Field testing of water pumping windmills by CWD


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FIELD TESTING OF WATER PUMPING WINDMILLS
BY CWD

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ABSTRACT

Field testing of water pumping windmills is an important part of CWD's activities. Measurements are performed by means of Apple II computers and thereafter elaborated by means of the same computers, using software developed by the Wind Energy Group. This article discusses some aspects related to the hysteresis behaviour of windmills driving piston pumps.

The behaviour of a windmill in the hysteresis region depends on the history of the wind speed. Therefore the average curves measured according to the generally accepted IEA recommendations depend on the frequency distribution and time history of the wind speed during the measurements. The IEA practices were conceived to provide a means of measuring output curves in a reproducible way. The underlying assumption is that an output curve is a characteristic of a wind machine, valid at any site, in any wind regime. As indicated above, this is not the case for windmills driving piston pumps, or for that matter for any wind machine, having hysteresis behaviour. Two examples are presented of output curves, measured for one machine at one site under different wind conditions. Considerable differences were found. Annual water outputs calculated on the basis of the two curves can differ as much as a factor of two.

Procedures for output prediction of water pumping windmills will have to involve three steps instead of two. The procedure must start by determining an output curve, including hysteresis effect, which only depends on characteristics of the wind machine. Subsequently the curve must be converted into a simple but site specific curve by means of probabilities derived from the site's wind speed frequency distribution. The third step is the conventional multiplication and integration of output curve and frequency distribution. A simple theoretical model has been developed including these three steps. Procedures for field measurements based on this concept will need to be developed.

List of symbols

- $A$: rotor area ($m^2$)
- $C_E$: energy production coefficient (-)
- $C_p$: power coefficient (-)
- $C_T$: torque coefficient (-)
- $D$: diameter (m)
- $E$: energy (J)
- $k$: Weibull shape factor (-)
- $N$: number (-)
- $P$: power (W)
- $p$: probability (-)
- $p_r$: probability of running in hysteresis region (-)
- $p_{idem}$: idem, including wind speed variations within 10 minutes (-)
- $q$: pumping rate (1/s)
- $T$: time (s)
- $V$: wind speed (m/s)
- $V_{rel}$: relative wind speed in hysteresis region (-)
- $V_{st}$: relative wind speed in hysteresis region (-)
- $q_{eff}$: efficiency (-)
- $\lambda$: tip speed ratio (-)
- $\omega$: air density (1.2 kg/m$^3$)

Subscripts

- $d$: design, i.e. the point for which $C_E \omega$ reaches its maximum
- max: maximum

1. INTRODUCTION

CWD (Consultancy Services Wind Energy Developing Countries) is an organization initialized and funded by the Netherlands' Ministry of Development Cooperation. It aims to help governments, institutes and private parties in the Third World in their efforts to use wind energy and in general to promote the interest for wind energy in developing countries. The emphasis of the activities of CWD is on water pumping windmills, coupled to single acting piston pumps. Participants of CWD are DW Consulting Engineers (Amersfoort), Eindhoven University of Technology, Iwante University of Technology and ILRI, Institute of Land Reclamation and Improvement (Wageningen). CWD designed water pumps are in operation in Sri Lanka, Pakistan, Tanzania, Mozambique, Sudan, Mauritania, Tunisia, Peru, Cape Verde and Ghana.
Three commercially available windmills have been tested: OASIS (2 m diameter, manufactured in France), FAIYA (3 m, Argentina), Southern Cross (5.2 m, Australia). Another series of tests on three commercial windmills started recently: BOWDON (2.56 m, driving an air compressor, and a lift pump, ISO), LIDING (1.50 m, W. Germany), and DEMPSTER (4.3 m, USA). Also a wind pump (2 m) was installed for endurance tests.

The Vrijzenveen testfield is used for functional tests and output performance measurements on prototypes developed by the Windmill Group of ETH. The CWD 5000 (the number refers to the rotor diameter in m) has been tested there in a version with a deep well pump and one with a low lift/volume pump. A newly designed 5 m diameter prototype is being tested.

The Eindhoven testfield (Figure 2) is meant for:
- functional testing of prototypes
- performance testing of prototypes
- special measurements (like start tests, measurements, measurements of stress, etc.)
- field testing of innovative concepts
- development and testing of monitoring systems
- anemometer tests

In this article special attention is paid to output performance measurements for mechanical wind pumping windmills. A specific problem will be presented, which is the presence of a large hysteresis loop in the start/stop region of the output curve. The consequences for output predictions will be shown.

