OPTIMUM-CONFIGURATION STUDIES AND PROTOTYPE DESIGN OF A WIND-ENERGY-OPERATED IRRIGATION SYSTEM

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Summary

This paper describes the design approach to a four-stage Savonius-rotor-based irrigation system suitable for a small farm of ~5 acres. The rotor construction is based on an optimum configuration of the blade geometry and aspect ratio, as given by an extensive wind-tunnel test program. The essential features of the full-scale system, including the microprocessor-based braking and load-matching procedures, are described. The prototype, designed specifically for field tests, is provided with appropriate performance and meteorological information-monitoring instrumentation to permit their correlation. Based on the wind-tunnel data, the wind turbine is expected to deliver 10,000 l of water per day to a head of 4 m in a 20 km h⁻¹ wind.

Notation

- $a$: blade gap size
- $A$: aspect ratio ($h^2/S = h/d$)
- $b$: blade overlap
- $C_p$: power coefficient ($P/(1/2)pV^3S$)
- $D$: shaft diameter
- $d$: blade diameter ($2r$)
- $h$: blade height
- $p$, $q$, $\theta$: parameters defining blade geometry (Fig. 5)
- $P$: power output
- $r$: blade radius
- $S$: projected blade area ($dh$)
- $V$: wind speed
- $\rho$: air density
- $\omega$: rotor angular velocity

Introduction

Although the utilization of wind energy has received some attention in recent years, a careful review of the literature brings to light an interesting
aspect. In general, most investigations in the area may be classified into two broad categories [1–5]:

(a) laboratory scale-model investigations, normally conducted at academic institutions by technically qualified personnel, which seldom evolve to a prototype stage for field tests and production; and

(b) operational devices, put together by environment enthusiasts with limited technical background, which function as a novelty at an uncertain efficiency; being isolated devices, these also fail to reach the production stage.

This paper describes the evolution of a wind-energy-operated irrigation system (Fig. 1), from model tests in wind tunnels for optimization of the system parameters, to a prototype prepared for field tests. The ultimate objective was to emphasize simplicity of design and ease of maintenance using infrastructure readily available in rural areas of developing countries. In particular, the system attempts to meet the irrigation requirements of small farms (~ 4–6 acres in size) in Indonesia, a country of around 10 000 islands with regular wind patterns and which has shown interest in the concept.

The project approaches the problem in several stages:

(i) a scale-model study of a Savonius rotor (0.12 m² projected area) in a wind tunnel, with systematic variation of the blade profile and gap size and of overlap and aspect ratio, to arrive at an optimum configuration;

(ii) wind-tunnel tests with larger two-stage models of the Savonius rotor
using the optimum configuration arrived at in (i), together with several
designs of commercial pumps;

(iii) assessment of the blockage effect during the wind-tunnel tests;

(iv) detailed design of a prototype and its construction using materials
readily available in an advanced industrial society such as Canada;

(v) instrumentation of the prototype for field tests to assess performance
and structural integrity (stages (iv) and (v) were added to the program due
to interest shown by farmers in Canada);

(vi) technology-transfer phase, involving simplification of the design using
materials readily available in Indonesia;

(vii) field tests in Indonesia to assess performance and establish mainte-

nance procedures (this will also provide an indication as to the loss of
efficiency due to the design simplification); and

(viii) production of the two versions of the same design as indicated above,
one for use in advanced-technology areas and the other in developing nations.

This paper describes briefly the progress made so far in the first five stages.

Model studies

The Savonius geometry was selected for the project because of its relative
simplicity and low starting wind speed. Several families of single- and two-
stage models were used in the test program to assess the effects of blade
profile and gap size and of overlap, aspect ratio and blockage. The models
were tested under several smooth-flow conditions using two wind tunnels,
of different cross-sectional areas, ideally suited for this class of studies.

Single-stage rotors

Preliminary experiments with four different blade configurations, includ-
ing semicircular geometry, suggested the one similar to that proposed by
Khan [6] to be promising (Fig.2). Hence the blade gap size and overlap study
was confined to this geometry. A typical two-blade model had a projected
area of 0.12 m². The blades, rolled into the desired shape, were constructed
from 16-gauge aluminum sheet and supported by two Plexiglas end-plates.
No vibration problems were encountered even at rotational speeds as high
as 1600 r.p.m.

The models were tested in a low-speed, low-turbulence, return-type wind
tunnel with a test-section of 0.91 × 0.68 m. The air speed could be varied
in the range 1–50 m s⁻¹ with a turbulence level less than 0.1%. The rotor
speed was measured by a Strobotac. For each blade setting, the torque out-
put was measured using a variation of the conventional Prony-brake ar-
rangement. The sensitivity of the system was 0.5 × 10⁻³ N m.

Typical results for the variation of power output with rotor r.p.m. for
various blade separations are given in Fig.3. The results show clearly that as
the separation α is increased, the maximum power for a given overlap dimin-
ishes. The maximum power with near-zero separation between the blades
was found to be 50.7 W at 885 r.p.m. In general, an increase in gap size tends to cause the maximum output to occur at a higher shaft speed for a given wind velocity.

