Experimentally Determining the Optimum Design Configuration
for Savonius Rotors*

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The Savonius rotor was proposed in the early 1920's. Until now, there has been no systematic work on the optimum design configuration of Savonius rotors. In the present work, various model tests were carried out in a wind tunnel, in order to determine the optimum design configuration of Savonius rotors. The effects of seven design parameters on the aerodynamic performance of the rotors were experimentally determined. The parameters were the rotor aspect ratio, the overlap and the gap between rotor buckets, the profile of the bucket cross-section, the number of the buckets, the presence or absence of rotor endplates, and the influence of the stack of buckets. In addition, the flow around the rotor was investigated by the flow-visualization method. In this study, the influence of important design parameters of the Savonius rotor has been investigated and the rotor configuration giving the maximum torque and power has been determined.

Key words: Fluid machine, Savonius rotor, Vertical-axis windmill, Wind tunnel test, Torque Characteristics, Power Characteristics

1. Introduction

The Savonius rotor, proposed by S.J. Savonius in 1925, is a vertical axis rotor using the drag force(1). Due to their low rotational speed and efficiency, the Savonius rotors have not been developed sufficiently; they have been applied only to such a limited use as ventilation. As the utilization of the natural energy has come to be re-appreciated in recent years, the Savonius rotors have been finding their application in pumping up water for irrigation, agitating water for rearing of ponds, and starting up in combination with the Darrieus rotors.

Experimental studies on the Savonius rotors have been reported by Bach(2), Newman(3), Khan(4), Sheldahl(5), Sivasagaram(6), and others. All these studies investigated, the effects of factors on the rotor performance with attention paid to particular design configuration factors. Theoretical studies on the Savonius rotors have also been reported by Wilson(7), Van Dusen(8), Ogawa(9), and others. However, it has not led to establishing a general theoretical method of analysis. In an activity of Japan International Cooperation Agency (JICA) to assist developing countries, authors are engaged in designing Savonius rotors in order to determine the optimum design configuration at the preliminary design stage, it is essential to clarify and systematize the effects of various design configuration factors.

This study examined all the main design configuration factors including aspect ratio, overlap ratio, gap ratio, profile of bucket cross section, number of buckets, bucket endplates, and stack of buckets to clarify their effects on the performance of the Savonius rotors.

2. Nomenclature

Main symbols and units used in this paper are listed below:

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>A</td>
<td>swept area of the rotor (m²)</td>
</tr>
<tr>
<td>a</td>
<td>overlap (m)</td>
</tr>
<tr>
<td>AR</td>
<td>aspect ratio (=H/C)</td>
</tr>
<tr>
<td>b</td>
<td>separation gap (m)</td>
</tr>
<tr>
<td>C</td>
<td>chord length of bucket (m)</td>
</tr>
<tr>
<td>D</td>
<td>rotor diameter (m)</td>
</tr>
<tr>
<td>GP</td>
<td>gap ratio (=b/C)</td>
</tr>
<tr>
<td>H</td>
<td>height of bucket (m)</td>
</tr>
<tr>
<td>n</td>
<td>rotational speed of axis (rpm)</td>
</tr>
<tr>
<td>OR</td>
<td>overlap ratio (=a/C)</td>
</tr>
<tr>
<td>P</td>
<td>power (Nm/s)</td>
</tr>
<tr>
<td>T</td>
<td>axial torque (N m)</td>
</tr>
<tr>
<td>U</td>
<td>circumferential velocity of the rotor (m/s)</td>
</tr>
<tr>
<td>V</td>
<td>wind velocity (m/s)</td>
</tr>
<tr>
<td>λ</td>
<td>tip speed ratio (=U/V)</td>
</tr>
<tr>
<td>ρ</td>
<td>air density (kg/m³)</td>
</tr>
<tr>
<td>Cp</td>
<td>power coefficient (=P/(1/2) AV³)</td>
</tr>
<tr>
<td>Cq</td>
<td>torque coefficient (=T/(1/2) Aρ(V²)</td>
</tr>
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3. Experimental Apparatus and Method

Figure 1 shows an installed rotor and the measuring apparatus. The open-circuit
wind tunnel has a square exit of 1.05 m x 1.05 m in cross section. The wind velocity can be varied in the range from 2 m/s to 20 m/s with a variable speed motor. In order to avoid the blockage effect, the tested rotor was placed about 1 m apart from the exit of the wind tunnel. A torque meter (maximum capacity of 2.0 Nm) and a pulse-type revolution counter are connected to the lower part of the rotor through coupling. For measuring the wind velocity, a hot-wire probe was used at the wind tunnel exit. The accuracy of the probe had been verified with a Bartz type manometer.

