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Research Article

Experimental Study into The Effect of Multi-staging and Check Valve Addition on The Performance of Savonius Wind Rotors with Modified-Bach Blade

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Abstract: Despite having a higher power coefficient than a semicircular Savonius, a modified-Bach rotor still suffers from significant static-torque fluctuation and negative static-torque coefficient at certain positions. This study investigated the effect of multi-staging and valve addition on a modified-Bach rotor's performance by conducting experiments in an open-jet wind tunnel, varying the valve locations, stage numbers, and Reynolds number. The results showed that single-stage modified-Bach rotors with a valve near the tip improved 8.5% and 28.6% maximum power coefficient over the non-valve modified-Bach and semicircular rotor, respectively. Multistaging the modified-Bach rotor significantly reduces the static-torque fluctuation and improves the self-starting ability but at the cost of a lower power coefficient. The combination of multi-staging and valve-addition methods showed the ability to obtain the benefit of a multi-stage rotor with a higher power coefficient than a single-stage rotor. In comparison to a non-valve single-stage modified Bach rotor, the two-stage rotor with an added valve exhibited a significant 68% reduction in static-torque fluctuation, a 4% increase in maximum power, and a noteworthy 17% improvement in average static-torque coefficient.

Keywords: Augmentation; Check valve; Renewable energy; Savonius; Wind turbine

1. Introduction

Wind turbines can be classified as vertical-axis wind turbines (VAWT) or horizontal-axis wind turbines (HAWT). Regarding efficiency, the HAWTs' power coefficient (C_P) is higher than those of VAWTs. Hence, most commercial wind powers use horizontal-axis wind turbines (Hamza et al., 2023). However, VAWT, such as the Savonius wind turbine, has several advantages over the HAWT: omnidirectionality, simple design, good-starting ability, lower noise, and easier maintenance (Al-Gburi et al., 2022; Kumar et al., 2018). These advantages make the Savonius wind turbines suitable for harnessing wind power in remote and urban sites (Le et al., 2022; Ishugah et al., 2014). Combined with a suitable generator design, such as a reduced cogging-torque permanent magnet generator (Nur and Siregar, 2020), the Savonius rotor may provide an interesting method for small-scale wind power generation in an urban area that can eliminate energy transmission losses by allowing direct use of energy (Krasniqi et al., 2022; Cho et al., 2011).

Savonius wind turbines work primarily based on drag force with a small contribution from the lift force (Alom et al., 2018). The advancing blade generates positive torque, while the returning blade moving against the wind generates negative torque. The production of negative torque by

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the returning blade reduces the Savonius rotor's power coefficient. One method to improve the Savonius rotor performance is modifying the blade shapes (Dewan et al., 2023; Abdelaziz et al., 2022; Elmekawy et al., 2021; Chen et al., 2018; Roy and Saha, 2015). The conventional Savonius rotor comprises two semicircular buckets (Figure 1a), while the Bach rotor profile consists of a straight and arc section (Figure 1b) (Kacprzak et al., 2013). Kamoji et al. (2009) investigated the effect of several geometrical parameters on a Bach-type Savonius rotor's performance. They found that the rotor with an overlap ratio (a/d) of zero, blade arc angle (ψ) of 124°, and blade shape factor (p/q) of 0.2 produced the highest power coefficient of 0.21, which was a 20% improvement over the conventional Savonius rotor. Through a numerical study, Roy and Saha (2013) introduced a modified-Bach blade design with an arc angle of 135° and an overlap ratio of 0.1 (Figure 1c). This particular blade configuration demonstrated a significant 20% improvement in C_{PMax} compared to a conventional Savonius rotor. Roy and Saha (2015) conducted an experimental study and observed a 28.5% C_{PMax} improvement, confirming the modified Bach's superior performance over the conventional semicircular rotor.

A single-stage Savonius rotor has a significant torque coefficient fluctuation over a complete revolution and a negative static-torque coefficient (C_{TS}) at certain angular positions, preventing the rotor from self-starting (Saad et al., 2021). Multistaging the rotor can overcome these issues (Shamsuddin and Kamaruddin, 2023; Saha et al., 2008). Kamoji et al. experimentally studied the effects of multi-staging on Savonius rotors and found that the static torque coefficient fluctuation was reduced as the number of stages increased (Kamoji et al., 2011; 2008). However, the rotors' power coefficient also decreased as the number of stages increased. Another method to improve the Savonius rotor performance is by augmentation, such as deflector (Nimvari et al., 2020; Salleh et al., 2020; Jiang et al., 2020), guide plates (Mazlan et al., 2021; El-Askary et al., 2015), and guide box (Manganhar et al., 2019). Although these augmentation methods significantly improved the rotor performance, they increased the rotors' complexity and eliminated the omnidirectional and simplicity of a Savonius rotor.