2. STARTING AND STOPPING: HYSTERESIS BEHAVIOUR OF WINDMILLS DRIVING FISTON PUMPS

Mechanical windmills driving piston pumps have a rather peculiar starting behaviour, which is quite different from wind electric generators.

The special behaviour is due to the characteristic of the load.

A piston pump requires a torque which is in first approximation independent of the speed of operation. The torque is determined by the stroke length and by the water pressure on the piston, and only increases slightly at high speeds due to pressure losses in the valves and pipes.

Moreover, the torque is cyclic: during the upward stroke the piston has to lift the water, requiring a large torque, and during the downward stroke the torque is practically zero. The maximum torque during one cycle is 2 times the average torque.

Starting from stand still in such a situation is quite difficult for a wind machine.

In order to start the load, a high torque is required. In order to lift the piston for the first time, the maximum torque is needed (2 times the average).

The windmill blades are in stall, and the torque available from the windmill is relatively low. This means that the wind speed at which the windmill starts from stand still is relatively high: \( V_{start} \).

Once running, the situation becomes much more favourable.

The cyclic character of the load has no influence any more due to the large inertia of the windmill rotor. Only the average torque is needed.

The windmill blades work in their normal range of operation, i.e. in lift.
Due to this start-stop behaviour one will find a hysteresis loop in the output curve as indicated in figures 3 and 4.

\[ C_p = C_p \max - \lambda / \lambda \max \lambda_d \]

The pump is assumed to demand a constant torque for all speeds, including the design wind speed, therefore the windmill will deliver a constant torque at all points of operation.

\[ C_p V^2 = C_{pd} V_d^2 \]

From these two equations one finds \( \lambda \) as a function of \( V \). Substituting the result into the first equation, and using the fundamental relationship \( C_p \lambda C_d \), one finds an expression for \( C_p \) as a function of \( V \):

\[ C_p = \frac{V_d^2 \lambda \max}{(1 - \lambda)^2 \lambda_d} \]

Assuming a constant efficiency for the pump, expression 3 also represents the shape of the \( C_p \) curve (see fig. 4). Of course, it can easily be converted into a \( P(V) \) curve. For a windmill-piston pump system the point at which \( C_p \lambda \max \) is sharply defined, since the locus of maximum power points in the torque-speed characteristic of a windmill is a second order curve, whereas the torque characteristic of a piston pump is basically a horizontal line. The point of intersection corresponds to the design wind speed \( V_d \).

Expression 3 describes the upper branch of the hysteresis loop (see figures 3 and 4). It is similar for a wide range of mechanical water pumping windmills. Only the values of start and stop wind speeds are different for different types of windmills.

3. FIELD MEASUREMENTS OF OUTPUT CURVES WITH HYSTERESIS LOOP

In this section some problems of field measurements are presented which are caused by the hysteresis effect. This is done on the basis of measurements performed at the Almace test facility for the Argentina manufactured FIASA windmill. The FIASA is a typical example of a classical "American" windmill. The rotor is 3.06 m in diameter (about 10') and has 18 blades. It is back geared (1:3.29). During the test it was driving a piston pump (diameter .101 m, and stroke .243 m). This configuration was specified by the manufacturer. This corresponds to a design wind speed \( V_d \) of 2.5 m/s.

A complete report of the tests and measurements is available, see reference 4. Some of the results were already published at a conference in London, reference 3.

Complete and reliable measurements were performed in the period October. November 1965. The measurements were performed according to the recommendations of the
I. Introduction (2). No selection of measurements was applied except for selection of wind directions as recommended by IEA.

3.1 Measured and calculated $C_p$ curves

When performing 10 minutes average measurements according to the IEA recommendations, the results in the hysteresis region will be some average of the upper and lower branch of the hysteresis loop (see figure 4). Sometimes the windmill is running (upper branch), and sometimes it is standing still (lower branch). For this region one expects to find average values below the theoretical curve, as well as a considerable spread in the measurements: a large standard deviation. This was indeed the case as can be seen in figure 5.

Fig. 4a Wind speed frequency distribution

Fig. 5b $C_p$ curve

Fig. 5 Results of measurements of FIASA windmill October-November 1985, 4143 measurements (ref. 4).

Figure 5a shows the frequency distribution of the wind speed during the measuring period, which will prove to be an important reference.

