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A Novel Blade-Pitching Mechanism Design and Testing for Micro Vertical-Axis Water Turbines

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Abstract- This paper deals with improving the power output of a vertical-axis water turbine by controlling blade pitch-angle. During turbine rotation, the angle-of-attack of the blades varies at each azimuthal location due to constantly changing relative velocity. In the case of the H-rotor vertical-axis water turbines, the output torque is lift-dependent. The constantly changing angle-of-attack results in sub-optimal lift generation. Hence, the output torque (or the turbine power output) is compromised. This script introduces a novel design for controlling the turbine blade pitch-angle. The new design increases the overall lift-force produced by each blade during each azimuthal rotation cycle. The design incorporates a novel sun-planetary gear mechanism to control the blade pitch-angle continuously, to maintain a constant pre-set angle, with the incoming flow velocity. This improves the blade angle-of-attack by limiting angle variation to $\pm 90^{o}$ from the $\pm 180^{o}$ variation experienced by fixed blade turbines, during its rotation cycle. This results in better lift generation. The experimental results show that the proposed design substantially increases the amount of flow kinetic-energy harvested by the turbine, providing up to a 38.5% increase in turbine power output.

Keywords- Vertical-Axis Water Turbine, Blade Pitch-Angle Control, Turbine power output.

I. Introduction

Water turbines have been used for deriving energy from water for centuries. Turbines with varying designs have been used to convert the water kinetic/potential energy into mechanical energy. Water turbines are rotary machines that convert the kinetic or potential energy of water into mechanical energy. Water flowing over the blades, creates hydrodynamic forces on the blades, causing water's energy to be transformed into mechanical torque [1-4]. The energy, both kinetic and potential, of flowing water, has been harnessed for over a century to produce electricity [5]. The earliest use of hydel-energy was during the Han Dynasty around the year 200 BC [6]. One of the main uses of water energy by the Chinese at that time was for paper-making. The use of hydropower later proved to be one of the catalysts for the first Industrial Revolution in England during the latter half of the eighteenth century. In the 19th century, French engineer Benoit Fourneyron and British engineer James Francis and the American inventor Lester Allan Pelton developed the first of the modern water turbines – the Fourneyron, the Francis and the Pelton turbines. Even today, the Pelton and Francis turbines remain at the forefront of turbine designs. In the early 20th century, Kaplan turbine was developed by the Austrian professor Viktor Kaplan, this was one of the first turbines with adjustable blades [5-6]. During most of the 20^{th} century, the USA and Canada remained the leaders in hydropower generation, however, in the current century, Brazil and China have taken the lead in hydropower generation. Throughout the last two centuries, Energy harvesting from hydel and wind sources has been studied widely. However, in the last few decades, global warming has become a looming threat, thus research in the new and improved design of both horizontal-axis water/wind turbines (HAWT) and the more recently, vertical-axis water/wind turbines (VAWT) has been at its peak. This effort especially, in the area of VAWT has resulted in designs with efficiencies as high as 35% or greater [7]. Several research efforts have explored various designs of HAWT and VAWT for achieving better energy harvesting efficiency [8-17]. However, complex passive mechanical or active-control designs, induce complexities which result in reduced mechanical efficiency. Here, it needs to be pointed out that a turbines mechanical efficiency and its energy harvesting efficiency are two entirely different concepts and should, therefore, not be considered as the same from the design perspective. Therefore, designs using a simple mechanical control mechanism can prove to be more beneficial. The use of passive and semi-active blade pitch-control for VAWT using numerical studies has shown improvement in energy harvesting efficiencies [18-31] proving that the use of

simple mechanical blade pitch-control and flow control designs can be beneficial. Oscillating and flapping airfoil and hydrofoils have also been used as variable-pitch blades in VAWT [32-41].
This script deals with improving the power output of a vertical-axis water turbine through controlling blade pitch-angle. During turbine rotation, the angle-of-attack of the blades varies at each azimuthal location due to two reasons. Firstly as the blade rotates, the blade pitch-angle with the incoming flow constantly varies, as the blade maintains a tangential orientation to the turbine circumference. Secondly, the direction of the relative water velocity constantly changes due to the interaction of the incoming water velocity V_∞ and the blade tangential velocity $V_t = \omega r$. This causes the blade angle-of-attack to constantly change. In the case of the H-rotor vertical-axis water turbines, the output torque is lift-dependent, and the constantly changing angle-of-attack results in sub-optimal lift generation, hence, the output torque (or the turbine power output) is compromised. This script introduces a novel design for the turbine by controlling the individual blade pitch-angle during the rotation cycle, hence increasing the overall lift-force produced by each blade throughout the complete azimuthal rotation. The design is based on a passive blade pitch-control strategy using a sun-planetary gear mechanism application, to maintain a constant pre-set individual blade pitch-angle with the incoming water velocity. The mechanism is explained in detail below.