Ideal augmentation methods should improve rotor performance while keeping all the Savonius advantages intact. An example of this method is check valve addition on the rotor blades. A check valve allows a part of the wind freestream to pass through the returning-blade convex side freely, reducing the drag force and lowering the negative torque. The method was first studied by Rajkumar and Saha (2006) and later by Saha et al. (2008), who found that the two-stage and three-blades, valve-aided Savonius rotor had a 19% higher C_{PMax} than a non-valve-aided rotor. Amiri and Anbarsooz (2019) numerically and experimentally investigated the effect of valve location (near the rotation axis, in the middle, and near the tip of the rotor) on a conventional Savonius rotor's performance. The study used a rectangular pivot-type with a fixed valve's opening area ratio (OAR), which is the ratio between the area of the valves and the rotor's frontal area (D.H). The results showed a 20.8% coefficient of power improvement over a non-valve semicircular rotor. A previous study by Farozan and Indartono (2024) also found an 8.7% C_P improvement from the rotor with a valve placed near the rotor tip and valve OAR=0.02. The effect of valve addition on the performance of a three-bladed conventional Savonius rotor was numerically studied by Borzuei et al. (2021). They observed a 14.5% coefficient of torque (C_T) improvement indicated by the rotor with a large-pivot valve having an unlimited angle and counter-clockwise opening direction placed at the center of the rotor blade.

Previous studies showed that a Savonius rotor with a modified-Bach blade has a better coefficient of power than a conventional Savonius. However, significant torque fluctuation and poor starting torque at certain rotor angles remain for a single-stage modified-Bach Savonius rotor. The effect of multi-staging and valve addition on a modified-Bach Savonius rotor's power coefficient and self-starting performance has not been studied. This study aims to fill this gap by conducting an experimental investigation on a multi-stage modified-Bach Savonius rotor. The effect of valve addition on the performance of single and multi-stage modified-Bach Savonius rotors is also investigated. The parameters investigated in the study are the number of stages (one, two, and three), Reynolds number (73,000 and 99,000), and valve locations. In addition, this study used a membrane-type valve instead of the hinge or pivot type used by previous studies on a valve-augmented Savonius rotor (Borzuei et al., 2021; Amiri and Anbarsooz, 2019; Saha et al., 2008).

2. Material and Methods

2.1. Studied Rotor Design and Manufacturing

This study investigated single and multi-stage Savonius rotors with a modified-Bach blade. All the studied rotors had the same blade design and dimension, based on the work of Roy and Saha (2015).

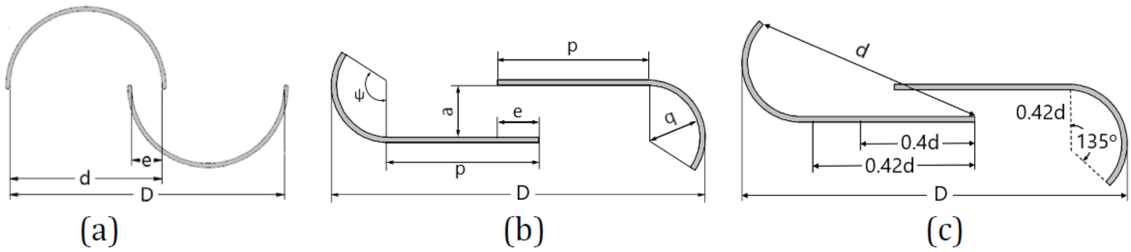


Figure 1 (a) Conventional Semicircular blade; (b) Bach blade; and (c) Modified-Bach blade

The rotor aspect ratio (*RAR*) and swept area (*A*) were kept the same for the multi-stage and the single-stage rotors. The phase shift for each stage was 90° for the two-stage rotor and 60° for the three-stage rotor. Intermediate plates were inserted between the stages. Tables 1 and 2 display the geometrical dimensions and identification of the rotors.