Figure 5b shows the measured $C_p$ curve as crosses. The centre of a cross represents an average value, the length of the crosses corresponds to the standard deviation. The drawn curve corresponds to the theoretical $C_p$ relationship derived above (equation 3). The dotted curve corresponds to a correction which will be presented in section 4 of this article (equation 5). In the hysteresis region between $V_{1/3}$ and $V_{max}$, (2 and 4 m/s respectively) one sees that the measured values are far lower than predicted by the simple theoretical formula (3). As expected, a large standard deviation is found in this region. Below 2 m/s one finds some low, but non-zero values for $C_p$. This is due to wind speed variations within 10 minutes. Even in a 1.5 m/s wind, one will have some moments with a wind speed over 4 m/s. Between 4 and 9 m/s the measurements coincide very well with the theory. At high wind speeds the measured value is lower due to the safety system which limits the output.

3.2 Reproducibility of output curves

As indicated before, a windmill-man system may operate either in the upper, or in the lower branch of the $C_p$ curve (figure 4). What exactly happens depends on the history: Once the windmill is running it will continue doing so when it enters the hysteresis region. Once standing still, it will remain standing still when entering the hysteresis region. Therefore, the probability of either situation depends on the wind speed distribution. In a period of strong winds the windmill will be running most of the time and the system will follow more often the upper branch of the hysteresis loop than the lower one. In a period of weak winds the opposite is expected.

In order to verify this, two different data series were chosen from the total data base on which figure 5 was based. One series was chosen so as to have mainly high wind speeds. Another one was chosen so as to have mostly low wind speeds. For these two series, graphs were made of frequency distribution, and power coefficient, see figures 6 and 7. It is to be noted that the full data series were used, no selection of data was practised, except for selection of wind direction as recommended by IEA.
Indeed, the two curves of figure 6 and 7 are quite different. For the first series, having mostly high wind speeds the measured values approximate closely the simple theoretical relationship (3).

It is concluded that, following the recommendations of IEE, completely different Cpφ curves can be obtained for one and the same wind machine. This procedure of measuring output curves does not yield reproducible results if the output curve has a hysteresis loop.

In order to judge how seriously this affects output predictions, yearly average outputs were calculated both on the basis of the measurements of figure 6 and of figure 7. Especially for low average wind speeds, in which water pumping windmills are often applied, very large differences were found: 50% to 100%, see reference 3.

3.3 Distribution of observations within a bin

Because of the large standard deviations of the Cpφ measurements in the hysteresis region, it seems of interest to study in more detail which values have occurred, and with what frequency. Figure 8 shows two distributions of observations in typical bins: one within the hysteresis region (2.5 to 3 m/s), and one outside the hysteresis region (5.5 to 6 m/s). The figure was derived from the same series of measurements as figure 5. The difference between the two bins is quite clear. Inside the hysteresis region one finds a wide variety of values, ranging from 0 to 45%. Outside the hysteresis region one finds a distribution, which is nicely centered around one well defined value.

Figure 9 shows the influence of the wind regime on the distribution of Cpφ values inside the hysteresis region (again for the 2.5 to 3 m/s bin). Figure 9a refers to a period of high wind speeds (same as figure 6), figure 9b to a period of low winds (same as figure 7).

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Fig. 7 Results of measurements of FINNA windmill October 17 until October 21, 1985. 194 measurements. Low wind speeds prevail, average wind speed 2.4 m/s

Fig. 8 Distribution of measured Cpφ values within one bin Measurements of FINNA windmill October-November 1985
low minutes (upper branch) and stand still during the remaining 10 minutes period, resulting in some intermediate 10 minutes average. From figures 8 and 9 it may be concluded that it does not make much sense to take a simple arithmetic mean of all observations in a bin within the hysteresis region. Doing this, would not result in a unique C(T)-V relationship. If high wind speeds prevail, the frequency distribution of observations is distorted in favour of high C(T) values, and a high average value would be found. If low wind speeds prevail one would find a low average value.

4. CONSEQUENCES FOR OUTPUT PREDICTION

The total energy output of a wind machine over a longer period of time depends both on characteristics of the wind machine, and the site where it is installed. It is usual to separate the wind machine's characteristics and the site characteristics in the following ways:

- Output curve of the wind machine, the relationship between output power output of the machine and wind speed. This is assumed to be a unique characteristic of a given wind machine (with load), independent of site characteristics, universally applicable.
- Wind speed frequency distribution, summarizing information on the wind regime of a certain site.