II. Methodology

To extract energy from water and to generate electric power, water turbines can be broadly categorized as Horizontal axis, Vertical axis, and Crossflow turbines based on Axis of rotation [2]. The most common VAWT design used due to its simplicity is the Darrieus type turbine. The main difference between Vertical-axis and Horizontal-axis turbines is due to the component of the aerodynamic/ hydrodynamic force used for generating the driving torque. In the case of drag-driven HAWT, under ideal conditions, the torque produced by any of the blades is independent of the blade azimuthal position. On the other hand, the energy harvesting by an H-type rotor is entirely different and much more complex. In the case of VAWT, the flow experienced by each blade varies drastically, with the blade azimuthal position. Whereas the HAWT derive their power from the drag force acting on the turbine blades, the VAWT derive their power from the Lift force generated on the turbine blades. Though the physical construction of VAWT is quite simple, its operation, on the other hand, is very complex due to the constantly changing flow conditions, the turbine blades face at each new azimuthal position. The hydrodynamic force is created because the velocity of the water on two sides of the blade is not equal and hence, there exists a pressure difference between the two sides of the blade [30].
The main purpose of this script is to increase the lift force which, in turn, increases the torque generated by the turbine and hence the RPM at which the turbine will be rotating. The lift force is given by the formula:

$$L = \frac{1}{2}\rho_w V_R{}^2 S(\alpha C_{l\alpha}) \ldots\ldots\ldots\ldots\ldots \text{(Eq: 1)}$$

$$D = \frac{1}{2}\rho_w V_R{}^2 S(\alpha C_{d\alpha}) \ldots\ldots\ldots\ldots\ldots \text{(Eq: 2)}$$

where

L = Lift force

$C_{l\alpha}$ = Lift curve Slope

$C_{d\alpha}$ = Drag curve Slope

α = Blade angle-of-attack

V_R = Relative velocity of incoming water

ρ_w = Density of water

The design of a Darrieus rotor depends upon many geometric parameters, which include; the number of blades, rotor height, rotor radius, blade airfoil, and blade pitch angle. For this experimental paper, a 3-bladed H-type rotor design for a VAWT was selected, with radius r = 0.1524 m, height h = 0.3048 m using Standard NACA 0021 airfoil with 0o pitch angle.

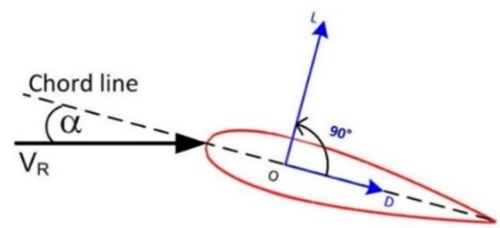

Fig. 1. Depiction of angle-of-attack and hydrodynamic forces

From Fig. 1 it can be seen that the magnitude of the relative velocity and its angle with the airfoil chord is defined as the angle-of-attack (α). The coefficient of lift, C_l is a dimensionless number which mainly depends on the angle-of-attack. Increasing the value of C_l increases the amount of lift generated. As C_l is highly dependent on α; it is obvious that maintaining a reasonable α throughout the turbine rotation is an important factor in achieving better energy harvesting efficiency of the turbine.

Fig 2 below depicts the standard behavior of C_l - α curve.