Table 1 Geometrical dimension of the studied rotors

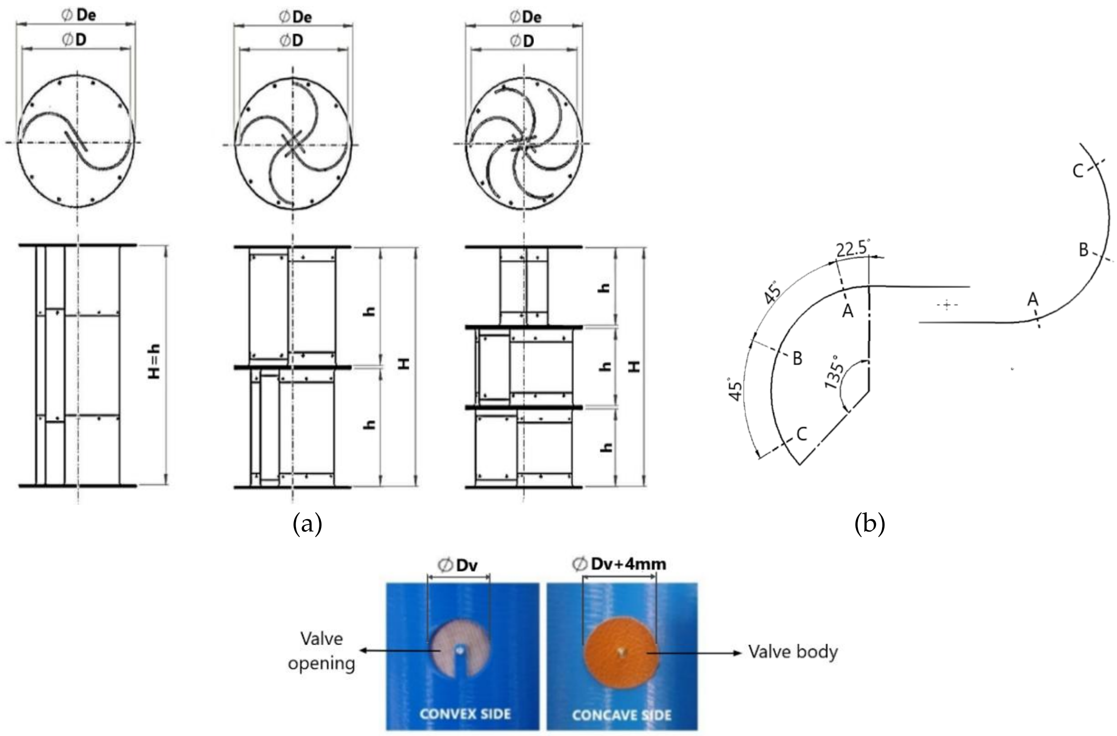
Parameter	Semicircular	Modified Bach		
	Single stage	Single stage	Two stages	Three stages
Blade chord, d (mm)	100	108.1	108.1	108.1
Overlap (gap) ratio, a/d	0.2	0.1	0.1	0.1
Rotor diameter, D (mm)	180	180	180	180
Rotor height, H (mm)	360	360	360	360
Stage height, h (mm)	360	360	180	120
Rotor Aspect Ratio, RAR=H/D	2	2	2	2

Table 2 Studied rotors' identification

Rotor Specification	Rotor Identification								
	SC1NV	MB1NV	MB2NV	MB3NV	MB1A	MB1B	MB1C	MB2V	MB3V
Stage no.	1	1	2	3	1	1	1	2	3
Blade shape	Semicircular	-------------------------------------- Modified Bach --------------------------------------							
Valve location	-	-	-	-	Rotation axis	Arc center	Rotor tip	---Rotor tip---	
OAR	-	-	-	-	0.02	0.02	0.02	0.02	0.02

2.2. Experimental Setup

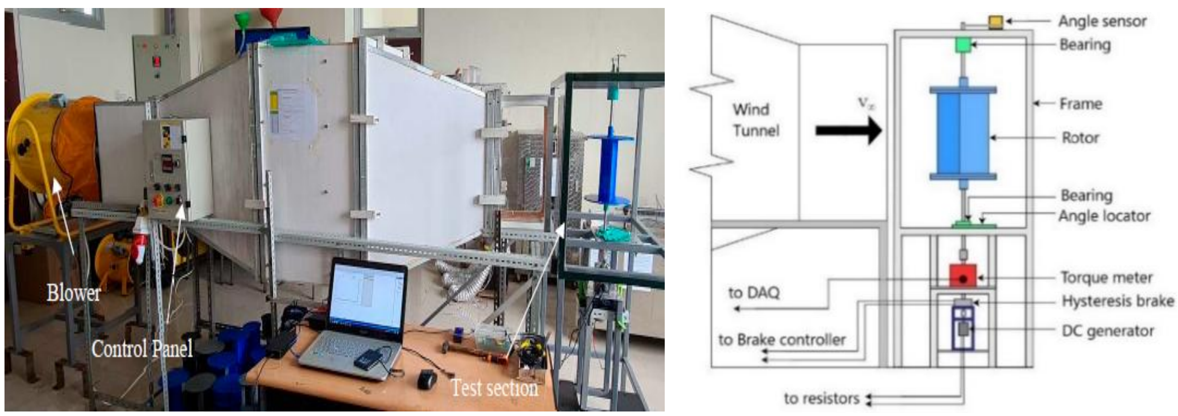
Performance tests were conducted to obtain the rotors' performance characteristics under dynamic and static loadings. In addition to the modified-Bach rotors, a conventional Savonius rotor was tested and used as a benchmark. The tests were done in a low-speed open jet wind tunnel. The average wind velocity exiting the wind tunnel (V_∞) was varied and measured using a calibrated hotwire anemometer. The wind tunnel velocity was adjusted using a variable frequency drive (VFD) to control the axial fan rotation speed. The experiments were conducted at Reynolds numbers of 73,000 and 99,000. The rotor axis was placed on an open test section 300 mm from the wind tunnel exit. The rotor blockage ratio was calculated at 12%, which is considered low for an open-type wind tunnel test and did not require a blockage correction factor (Gonçalves et al., 2022).