The IEA recommendations for output performance testing (reference 2) are based on this concept. They describe how to measure an output curve during a relatively short period of time. Total output at a certain site is to be calculated by "multiplying" the output curve, and the frequency distribution, i.e., multiplying corresponding points and integrating the result.

For a long time it has been attempted to conceive of output prediction models for water pumping windmills along the same lines as energy yield calculations with respect to the calculation of an unambiguous probability of pumping in the hysteresis region, which was needed to determine a unique output curve in this region.

On the basis of the experience with output measurements presented above, the solution to the problem has become quite obvious: one must leave the concept of a unique output curve, which would be generally applicable for any site. Instead, a three step procedure will be required for the calculation of total output of a water pumping windmill:

- An output curve is determined including the two branches of the hysteresis loop. A theoretical model to do this can be rather simple (see section 1 of this paper). A measuring procedure will be more complicated and is being developed.
- Using the actual wind speed frequency distribution of a certain site one calculates the probability of pumping in the hysteresis region and corrects the output to find a curve which is valid for this particular site only.
- The first task is to establish the probability of pumping in the hysteresis region. Once in the hysteresis region, the windmill must go back in time until finding a wind speed outside the hysteresis region. If this wind speed happens to be higher than \( V_{start} \), the windmill is running all the time; if it happens to be less than \( V_{stop} \), the windmill is standing still. Writing the probability of a wind speed greater than \( V_{start} \) as \( P(V>V_{start}) \), and writing the probability of a wind speed outside of the hysteresis region as \( P(V>V_{start}) + P(V<V_{stop}) \), one may express the probability of the windmill running as follows:

\[
P(V>V_{start}) = \frac{P(V>V_{start})}{P(V>V_{start}) + P(V<V_{stop})}
\]

The probabilities \( P \) can be simply calculated from measured wind speed frequency distributions or estimated from assumed Weibull distributions. The probability function \( (4) \) is constant throughout the hysteresis region. Applying this factor as a correction to the result in a rather strange output curve, with a steep step at \( V_{start} \). Also, a constant probability is not very realistic. The probabilities defined above refer to 10 minutes average wind speeds, whereas a windmill will react on a much shorter time scale: it may start or stop due to a gust or a lull of a few seconds only. For a 10 minutes average wind speed just below \( V_{start} \) the probability of running must be practically unity; within the 10 minutes one will soon observe a gust above \( V_{start} \); the windmill starts and keeps on running. For a wind speed just above \( V_{stop} \), the probability of running will be practically zero for a similar reason. Analyzing this process would be very complicated. For the time being, as a first guess, simple linear relationships are assumed. At \( V_{stop} \) a probability of zero is assumed, in the middle between \( V_{start} \) and \( V_{stop} \) a probability equal to \( p \) (see above), at \( V_{start} \) a probability of 1. In between the probability is assumed to vary linearly with wind speed, summarizing:

\[
\begin{align*}
\text{for } v < 0 & \Rightarrow p = 0 \\
\text{for } v > 0 & \Rightarrow p = 2v \quad \text{with } v = \frac{V_{V_{stop}}}{V_{start} - V_{stop}} \\
\text{for } 0 < v < 2 & \Rightarrow p = 1 \\
\text{for } v > 2 & \Rightarrow p = 1
\end{align*}
\]

This correction has been indicated with dotted lines in figures 5, 6, and 7. The probabilities were derived from the measured distribution. It corresponds reasonably well to the measurements.
calculate the total output, rather i.e. by the Cwor curve 1, with the correction for the windmill, according to equation (5) must be integrated after multiplication with a Weibull distribution. The results can be presented in a general format by defining an energy production coefficient, which is the ratio of energy produced and a reference energy:

\[ C_w = \frac{E}{\frac{1}{2} \rho A V^3 C_{p_{\text{max}}} T} \]  

\[ \text{(6)} \]

This coefficient will be a function of the ratio of the design wind speed of the windmill and the average wind speed at the site of installation: \( V_d / V \).

Figure 10 shows some results.