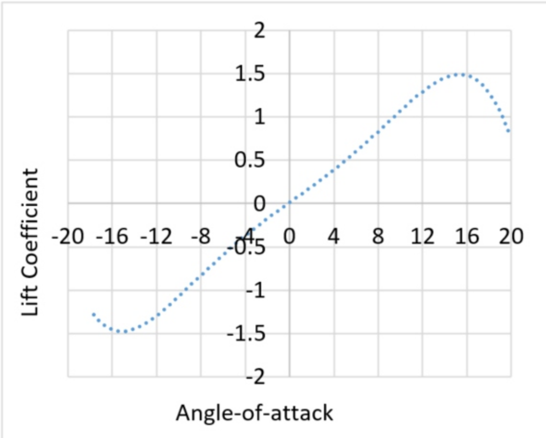

Fig. 2. Alpha VS lift coefficient standard behavior for symmetric NACA airfoils

It can be seen from Fig. 2, that optimum values of C_l are achieved as α approaches α_{max}, which for most standard hydrofoil this is between 12°-16°. If the angle of attack increases above α_{max} the value of C_l starts to decrease rapidly as the hydrofoil experiences stall. Therefore, it is of utmost importance for achieving efficient VAWT performance, that the blade angle-of-attack remains within a range where the value of C_l remains close to its maximum. However, as α changes constantly at each azimuthal position, as depicted below in Fig 3, it becomes complicated to maintain the required C_l value.

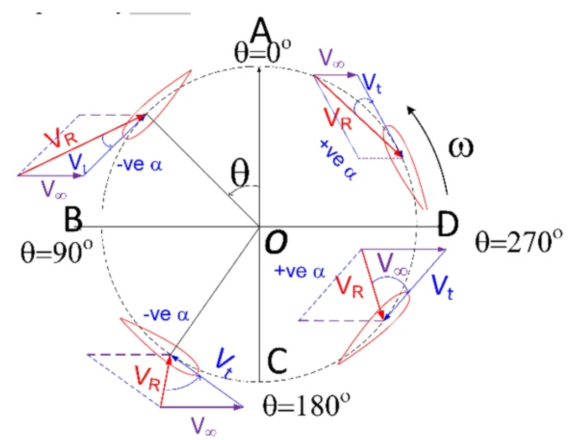

Fig. 3. Blade velocity profiles at different azimuthal angles for a turbine with fixed blades

The incoming flow is considered perpendicular to the turbine vertical-axis moving left to right in Fig. 3 above. The azimuthal (turbine rotation) angle θ at point A is θ = 0°, at point B azimuthal angle is θ = 90°, at point C, θ=180°, and at point D, θ=270°. The blade pitch angle at point A is taken as ψ. The relative velocity of water and the blade $\overrightarrow{V_R}$ is constantly varying at each azimuthal point due to the constant change in the direction of the tangential velocity, $V_t = \omega r$.

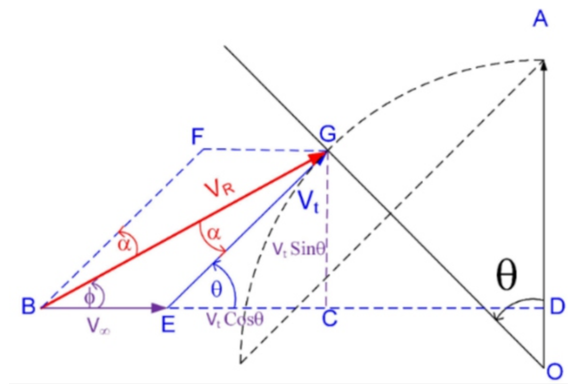

Fig. 4. Velocity vectors and angles for H-rotor VAWT.

It is clear from Fig. 4 that the velocity profile faced by the turbine blades continuously changes at each azimuthal angle. While, from the greater details in Fig 4 it can be seen that, though, the process of calculating the magnitude and direction of the relative velocity at each point is complex, it can be formulated as a function of the azimuthal angle θ.

The relative velocity:

$$\overrightarrow{V_R} = \overrightarrow{V_\infty} + \overrightarrow{V_t} \qquad \text{.....................(Eq: 3)}$$

The magnitude of

$$\overrightarrow{V_R}:\ |V_R| = \sqrt{V_\infty{}^2 + V_t{}^2 + 2V_\infty V_t Cos\theta} \quad \text{..(Eq: 4)}$$

The direction of the relative velocity $\overrightarrow{V_R}$ is given by the equation:

$$\alpha = tan^{-1}\left(\frac{V_t Sin\theta}{V_\infty + V_t Cos\theta}\right) \text{................(Eq: 5)}$$

The blade Tip Speed Ratio (TSR) is defined as:

$$\lambda = \frac{\omega r}{V_\infty} = \frac{V_t}{V_\infty}$$

Thus angle-of-attack can be written as:

$$\alpha = tan^{-1}\left(\frac{sin\theta}{1/\lambda + cos\theta}\right) \text{...............(Eq: 6)}$$

III. EXPERIMENTAL WORK

The turbine design is first modeled on CAD software and as the current model is a Lab-model designed only for limited testing, detailed structural analysis is not performed. The CAD model of the designed turbine is shown in Fig. 5 and

Fig. 6 below, showing the gear mechanism construction.