(c)

Figure 2 (a) Rotor configuration; (b) Valve locations; and (c) Valve design

The rotor's torque (*T*) and rotation speed (*N*) measurements were done using a DYN-200 rotary torque meter. The torque measurement was calibrated using known torques, while the rotation speed was compared against a calibrated optical tachometer. A Labjack U6 data acquisition module connected the torque meter analog output to a laptop. A DC generator and a hysteresis brake were used to simulate the dynamic and static load. The rotor's angle position was measured using a hall-effect angle sensor. All measurements during the dynamic and static tests were taken at a sampling rate of 4Hz for a fixed period and then averaged. Figures 3a and 3b show the overall experimental and instrumental setup, respectively.



(a) (b)

Figure 3 (a) Overall experimental setup; (b) Instrumentation setup

2.3. Data Reduction

The measurements taken during the dynamic test were the rotor rotational speed (*N*) and rotor torque (*T*). During a static test, the rotor's angle (θ) and static torque (T_S) were measured when the rotor was locked in position using the hysteresis brake. Measurements were taken for a half-cycle (0^{o} to 180^{o}) in 15^{o} steps. The remaining half-cycle was considered a repetition of the first half due to the symmetrical nature of the Savonius rotor. The rotor angular velocity (ω) (rad/s), tip speed ratio (*TSR*), coefficient of power (C_P), coefficient of torque (C_T), and static-torque coefficient (C_{TS}) were calculated using the following Equations 1 ~ 5:

$$\omega = \frac{2\pi N}{60} \tag{1}$$

where *N* is the measured rotor rotation speed (rpm).

$$TSR = \frac{\omega D}{2V_\infty} \tag{2}$$

where *D* is the rotor diameter (m), and V_∞ Is the wind velocity (m/s).

$$C_P = C_T\, TSR \tag{3}$$

$$C_T = \frac{4T}{\rho V_\infty^2 H D^2} \tag{4}$$

$$C_{TS} = \frac{4T_S}{\rho V_\infty^2 H D^2} \tag{5}$$

where *T* is the measured torque (N.m), *H* is the rotor height (m), ρ is the air density in (kg/m^3), and T_S is the measured static torque (N.m). The uncertainties for derived quantities (*TSR*, C_P, and C_{TS}) were calculated using the propagation of error method as described by Wheeler and Ganji (2010) and shown in Equation 6:

$$u_R = \left(\sum_{i=1}^{n}\left[u_{xi}\frac{\partial R}{\partial x_i}\right]^2\right)^{1/2} \tag{6}$$

where u_R is the total uncertainty for the derived quantities, u_{xi} is the variable uncertainty, and $\frac{\partial R}{\partial x_i}$ is the sensitivity coefficient of derived quantities R with respect to variable x_i. The total uncertainties for the *TSR*, C_{TS}, and C_P were 2.3%, 4.2%, and 6.3% respectively. In addition, the experiments' Reynolds numbers were calculated using the following Equation 7:

$$Re = \frac{\rho V_\infty D}{\mu} \tag{7}$$

where μ is the air dynamic viscosity (kg/(m.s)).

