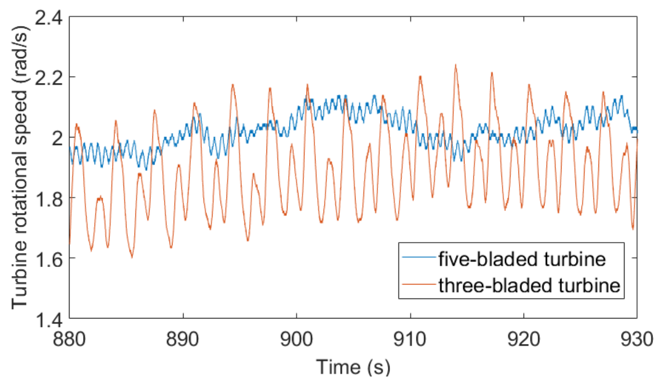

Fig. 4. Measured rotational speed at water speed 1.34 m/s.

TABLE II
VARIANCE OF ANGULAR VELOCITY DURING 30 MINUTES

Water speed (m/s)	Three-bladed turbine (rad²/s²)	Five-bladed turbine (rad²/s²)
1.34	$2.48 \cdot 10^{-2}$	$0.77 \cdot 10^{-2}$
1.47	$2.69 \cdot 10^{-2}$	$0.45 \cdot 10^{-2}$

TABLE III
AVERAGE OF ANGULAR VELOCITY DURING 30 MINUTES

Water speed (m/s)	Three-bladed turbine (rad/s)	Five-bladed turbine (rad/s)
1.34	1.85	1.98
1.47	2.07	2.10

The average speed produced by the three-bladed turbine is only approximately 1.4% lower compared to the five-bladed turbine (see Table III). In general, comparing to the five-bladed turbine, the three-bladed turbine has small difference in term of the average of the turbine rotational speed but its variance is much higher.

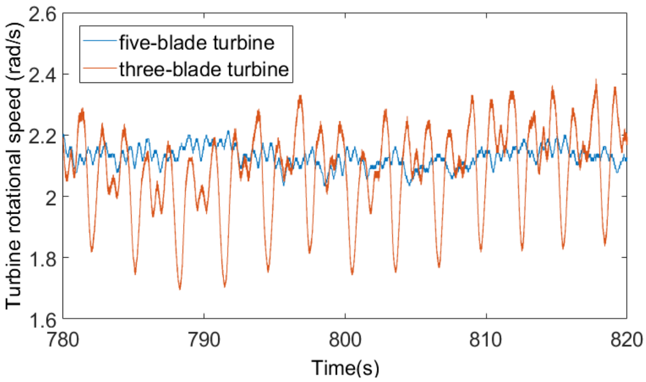

Fig. 5. Measured rotational speed at water speed 1.47 m/s.

F. *Numerical results*

The simulation was compared to the instantaneous angular speed data of the turbine obtained from experiment at 1.34 m/s, plotted in Fig. 6. Good agreement is noticeable in speed trend in upstream and downstream of the functioning curve of the turbine. In particular, the rotational speed average in the numerical model is 2.09 m/s while that found in the experiment is 1.85 m/s, which is 12.97 % lower.

The simulated normal force of the two turbines is presented in Fig. 7. Based on the findings from the numerical data, it is noticeable that the arrangement of blade positions and the blade number can notably affect the normal force. The data revealed the three-bladed turbine has unequal forces among blades. In particular, the three-bladed turbine has experienced approximately 26.58 % higher in upstream and 77.68 % higher in downstream in term of the maximum normal force on a single blade compared to the five-bladed turbine, see Table IV.

TABLE IV
MAXIMUM NORMAL FORCE ON SINGLE BLADE

Position	Three-bladed turbine (N)	Five-bladed turbine (N)
Upstream	13380	10570
Downstream	7365	4145

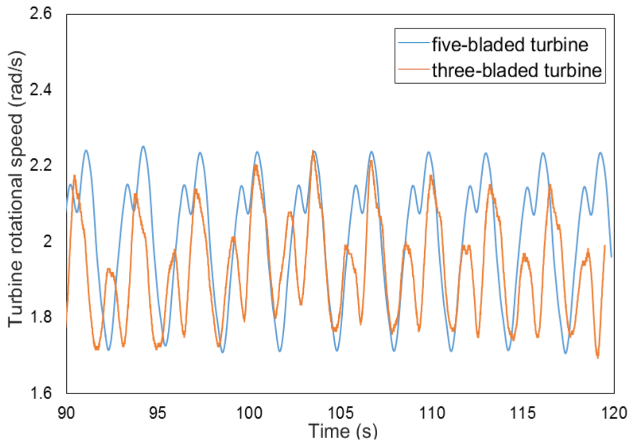

Fig. 6. Comparison between simulated and measured rotational speed of the broken turbine at 1.34 m/s.

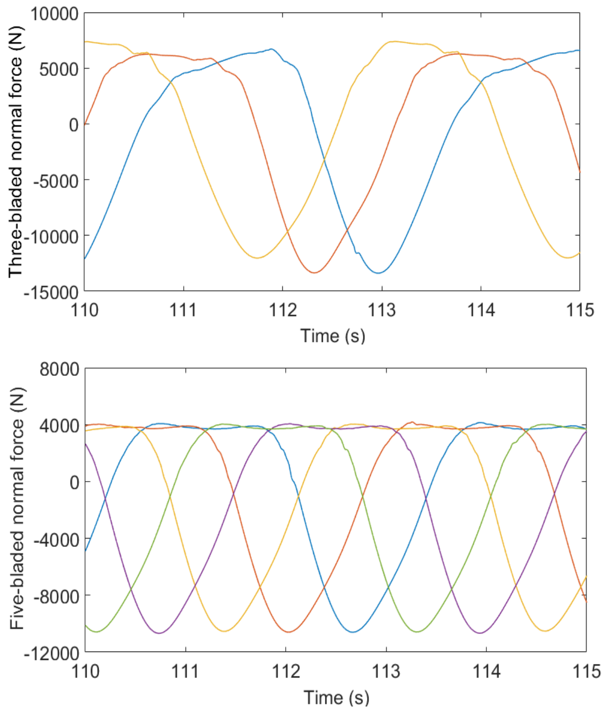

Fig. 7. Simulated normal force on the blades of the three-bladed turbine and five-bladed turbine at water speed 1.34 m/s.

IV. CONCLUSIONS

In the presented study, the investigation of the characteristics of the five-bladed vertical-axis turbine before and after the loss of two blades during free-spin operation was conducted. The key point was that the turbine velocity and normal force of the broken turbine were compared to those of the five-bladed turbine in the same manner.

The study demonstrated the effect of the number of blades and asymmetric arrangement on the dynamic behaviour of the marine current turbine. When two blades detached, resulting in an asymmetrical turbine, the angular speed of the three-bladed turbine was less than

7 % lower than that of the five-bladed turbine, while the variance was much higher than the five-bladed turbine.

The experimental results were as input to a simulation model to estimate the normal forces on the blades. The asymmetric turbine was subjected to significantly higher forces (77 %) on each blade as a result of the asymmetric geometry.

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