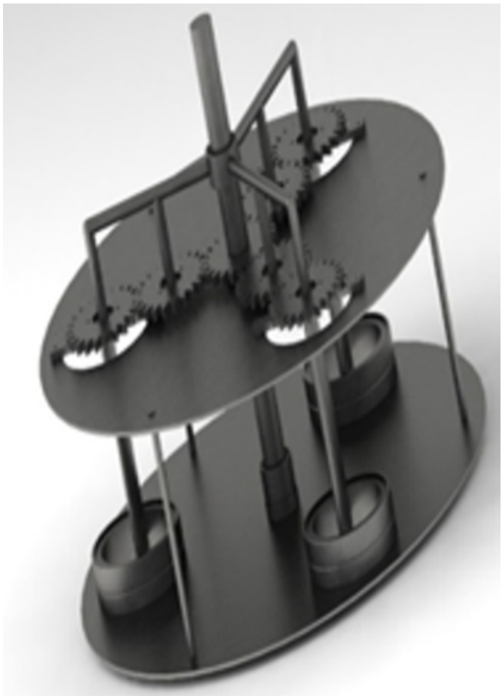

Fig. 5. Turbine solid model.

A complete shemetic diagram of the exoerimental setup is depicted in Fig. 6.

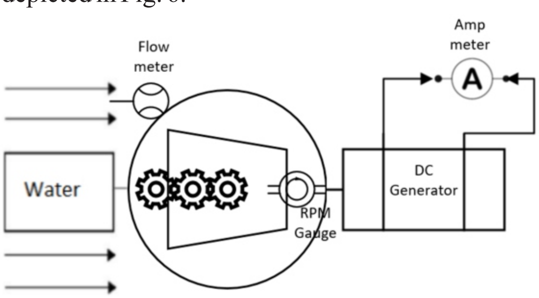

Fig. 6. The corresponding gears and blade configuration schematic diagram

A detailed view of the gear mechanism is shown in Fig.7 below.

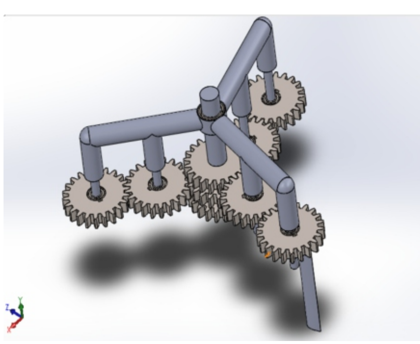

Fig. 7. The gear configuration CAD diagram.

To carry out experimental testing the designed turbine (Fig. 8) was manufactured and various sensors were integrated into the turbine to measure required parameters like RPM, the incoming flow velocity, voltage and electric power output of the 12V 6W Bicycle Friction Generator Dynamo attached to the turbine.

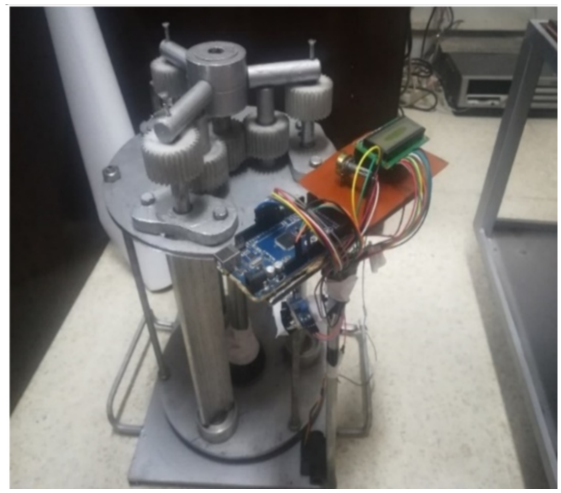

Fig. 8. Complete experimental lab model of the turbine, with externally driven gears disconnected to simulate fixed blades case.