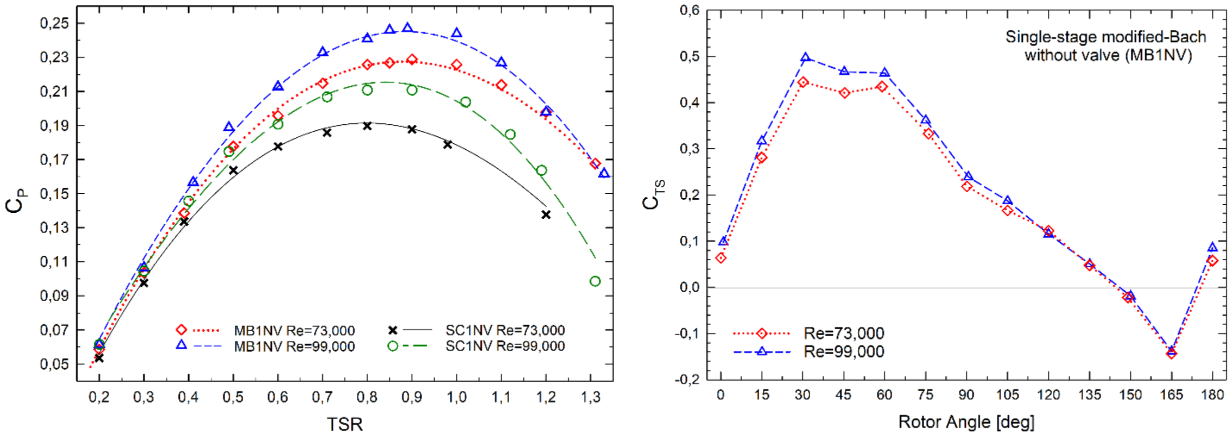
3. Results and Discussion

3.1. Single-Stage Rotor Performance

Single-stage rotors with a modified Bach (MB1NV) and conventional semicircular blade (SC1NV) were tested dynamically. The modified-Bach rotor's dynamic test result shows a C_{PMax} of 0.228 at TSR=0.88 and C_{PMax} of 0.245 at TSR=0.89 for Reynolds numbers 73,000 and 99,000, respectively. The result indicates that the power coefficient increased as the Reynolds numbers increased. Kamoji et al. (2009) and Aliferis et al. (2019) observed similar findings in their works. They proposed the delayed flow separations around the blade as the apparent reason for the finding. Aliferis et al. (2019) provided a detailed mechanism for how the increase in Reynolds number (wind velocity) leads to a rise in the rotor's power coefficient.

The modified-Bach rotors also produced a better power coefficient than a conventional semicircular rotor, with 19% and 14.5% C_{PMax} improvement for Reynolds numbers 73,000 and 99,000, respectively. This result supports the previous finding from Roy and Saha (2015). Figure 4a shows the power coefficient of a single-stage semicircular and modified-Bach rotor against the tip speed ratio under increasing Reynolds numbers.

Figure 4b depicts the static-torque coefficient (C_{TS}) for a half revolution of a single-stage modified-Bach rotor at increasing Reynolds numbers. The single-stage rotor had a significant C_{TS} fluctuation. The MB1NV rotor's C_{TS} range was from -0.141 to 0.446 and from -0.136 to 0.498 for Reynolds numbers 73,000 and 99,000, respectively. The maximum C_{TS} was generated within 30° to 40° angles, while negative C_{TS} was observed within 150° to 165°. For most rotor angles, the C_{TS} results for both Reynolds numbers overlapped, indicating that the static-torque coefficients were almost independent of the Reynolds numbers. A similar trend was observed by Kamoji et al. (2011; 2009). At rotor angles ranging from 30° to 60°, the rotor's C_{TS} at a Reynolds number of 99,000 was significantly higher than that at a Reynolds number of 73,000. This increase in C_{TS} was attributed to the higher coefficient of lift (C_L) exhibited by the rotor at these angles, as reported by Alom et al. (2018). The higher C_L resulted in a greater contribution from the lift force as the Reynolds number (wind velocity) increased.



(a) (b)

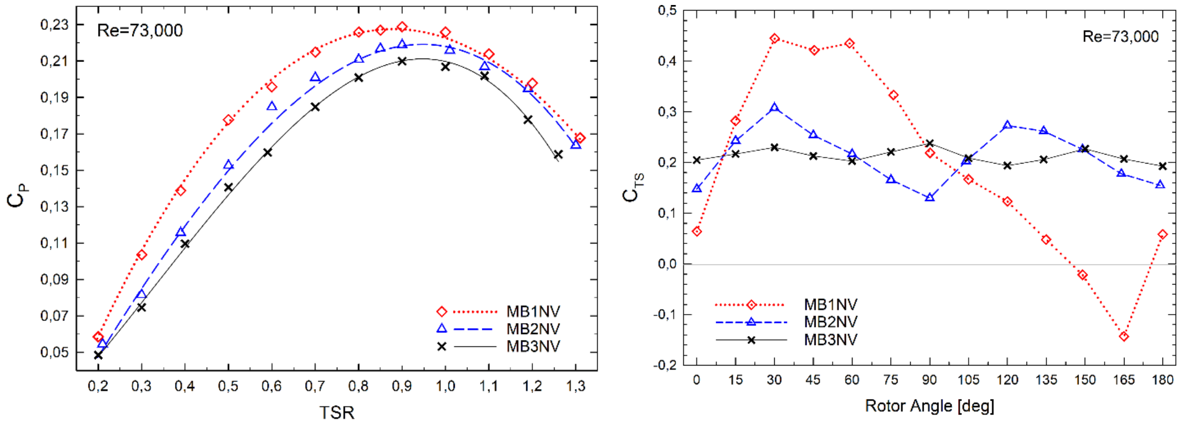
Figure 4 The effect of Reynolds number on the: (a) single-stage modified-Bach and semicircular rotors' coefficient of power; and (b) single-stage modified-Bach rotor's coefficient of static torque