4. Experimental Results and Considerations

The experiments were carried out for each design configuration factor of the tested rotor, at wind velocities of 4 m/s, 6 m/s, and 8 m/s. In this paper the case of 6 m/s is mainly discussed.

4.1 Effect of aspect ratio. The effect of the aspect ratio, which previously had not been clarified quantitatively, was studied. Four types of rotors (OL = 0.20) having aspect ratios of AR = 1.28, 2.00, 3.00 and 4.29 were tested while the swept area was kept constant at A = 0.128 m².

The distribution of static torques is illustrated in Fig. 3. The figure shows that, at all phase angles, the smaller the aspect ratio, the larger becomes the distribution of static loads. This is because when the aspect ratio is small, the radius of rotor becomes large resulting in a large torque, provided the swept area is kept unchanged. In the case of AR = 1.28 and AR = 2.00, the maximum static torque is obtained at phase angles of approximately 120° and 300°. The maximum static torque appears at phase angles of approximately 150° and 310°.

![Static torque distribution (aspect ratio)](image_url)

Figure 4 illustrates the starting characteristics. From this figure, it is seen that the larger the aspect ratio, the higher becomes the maximum rotational speed and the faster becomes the rise of the characteristics curves. This is because the rotor radius decreases, reducing the air resistance of the buckets, as the aspect ratio increases. When the cases of 6 m/s and 8 m/s in wind velocity are compared, the higher wind velocity produces the larger revolution number and the rise of starting characteristic becomes steeper.

![Rotor and bucket geometry](image_url)
Figure 4 illustrates the starting characteristics (aspect ratio).

Figure 5 shows the variations of the torque characteristics. At any aspect ratio, the torque coefficient is large in the low tip speed ratio range, and decreases as the tip speed ratio increases. In the tip speed ratio range of $\lambda \leq 0.75$, the torque coefficient at $AR = 4.29$ is larger than that at $AR = 3.00$, while the torque coefficient at $AR = 2.00$ is almost the same as that at $AR = 1.28$. In the tip speed ratio range of $\lambda > 0.75$, the torque coefficients at $AR = 4.20$, $AR = 3.00$ and $AR = 2.00$ are almost the same, while the torque coefficient at $AR = 1.28$ is 3 - 4 percent smaller than those of other aspect ratios. This is explained as follows. A rotor with a large aspect ratio rotates with high speed, producing a lift-force and increasing the torque. However, as the tip speed ratio increases, it generates an induced vortex behind the returning bucket, thereby increasing the resistance.

Figure 6 illustrates the power characteristics. According to Fig. 6, the power coefficient, which is small at any aspect ratio in the low tip speed ratio range of 0.5, increases as the tip speed ratio becomes larger, reaching the maximum value at approximately $\lambda = 1.0$, and then decreases sharply as the tip speed ratio increases further. In the case of the largest aspect ratio of $AR = 4.29$, the power coefficient has the largest value covering all tip speed ratio ranges. In the cases of $AR = 3.00$ and $AR = 2.00$, the power coefficients have almost the same value. In the case of $AR = 1.28$, the power coefficient is the smallest throughout the whole tip speed ratio range. It has been also clarified that the larger the aspect ratio, the higher becomes the tip speed ratio which corresponds to the maximum power coefficient.

From the above, the most suitable rotor would be $AR = 4.29$ in aspect ratio and $\lambda = 1.0$ in the tip speed ratio.

4.2 Effect of overlap ratio.
Experiments were carried out on semi-circular buckets ($AR = 2.00$) at 6 steps of overlap ratio ranging from $OL = 0.00$ to $OL = 0.50$.