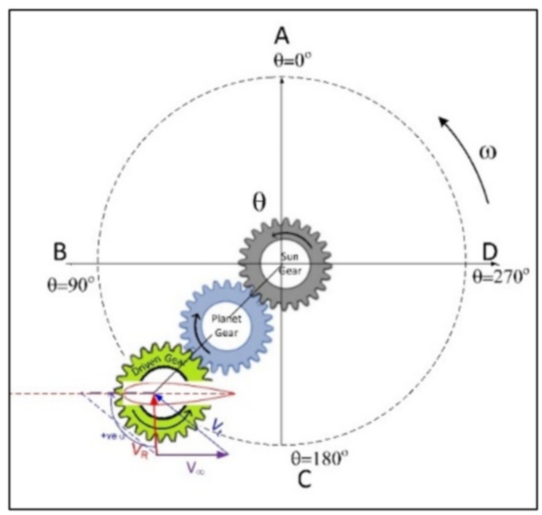

Fig. 9. The corresponding gears and blade configuration schematic diagram.

Complete experimental lab model of the turbine – with externally driven gears connected.

The turbine was equipped with a disengagement mechanism for the gears. The gear mechanism in disengaged status is shown in Fig. 8. In this situation, the turbine blades became fixed and no pitching occurs. However, when the gear mechanism was engaged (Fig.8), the blades start to pitch with the turbine rotation

and maintained a constant pitch angle with the free stream velocity V_∞ as shown in Fig 9.
The manufactured turbine was tested in a water stream with the blades fixed as well as blades pitching with the help of the gear mechanism as shown in Fig. 10 below.

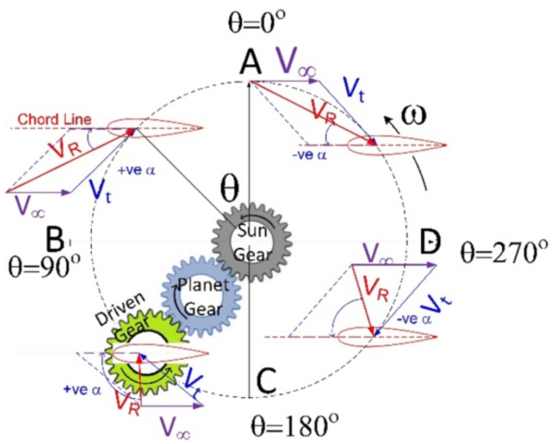

Fig. 10. Blades pitching with the help of the gear mechanism

IV. Results and Discussion

From previous analysis, it is evident that the variation of angle-of-attack along azimuthal location is not very smooth and a jump occurs at $\theta=180^{o}$ inversing the values of α from negative to positive values. It is also seen that the value of α goes well beyond α_{max} and the blade undergoes stall conditions. To avoid this problem, a sun-planet gear mechanism is designed so that the pitch angle of each blade can be kept constant with respect to the incoming water velocity. The gear mechanism is shown in detail below. As the turbine rotates, the gears rotate each blade about its axis of rotation (at 1/4th of the chord length from the blade leading ledge). This ensures that the blades keep pointing towards the incoming water stream throughout the rotation cycle, as depicted in Fig. 11 below.