3.2. Multi-stage Modified-Bach Rotor Performance

Modified-Bach rotors with two (MB2NV) and three stages (MB3NV) were manufactured and tested under different Reynolds numbers. The performances of both rotors were compared to a single-stage modified-Bach rotor to study the effect of multi-staging on the rotors' power coefficient and self-starting ability. Figures 5a and 5b illustrate the rotors' power and static-torque coefficient results under Reynolds numbers 73,000.

The rotors' maximum power coefficient decreased as the number of stages increased. For instance, at Reynolds number 73,000, the power coefficients yielded by the two-stage and three-stage rotors were 3.8% (C_{PMax}=0.219) and 7.9% (C_{PMax}=0.210) lower than the single rotor's, respectively. Like the single-stage rotor, the multi-stage rotors' power coefficient increased following the Reynolds numbers. At Reynolds number 99,000, the C_{PMax} for the two and three-stage rotor were 0.237 and 0.228, respectively. A similar trend was observed by Kamoji et al. when investigating multi-stage Savonius rotors with a semicircular and Bach blade (Kamoji et al., 2011; 2009).

The multi-stage rotors' static-torque coefficients were positive at all rotor angles and fluctuated significantly lower than the single-stage's. This result indicates an improved self-starting ability for the multi-stage rotors. In a half revolution (0°~180°), the two-stage rotor had two C_{TS} peaks and troughs, while the three-stage rotor had three of each. The rotor angles for the C_{TS} peaks were at 30° and 120°, and 30°, 90°, and 150° for the two and three-stage rotor, respectively. Furthermore, the C_{TS} troughs were at 0° and 90°, and 0°, 60°, and 120° for the two and three-stage rotor, respectively. Like the single stage, the multi-stage rotors' static-torque coefficients were also almost independent of Reynolds numbers. Furthermore, the locations of the peaks and troughs did not change with the change in Reynolds number.

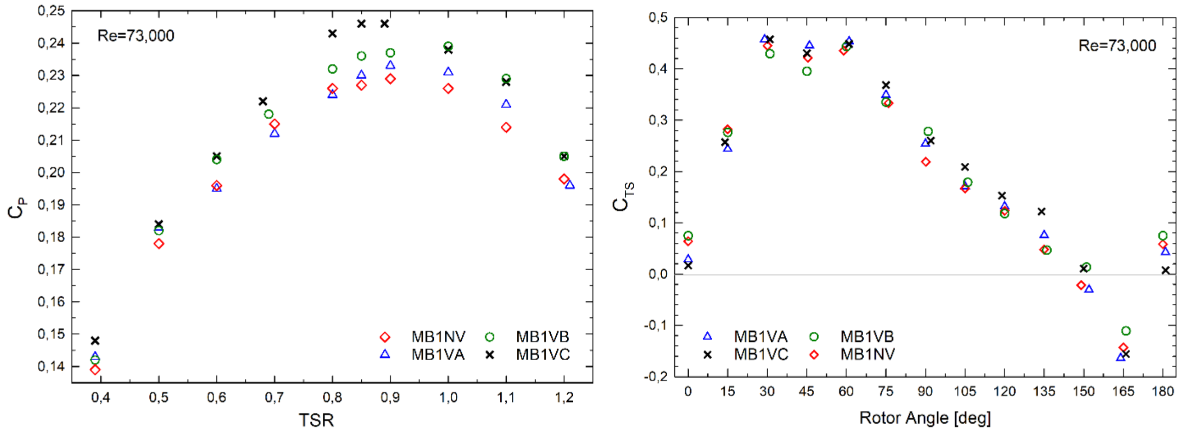


(a) (b)

Figure 5 The effect of multi-staging on a modified-Bach rotor (a) C_P vs. TSR at Re=73,000; and (b) C_{TS} vs. rotor angle at Re=73,000

3.3. Valve-Augmented Rotors Performance

Initially, valves were added into a single-stage modified-Bach rotor. The valve opening area ratio (OAR) was fixed at 0.02, while the valve locations and test Reynolds numbers were varied. A total of three valve-augmented modified-Bach rotors (MB1VA, MB1VB, and MB1VC) were made and tested. Figures 6a and 6b depict the effects of valve locations on the single-stage modified-Bach rotors' power and static-torque coefficients, respectively.