Figure 7 shows the static torque distribution obtained through the experiments. In the cases of small overlap ratios of $OL = 0.10$ and $OL = 0.20$, the static torque value becomes maximum at the phase angles of approximately 120° and 300°. In the case of larger overlap ratios of $OL = 0.30$, $OL = 0.40$, and $OL = 0.50$, the static torque value becomes maximum at the phase angles of approximately 120° and 310°, and minimum at the phase angles of approximately 70° and 250°. The static torque has even negative values and it acts against the rotating direction of the rotor at the phase angles of 70° and 250°. All the torque curves show a trend that the static torque at each phase angle increases as
the overlap ratio increases from 0.00 to 0.20, and decreases as the overlap ratio increases from 0.30 to 0.50. The reason is as follows. Up to OL = 0.20, the pressure in the negative pressure area behind the returning bucket is quickly recovered by the air passing through the overlap part; as the overlap ratio increases, the radius of rotor decreases, reducing the rotor moment.

Figure 9 shows the variations of the torque characteristics. In the case of no overlap, the torque coefficient is the lowest throughout the whole tip speed ratio ranges. In the case of an excessive overlap of OL = 0.50, the torque coefficient drops markedly at the tip speed ratio of approximately OL = 0.50. In the case of OL = 0.20, the torque coefficient maintains its highest values over a wide range of the tip speed ratios. The overlap ratios of OL = 0.30 and OL = 0.10 show the same trend, but more moderately. The characteristics of OL = 0.20 and OL = 0.30 are considered preferable because the torque coefficient decreases slowly even in the tip speed ratio range of λ > 0.75.

Figure 8 presents the starting characteristics. The figure shows that a rotor of a high overlap ratio develops a large number of revolutions, although this is not remarkable where the overlap is more than OL = 0.20. Although all the rotors show similar starting characteristics, the rotors of OL = 0.20 and OL = 0.30 start up more sharply than the other rotors. At the wind velocity of 8 m/s, the rotors start up more sharply and rotate at a higher number of revolutions than 6 m/s, provided the overlap is unchanged.

Figure 10 presents the variation of the power coefficient. In the low tip speed ratio range of λ < 0.50 at any overlap ratio, the power coefficient is small; \( C_P < 0.1 \). The power coefficient increases as the tip speed ratio increases, reaches the maximum value at the tip speed ratio ranging from \( λ = 0.75 \) to \( λ = 1.00 \), and decreases significantly as the tip speed ratio increases further. In the case of no overlap (OL = 0.00), the power coefficient is low in the whole tip speed ratio range, even the maximum being \( C_P = 0.14 \).

In the case of OL = 0.20, on the contrary, the power coefficient is the largest throughout the whole tip speed ratio range, it reaches maximum \( C_P = 0.21 \). The overlap ratios of OL = 0.30 and OL = 0.10 follow a similar trend but less remarkable than OL = 0.20. In the case of OL = 0.50, the power coefficient becomes low and the trend is close to the no overlap case. Also it can be seen that in the case of the maximum value of the power coefficient, the value of the corresponding tip speed ratio is accordingly large. The results of experiments by other researchers(3)(4) show similar trends. However, since the values of \( C_P \) according to their experiments were excessive due to the blockage effect of the closed wind tunnels,
the values obtained through the author's experiment would be more accurate.

From the above, it can be concluded that the torque characteristics and the power characteristics would be remarkably improved with a bucket overlap of 20 - 50 percent.

**Fig. 10** Power characteristics (overlap ratio)

4.3 Effect of gap ratio. At a constant overlap of OL = 0.20, the effect of the gap, or the clearance between buckets that are opposite to each other, was studied. The gap ratios have four variations: GP = 0.00, 0.05, 0.10, 0.20.