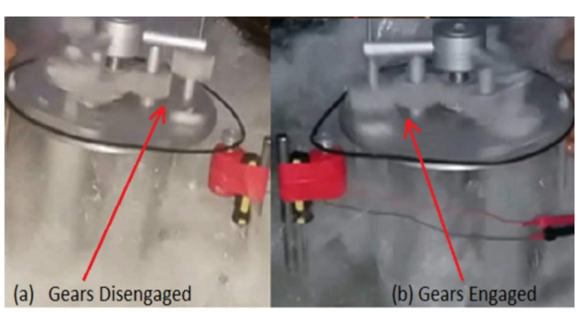

Fig. 11. Pitching blades with Sun-planet gear mechanism

The designed turbine has a radius of 0.1524 m. Calculations are, therefore, conducted for the fixed blade turbine experimental conditions corresponding to $\lambda=0.433$. The variation of relative velocity and α, for these conditions for a fixed blade VAWT along the azimuthal positions is shown in Fig. 12 below.
For the pitching blades case, the variation of relative velocity V_R and α, for the experimental conditions i.e. $\lambda=0.93$, along the azimuthal positions are calculated and given in Fig. 13.
From Fig 13 it can be seen that the relative velocity is increased to 2.5 m/s from the fixed blade case of 1.6 m/s. The increase in relative velocity is due to the higher turbine rotation speed. In the case of the angle-of-attack, its variation is reduced substantially from the maximum value of $\pm180^{o}$ for the case of the fixed blade turbine to a maximum value of $\pm90^{o}$ for the pitching blades case. This results in the blades remaining in unstalled condition for a much large part of the turbine rotation. Thus producing a much larger cumulative lift and hence a substantially increased turbine torque.
The measurements were repeated 3-5 times during the experimental work and average values were taken. With the given resources available higher accuracies could not be achieved. For higher accuracies which meet international standards [42], a proper water tunnel would be required. However, as this study deals with proof of concept of the novel design and does not deal with quantitative analysis, the current accuracy is considered appropriate.

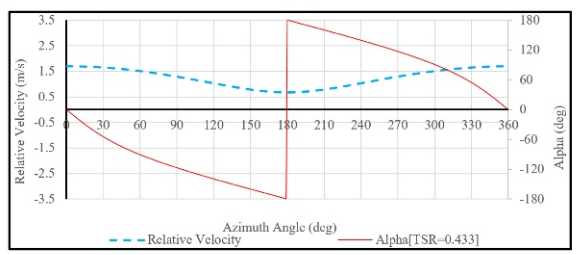

Fig. 12. Alpha and Relative Velocity Variation with Azimuthal Angle for fixed blade case, $\lambda=0.433$

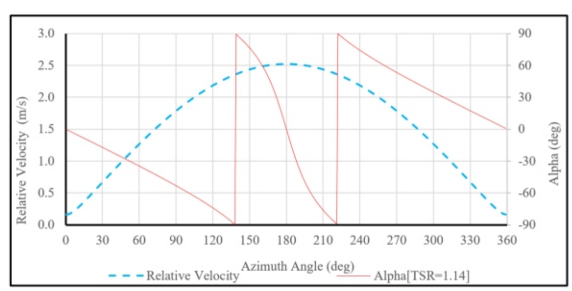

Fig. 13. Alpha and Relative Velocity Variation with Azimuthal Angle for pitching blade case, $\lambda=0.93$

The data gathered experimentally is given in Table 1 below.

Table 1: Experimental Results

Blades Config	V_∞ (m/s)	Turbine RPM	Avg Voltage (V)	Max voltage (V)	TSR	Turbine Electric Power (W)	% Increase in Power output
Fixed blades	1.18	32	5.8	7.9	0.35	1.6	-
Pitching blades	1.18	84	12.7	13.8	0.93	2.6	38.5%

V. CONCLUSION

A quick experimental verification has been carried out to ascertain the efficacy of the novel vertical-axis-water-turbine design with the blade-pitch angle controlled through the use of a sun-gear mechanism. Due to current resource constraints, an expensive and highly accurate experimental setup could not be made. The testing was carried out in a natural water stream. The testing could only be carried out under one condition (the available water velocity) of 1.18 m/s. However, the lab-model of the designed turbine, along with a crude measurement setup, was still able to provide a proof-of-concept, showing that major improvement in the power output (≈38.5%) of the micro-VAWT was achieved using this novel design. Currently, authors are trying to obtain the required funds for forming an accurate experimental setup. Work is also in progress for carrying out numerical simulations to achieve a better understanding of the underlying physical phenomenon and duplication of experimental results.

The angle-of-attack calculations showed that the use of the proposed gear mechanism allows passive pitching of the turbine blades results in reducing the angle-of-attack variation considerably, at low TSR regimes. The maximum angle-of-attack variation is also constrained from a maximum value of $\pm 180^{o}$ for the fixed blade turbine to a value of $\pm 90^{o}$ for the turbine with pitching blades, allowing the blades to operate in the unstalled regime for most of the turbine rotation cycle.

Though the experimental results were very encouraging and showed a power output increase of nearly 38.5% at low TSR values. It is, however, recommended that detailed testing be performed under a controlled environment to get more accurate results at various TSR values. Numerical analysis can also provide a better understanding as well as further design refinements.

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