(a) (b)

Figure 6 The effect of valve locations on a modified-Bach rotor (a) C_P vs. TSR at Re=73,000; and (b) C_{TS} vs. Rotor angle at Re=73,000

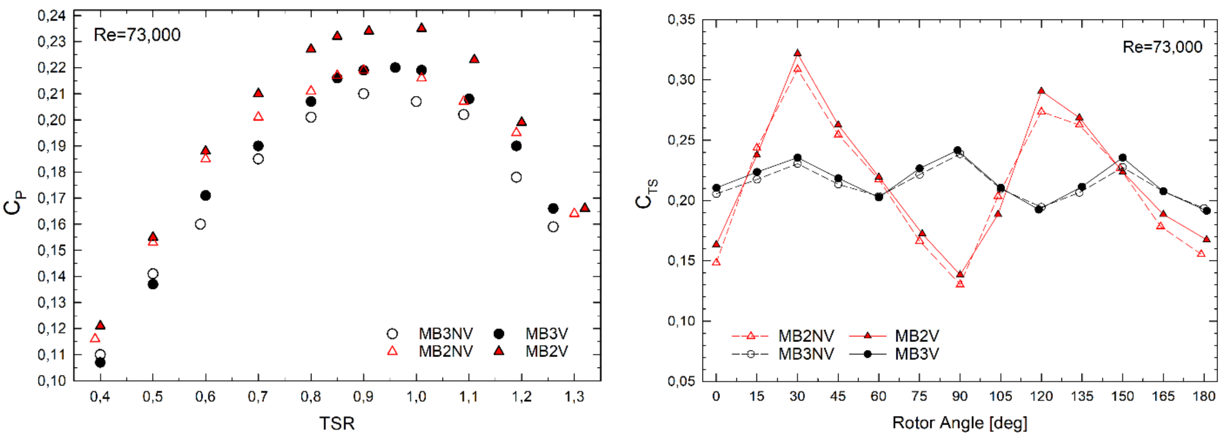
The rotor with a valve near the rotor tip (MB1VC) had a better power coefficient than all the other rotors. It yielded an 8.5% and 28.6% higher C_{PMax} than the non-valve single-stage rotors with a modified Bach and semicircular blade, respectively. A valve near the rotor tip enables a higher air flow rate, leading to a more significant negative torque reduction and, hence, a higher power coefficient. Conversely, placing a valve near the rotation axis (MB1VA) yielded the least improvement. A valve placed at this location impedes the overlapping-gap flow that is supposed to energize the returning blade and has the least distance from the moment axis, further reducing the valve's effectiveness in negative torque reduction (Nakajima et al., 2008).

The rotor with a valve at the rotor tip (MB1VC) also produced the best result when tested at Reynolds number 99,000. However, the magnitude of C_{PMax} improvement decreased as the

Reynolds number increased. For example, the MB1VC rotor yielded an 8.5% and 6.1% improvement over the non-valve modified-Bach rotor when tested at Reynolds numbers 73,000 and 99,000, respectively. The valve's presence may have disturbed the flow-separation delay mechanism that improves the rotor's C_P when the Reynolds number increases. These findings indicate a tradeoff between the negative and positive effects on each valve location and further support the observation found in Amiri and Anbarsooz's work (Amiri and Anbarsooz, 2019) and the authors' previous study.

The static test result shows that the effects of valve addition on a single-stage modified Bach rotor's static-torque coefficient depended on the valve locations. Placing the valve near the rotation axis (MB1VA) did not affect the rotor's average static-torque coefficient (C_{TS} average). The proximity of the valve location to the rotation axis and overlap gap resulted in a diminished negative torque reduction effect. On the other hand, the rotor equipped with a valve at the tip (MB1VC) exhibited the most favourable average static-torque coefficient for both Reynolds numbers. At Reynolds number 73,000, the MB1VB and MB1VC rotors obtained a 5% and 6.2% average C_{TS} improvement, respectively. The valve on the returning blade of the MB1VC rotor was opened from a 60^{O} to 165^{O} angle, which visibly improved the rotor's static-torque coefficient at those positions. The valve at the arc center (MB1VB) was opened at an almost similar angle to the valve at the tip. However, the effects were less pronounced due to the shorter distance to the rotation axis.