Figures 11 and 12 illustrate the torque characteristics and the power characteristics respectively. Those figures show the trends of the variations of the torque coefficient and the power coefficient relative to the tip speed ratio; the trends are generally similar to those of the overlap ratio described in above section 4.2. Both torque coefficient and power coefficient are the largest in the case of no gap (GP = 0.00) and they decrease as the value of gap increases. This is because the air flows excessively from the center part of the wind receiving bucket to the wake of the returning bucket as the gap value increases; so the effective drag-force component to the wind receiving side decreases. Also, Fig. 12 indicates that the tip speed ratios corresponding to the maximum value of the power coefficients are about \( \lambda = 1.0 \) irrespective of the gap ratios.

From the above, it can be said that an increase of the gap between buckets causes a decrease in torque coefficient and power coefficient. Therefore, it is better not to provide the gap.

**Fig. 11** Torque characteristics (gap ratio)

4.4 Effect of cross-section profile of buckets. Bach's study on the effect of the cross-section profile of buckets is known. In order to clarify the difference in performance depending on the bucket profile, the authors compare the "Bach type" profile and the semi-circular bucket. Up to the present, the Bach type gives the highest power coefficient among other known profiles. The overlap ratio of the Bach type rotor was varied in the range of 0.00 to 0.50.

The static torque distribution is shown in Fig. 13. The static torque increases sharply at the rotating phase angles of approximately 120° and 300° and is minimum at the phase angles of approximately 80° and 260°. This is explained by the smaller bucket thickness of the Bach type compared with the semi-circular type; the wind-receiving buckets of the Bach type can easily catch air flow at any phase angle. Another feature of the Bach type is
that other peaks appear at phase angles of approximately 60° and 240°. The trend of the distribution curve is generally similar to that of the semi-circular type. The static torque at each individual phase angle decreases as the overlap ratio increases because the radius of rotation increases, reducing the moment as the overlap increases.

From Fig. 15 it is seen that the Bach type, compared with the semi-circular type, shows higher torque coefficient values in the range of λ < 0.6. The torque characteristics of the Bach type are little affected by the overlap ratio.

The power characteristics are shown in Fig. 16. The Bach type reaches a maximum value of Cp = 0.23 at OL = 0.00 - 0.30, while the semi-circular type reaches a maximum value of 0.21. The tip speed ratio corresponding to the maximum power coefficient value appears to be approximately λ = 1.0 in the case of the semi-circular type; in the case of the Bach type, it appears at λ = 0.8, i.e., a little lower. This is caused by the fact that the moment arm of the Bach type rotor is longer than the one of the semi-circular type rotor of the same overlap. Experimental studies by other researchers show a similar trend.

From the above, it can be said that as the cross-section profile of the bucket, the Bach type would be preferable to the semi-circular type; the appropriate overlap ratio would be 0.10 - 0.30.
4.5 Effect of number of buckets. In order to clarify the effect of the number of the buckets, we examined the difference between a two-bucket rotor and a three-bucket rotor. The two-bucket rotor had a semi-circular cross section (AR = 2.00 and OL = 0.20). The three-bucket rotor had the same swept area as the two-bucket one. Their cross sections are illustrated in Fig. 2.

The static torque distribution is shown in Fig. 17. From this figure it is seen that static torque of the three-bucket rotor exhibits its peak at every 120° rotational phase angle at the same angle as the bucket mounting angle. Although the maximum static torque is smaller by approximately 20 percent than that of the two-bucket rotor, the three-bucket rotor rotates smoothly with little fluctuation of static torque by the phase angle. As shown in Fig. 18, the three-bucket rotor starts up more slowly, and its maximum number of revolutions is lower compared with the two-bucket rotor.

![Fig. 18](image)

4.6 Effect of stack of buckets. The effect of the number of the stacks of buckets is unknown up to now. In order to clarify the effect, we examined the difference in performance between the standard two-bucket single-stack type and the two-bucket double-stack type. The latter has the same swept area as the standard type, and its upper and lower buckets are 90° different from each other in phase angle.

As discussed above, the three-bucket rotor equalizes torque fluctuation, the three-bucket rotor exhibits markedly low values of the torque coefficient and the power coefficient. The three-bucket rotor has more negative than positive features. Therefore the two-bucket rotor is more preferable.
rotational speed than the single-stack type.