![Fig. 10 Energy production coefficient as a function of design wind speed vs average wind speed](image)

Drawn curves: theoretical model presented here

Dots: results of measurements, see table below

Of course, important parameters are start and stop wind speeds. Figure 10 shows as an upper limit the integration of the complete \( C_w \) curve, i.e. assuming that the windmill is always running in the hysteresis region. Three more curves are indicated which are believed to be typical for three classes of windmills: classical “American” windmills with and without balancing of the pump rod weight, and windmills having a starting nozzle in the pump and a balanced pump rod (like the CWO designs). For the start and stop wind speeds, values were assumed as indicated in figure 10. These values were derived from earlier work, see reference 3.

Some more assumptions, of minor importance were necessary for calculating the graphs. The shape factor of the Weibull distribution was taken to be 2, a usual value. The parameter \( \lambda_{\text{max}}/\lambda_1 \), see expression (3) was taken to be 1.6, a usual value (except for \( V_{\text{v}} \), a value of 2 was taken, since otherwise the maximum \( C_w \) would not occur at \( V_d \). It was assumed that the windmill’s safety system limits the output to a constant value for wind speeds above three times the design wind speed (i.e. \( V_{\text{rated}} = 3 V_d \)), and that it shuts down the windmill completely above six times the design wind speed (\( V_{\text{safety}} = 6 V_d \)) yielding a correction of not more than 10% of \( C_w \).

For the windmill with starting nozzle the \( C_w \) relationship was corrected for losses through the nozzle, according to

reference 1, a, \( V_d \) this case 2.

As does figure 10 indicate, the results of measurements, table I, summarize these measurements and indicate the references. The dots represent the average values during the whole measuring period. The tests of Southern Cross, Fiasa, and Oasis were performed at the AWE test site, with very high average wind speeds.

Therefore the corresponding points are found in the left part of the graph. The tests of the WEU T/5 and the CWO 2000 (both windmills with a starting nozzle and a relatively high \( V_d \)) were performed at the test site in Eindhoven with rather low average wind speeds, yielding points more to the right in the graph.

The table below summarizes some information of the measurements, and the assumptions made.

Table I. Measurements indicated as dots in figure 10.

<table>
<thead>
<tr>
<th>Windmill</th>
<th>( C_{\text{max}} )</th>
<th>( V_d )</th>
<th>( V )</th>
<th>( C_w )</th>
<th>ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiasa</td>
<td>0.35</td>
<td>0.86</td>
<td>2.3</td>
<td>5.0</td>
<td>0.37</td>
</tr>
<tr>
<td>So Cross</td>
<td>0.35</td>
<td>0.86</td>
<td>2.8</td>
<td>5.5</td>
<td>0.42</td>
</tr>
<tr>
<td>Oasis</td>
<td>0.35</td>
<td>0.66</td>
<td>1.9</td>
<td>4.1</td>
<td>0.24</td>
</tr>
<tr>
<td>WEU T/5</td>
<td>0.35</td>
<td>0.66</td>
<td>4.1</td>
<td>3.7</td>
<td>0.86</td>
</tr>
<tr>
<td>CWO 2000</td>
<td>0.35</td>
<td>0.35</td>
<td>4.6</td>
<td>3.3</td>
<td>0.62</td>
</tr>
</tbody>
</table>

* For the mechanical efficiency a value of 0.88 was taken for high head pumps, and 0.60 for low head pumps.

For the CWO 2000 a value of 0.35 was taken because of friction in this first prototype, to which the measurements refer. Later it was improved considerably.

5. CONCLUSIONS

In a general manner it may be concluded that systematic field measurements contribute significantly to the understanding of the performance of wind machines.

More specifically field measurements of output performance have produced a much better understanding of the importance of the hysteresis behaviour in the start/stop region on the total output of water pumping windmills.

It was found that field measurements performed according to the IAE recommendations do not result in reproducible output curves for water pumping windmills having a pronounced hysteresis behaviour. The differences in measured output curves may lead to differences in calculated total output as large as a factor two, especially for low average wind speeds, in which water pumping windmills are often applied.

On the basis of the experience with field measurements, a new procedure for output predictions is proposed, involving three steps:

- Determination of the output curve including hysteresis loop depending only upon characteristics of the wind machine.
- Conversion of this hysteresis output curve into a simple (site specific) output curve by means of probabilities.
derived from the wind speed frequency distribution at the site of installation.
- Multiplication and integration of the site specific output curve and the site's wind speed frequency distribution.

A simple theoretical model was developed including these three steps. It seems to be in reasonable agreement with the measurements available so far. However, it will need further validation and refinement.

Procedures for field measurements based on this "three step" approach still need to be developed. This may eventually lead to an extension of the IEA recommendations.

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