Two and three-stage modified-Bach rotors were augmented with a valve placed near the rotor tip (MB2V and MB3V rotors). The rotors were tested in dynamic and static conditions. Figures 7a and 7b illustrate the effect of valve addition on a multi-stage modified-Bach rotors' power and static-torque coefficients, respectively. The result shows that the valve-augmented multi-stage rotors' power coefficients were higher than the non-valve multi-stage rotors. The valve-augmented two-stage rotor (MB2V) achieved a C_{PMax} gain of 8.1% and 7.5% when tested at Reynolds numbers 73,000 and 99,000, respectively. Similarly, the valve-augmented three-stage rotor (MB3V) improved the C_{PMax} by 4.6% at Reynolds number 73,000 and 4% at Reynolds number 99,000. These results indicate that valve addition negates the power coefficient loss caused by the multi-staging method. However, valve addition appears to have minimal effect on the average static-torque coefficient of multi-stage rotors (ranging from 1.3% to 2.4%). Additionally, the rotor angles corresponding to C_{TS} peaks and troughs remained unchanged with valve addition and Reynolds numbers. A summary of the entire test can be found in Table 3.



(a) (b)

Figure 7 The effect of valve addition on a multi-stage modified-Bach rotor (a) C_P vs. TSR at Re=73,000; and (b) C_{TS} vs. Rotor angle at Re=73,000

Table 3 Experiments result in summary

Parameter	Reynolds Number=73,000								
	SC1NV	MB1NV	MB2NV	MB3NV	MB1VA	MB1VB	MB1VC	MB2V	MB3V
C_{PMax}	0.192	0.228	0.219	0.210	0.233	0.240	0.247	0.237	0.221
TSR at C_{PMax}	0.80	0.88	0.95	0.95	0.90	0.90	0.90	0.97	0.95
Minimum C_{TS}	-0.165	-0.141	0.131	0.194	-0.162	-0.109	-0.154	0.139	0.192
Maximum C_{TS}	0.455	0.446	0.309	0.239	0.458	0.444	0.458	0.322	0.242
C_{TS} average	0.183	0.188	0.214	0.214	0.190	0.197	0.200	0.220	0.217
Parameter	Reynolds Number=99,000								
	SC1NV	MB1NV	MB2NV	MB3NV	MB1VA	MB1VB	MB1VC	MB2V	MB3V
C_{PMax}	0.214	0.245	0.237	0.228	0.250	0.256	0.260	0.255	0.237
TSR at C_{PMax}	0.83	0.89	0.93	0.93	0.91	0.90	0.89	0.97	0.96
Minimum C_{TS}	-0.147	-0.136	0.138	0.203	-0.162	-0.101	-0.128	0.140	0.201
Maximum C_{TS}	0.506	0.498	0.315	0.246	0.501	0.495	0.491	0.329	0.247
C_{TS} average	0.222	0.211	0.222	0.222	0.208	0.221	0.223	0.227	0.225

4. Conclusions

This study investigated the effect of multi-staging and valve addition on the Savonius rotors with a modified-Bach blade. In this study, the valve locations and Reynolds numbers varied. The results showed that a single-stage modified-Bach rotor had a higher power coefficient than a conventional semicircular rotor. Adding the single-stage rotor with a valve near the rotor tip further improved the rotor's power and static torque coefficient. For both Reynolds numbers, the rotor with a valve at the tip shows the best result, while the rotor with a valve near the rotation axis shows the slightest improvement. The beneficial effect of negative torque reduction coexisted with adverse effects, such as overlapping flow disruption. However, significant fluctuation and negative values for the static-torque coefficients were still present for the single-stage rotor. Multi-staging the modified-Bach rotor significantly reduced the torque fluctuations at the expense of a reduced power coefficient. Adding a valve to the multi-stage modified-Bach rotor negated the power reduction drawback of the multi-staging method. In the case of a two-stage rotor added with a valve, the maximum power coefficient exceeded that of a single-stage rotor by 4%. These results indicate that combining the multi-staging and check-valve additions can effectively produce a Savonius rotor with low torque fluctuation and good self-starting ability while achieving a higher power coefficient.

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Author Contributions

Y.S. Indartono: Conceptualization, Funding acquisition, Investigation, Methodology, Formal analysis, Writing – review and editing, Supervision. I. Farozan: Data curation, Investigation, Formal analysis, Writing – original draft, Writing – review and editing, Visualization. G.T. Fauzanullah: Data curation, Formal analysis, Visualization.

Conflict of Interest

The authors declare that there is no competing financial interests or personal relationships in this study.

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