The torque characteristics and power characteristics are shown in Fig. 19 and Fig. 20 respectively. The torque coefficient of the double-stack type varies similarly to that of the single-stack type and is higher by 1 - 2 percent. The power coefficient of the double-stack type is also 2 - 3 percent higher at any tip speed ratio than that of the single-stack type, and its maximum value becomes as high as $C_p = 0.24$ at $\lambda = 0.9$. The operating tip speed ratio range of the double-stack rotor extends a little toward the higher tip speed ratio side.

From the above, it can be concluded that the double-stack rotor is better in both torque and power characteristics than the single-stack rotor.

4.7 Effect of bucket endplates. The effect of the bucket endplates is unknown up to the present. In order to clarify the effect, we compared the standard two-bucket single-stack rotor with upper and lower circular plates on each bucket with a rotor consisting of buckets without endplates.

Referring to Fig. 19 and Fig. 20, the torque coefficient of the rotor without endplates decreases rapidly in tip speed ratio range of $\lambda > 0.5$, the power coefficient of the same rotor is as low as 0.15 maximum and decreases rapidly in the tip speed ratio range of $\lambda > 0.6$, and the operating tip speed range becomes narrow. Therefore, the bucket endplates are indispensable to the Savonius rotor for improving the torque coefficient and expanding the operating tip speed ratio range.

4.8 Results of visualized experiment. In order to investigate the behavior of air flow around the rotor which is affected by the bucket cross-section profile and the overlap, a visualized experiment was carried out in a circulating water channel of 0.35 m wide and 0.30 m deep. The flow behaviors on revolving rotors are made visible with aluminum powder, and photographed in Fig. 21 (a)-(c).

Let us compare Fig. 21(a) for buckets with no overlap with Fig. 21(b) for buckets with an overlap. A large dead water area is observed at the wake of the returning bucket in Fig. 21(a), whereas the dead water area is small and the vortex producing a negative pressure has almost disappeared in Fig. 21(b). When Fig. 21(b) for the semi-circular type and Fig. 21(c) for the Bach type are compared, almost no vortex at the wake of the returning bucket is observed in Fig. 21(c), although the difference is not clear.

These results of the experiment imply that good torque and power characteristics of a Savonius rotor are obtained by a rotor configuration in which the air flow through the overlap position eliminates the negative pressure area occurring behind the returning bucket, and the pressure is rapidly recovered.

![Fig. 21 Flow visualization in a water-channel](image)

(a) Semi-circular type (b) Semi-circular type (OL = 0.00, $Re = 1.61 \times 10^5$) (c) Bach type (OL = 0.20, $Re = 1.45 \times 10^5$)

5. Conclusions

From this study, the following conclusions, which cover such effects of the aspect ratio, the stack of bucket, and the bucket endplates that had not been clarified up to the present, were obtained.

(1) Within the range of this study, a large aspect ratio provides the rotor with good torque and power characteristics; $AR = 4.29$ is optimum.

(2) For buckets of the semi-circular cross section, the appropriate overlap ratio is 20 - 30 percent.

(3) An increase in the gap ratio results in a decrease in the torque coefficient and the power coefficient; making no gap is preferable.

(4) Concerning the cross-section profile of the bucket, the Bach type is superior to the usual semi-circular type in the torque characteristics in low tip speed ratio range as well as in the power character-
istics. The appropriate overlap ratio for the Bach type is 10 - 30 percent.
(5) The three-bucket rotor is inferior to the two-bucket rotor in both torque and power characteristics, though the variation of static torque due to the rotational phase angle is equalized in the case of the three-bucket rotor. Therefore the two-bucket type is appropriate.
(6) The double-stack rotor is superior to the single-stack rotor in both torque and power characteristics. The single-stack rotor is suitable.
(7) The rotor with bucket endplates is superior to the rotor without endplates in the power coefficient and in the width of the operating tip speed ratio range. Bucket endplates are essential.
(8) The effects of the bucket overlap and the cross-section profile have been clarified through a visualized experiment in a circulating water channel.

As a result of the model experiments mentioned above, the effects of the design configuration factors of the Savonius rotor have been clarified. Therefore, this study would offer an effective guide to determination of the optimum design configuration in the preliminary design step for the Savonius rotor.

References