The corresponding effect of the blade overlap \( b \) on the rotor output in the absence of a gap is presented in Fig. 4, which shows a significant reduction in the maximum power coefficient beyond \( b/d > 22\% \). This suggests clearly that the relative magnitude of the straight-line portion of the blade with respect to its radius of curvature is an important parameter in the design of an efficient blade geometry.
Based on the above observation, a simple procedure for obtaining families of blade profiles was evolved, as illustrated in Fig.5. Note that by systematic variation of the major variables \( p/q, \theta, a \) and \( b \), together with the blade aspect ratio \( h/d \), their optimum combination can be established through an elaborate wind-tunnel test program. The amount of information generated through variation of even some of these parameters is rather enormous. For conciseness only some of the typical results useful in establishing trends are recorded here. In this study \( \theta \) was held fixed at 135°.

The variation of power coefficient with tip speed ratio for the three values of \( p/q \) studied showed that a decrease in the flat portion of the blade in relation to its radius of curvature improves the rotor output (Fig.6). Further tests are in progress with zero as well as negative values of \( p/q \) to establish an optimum blade configuration.
Fig. 6. Effect of $p/q$ on variation of power coefficient with tip speed ratio.

Fig. 7. Plots showing effect of aspect ratio on power coefficient of a single-stage Savonius rotor (note that an aspect ratio of 0.77 leads to a maximum $C_p$ of 0.24 (blockage ratio 16.4%).)
Of considerable interest is the effect of the aspect ratio $h/d$ on the wind-turbine performance, as shown in Fig.7. The results suggest an optimum value of $\sim 0.77$, which was used in the prototype design.

Wind-tunnel results presented by different investigators often do not correlate, because of differing test conditions. One of the major parameters affecting such test data is blockage. To have some appreciation as to the wall confinement effects, three single-stage and one two-stage rotor models with identical values of $a$, $b$, $A$ and $p/q$ but differing blockage ratios were tested in a wind tunnel with a large cross-section of $1.53 \times 2.44$ m. The results presented in Fig.8 show clearly a dramatic increase in $Cp_{\max}$, due primarily to an increase in local velocity with blockage. Note that an increase in wall confinement from 5 to 20% can raise $Cp_{\max}$ by $\sim 70\%$, thus leading to a highly optimistic performance estimate if the blockage effect is not corrected.

Two-stage rotors

Besides providing useful information concerning the optimum blade configuration, the single-stage model study emphasized, as expected, the presence of dead spots when the blades are aligned with the wind and the rotor fails to start on its own. Thus, from self-starting considerations, it was necessary to have at least a two-stage rotor, with blades in the individual stages oriented orthogonally to one another. Furthermore, the results suggested that to generate even 100 W at a wind speed of 25 km h$^{-1}$ would require a projected area of $\sim 3.5$ m$^2$. The requirement that ease of construction
be a guiding criterion, particularly in a rural environment, suggested a multistage construction. It was therefore decided to conduct tests with models of a two-stage rotor to assess interference effects due to staging. To this end, two scaled models with projected areas of 0.6 and 1.12 m$^2$ were designed, using the optimized parameters established earlier, and tested in the larger wind tunnel. The strain-gauge-based load-measuring device mentioned earlier proved to be inadequate at larger outputs. It was therefore modified into a bigger dynamometer using two concentric cylinders, one of them free to undergo rotational displacement under the action of the torque transmitted through high-viscosity oil in the gap. The torque-dependent displacement was measured through cantilever-mounted strain gauges as before. The details of the arrangement have been described in ref. 7.

Typical power plots at several wind speeds are shown in Fig. 9 for the smaller two-stage rotor with a blockage ratio of 16.4%. In general, the variation of power coefficient with tip speed ratio would be expected to be independent of wind speed. However, in the present case the power coefficient showed a slight increase at higher wind speeds. This may be attributed to frictional bearing-losses in the dynamometer which depend on the rotor speed and diminish with an increase in $\omega$ in the range of interest here.

It was thought more appropriate to evaluate the potential of the wind turbine in terms of its pumping capability, particularly given the present irrigation-oriented application. Hence tests were carried out in conjunction with the larger two-stage model driving a variety of pumps to establish their suitability for the intended purpose. A typical set of results is presented in

![Tip speed ratio](image)

Fig. 9. Typical plots showing effect of wind speed on output for a two-stage Savonius rotor with a projected area of 0.6 m$^2$. 
Fig. 10. Variation of flow rate with head and wind speed for a model of a two-stage Savonius rotor ($S = 1.2 \, \text{m}^2, p/q = 1, a = b = 0, A = 0.66, \text{blockage 27.4\%}$).

Fig. 10. The tests show that even a small Savonius rotor, of $1.12 \, \text{m}^2$ projected area, with the optimized parameters, can deliver $\sim 400 \, \text{l}$ of water per hour to a head of $5 \, \text{m}$ at a wind speed of $\sim 22 \, \text{km h}^{-1}$.

Prototype design

With the optimum blade geometry, aspect ratio, rotor staging and pumping characteristics in hand, design of a full-scale wind-turbine system was initiated. As stated before, the initial objective was to design a system for use in rural, farming communities in Indonesia. Accordingly, the guiding criteria which shaped the design were simplicity of construction, operation and maintenance, utilization of locally available material, and use of technology compatible with the rural environment.

However, as the design progressed, interest expressed by farmers in Newfoundland, Quebec and British Columbia suggested that there was a significant local demand for the device. It was therefore decided to design a prototype keeping in mind its ultimate application in a rural society but using relatively sophisticated materials readily available in an advanced industrial country such as Canada. Thus, with a technology-transfer phase, essentially the same basic design may serve the needs of farmers in Canada as well as in technologically developing nations.

System assembly

The prototype described here, which has been constructed and installed, was designed specifically for field tests. Essentially the system consists of four stages with each stage $1.2 \, \text{m}$ in diameter and $0.915 \, \text{m}$ high, thus giving a projected area of $4.45 \, \text{m}^2$. The rotor is built on a sleeve and supported by two ball-bearings, fixed to a mast $11.6 \, \text{m}$ tall. The mast is held in position
by eight guy-wires. A set of pulleys at the bottom of the rotor transmit power through a drive shaft to a system of pumps, located at the mast base to facilitate installation and servicing (Fig.11). Two water lines run between the supply and receiving water tanks, the former located at the bottom and the latter supported on the mast at the height desired to provide the required head.

In the actual application (i) the mast and the guy-wires will be replaced by a locally constructed support frame, (ii) the pump will be connected directly to the rotor sleeve, and (iii) the bottom tank will be an irrigation ditch, well or river, and the top tank a separately constructed reservoir as shown in Fig.1.

Braking and load-matching systems

The Savonius rotor system is provided with an emergency braking system to guard against possible structural failure at high wind speeds (> 70 km h⁻¹). Essentially it resembles the conventional automobile brake, consisting of a drum with spring-activated callipers carrying asbestos pads. The braking operation is governed pneumatically.

A comment concerning the pumps and the load matching procedure is appropriate. For a positive-displacement pump, the flow rate varies linearly with r.p.m.; however, the wind-turbine output varies as $V^3$. Thus for efficient operation a load-matching procedure is necessary. In the present case this is accomplished by three pumps rated at 9, 22 and 44 l min⁻¹ at 1750 r.p.m. Each of the pumps is provided with a magnetic clutch operated by a 120 V AC supply, which is switched on through a microprocessor circuit at a predetermined wind speed.
Monitoring instrumentation and controller

A literature review suggests that, in general, field-test results with prototype wind turbines and their correlation with model wind-tunnel data are indeed quite scarce. This is particularly true for the Savonius configuration. The present study promises to provide this vital information. It is intended to use the facility to correlate rotor r.p.m., instantaneous and integrated discharge rates, wind velocity and direction, and turbulence intensity. This will assist in assessing the effectiveness of blade geometry, pump configurations, and several load-matching techniques.

The system is provided with a digital r.p.m. meter, two paddle-wheel-type flowmeters with instantaneous and integrated discharge data outputs, and a well-proven Gill anemometer, all connected to a multichannel data-logger with variable data-sampling capability. Data concerning wind speed, direction, flow rate, etc., sampled at several preprogrammed rates, are recorded on magnetic tape for statistical and correlation analysis.

It was considered essential to incorporate a microprocessor-based controller to:

(i) apply the brake automatically at a desired preset wind speed, to assure safety of the structure; and
(ii) permit load-matching by actuating the magnetic clutches connecting or disconnecting the pumps according to the wind speed.

Figure 12 indicates the flow of signals to and from the data-logger and signal processor activating the brake solenoid and magnetic clutches to achieve the above objectives.

![Fig.12. Field-test configuration of rotor, showing relative position of meteorological mast and associated instrumentation. Directions of control signals are also indicated.](image-url)
Concluding remarks

Based on the results obtained, the following general conclusions can be drawn.

(i) The study with families of single- and two-stage models suggested substantial effects of aspect ratio and blockage. The optimum value of $A$ was found to be 0.77. Absence of a gap between the blades resulted in maximum output, while the influence of overlap was particularly noticeable only for $b/d > 0.22$. Reduction in $p/q$ over the range of 1.6–0.4 tested resulted in an improved performance. Experiments are in progress to establish the optimum value.

(ii) The wind tunnel tests suggested a projected area of ~ 4 m$^2$ to meet the irrigation requirements of a 4–6-acre farm.

(iii) Based on the wind-tunnel data, the prototype with a projected area of 4.45 m$^2$ is anticipated to deliver at least 10 000 l of water per day to a head of 4 m in a 20 km h$^{-1}$ wind.

(iv) There is considerable demand for wind turbines with a power output in the range 5–10 kW, particularly in rural communities. Unfortunately, rotors in this category have received relatively little attention. The Savonius-rotor-based irrigation system of moderate capability described here represents only a small step in the evolution of such a design. The planned field tests with the prototype will provide performance information helpful in achieving this goal.

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References