Aerodynamic Performance of Wind Microturbines and Their Dynamic Response

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Abstract
Wind microturbines typically have rotor diameters of 2m or less. For practical purposes the wind generated forces acting on the mounting poles can be estimated using the method described in Ref[1]; technical details of the derivations are given in Ref[2]. The method used to determine these wind induced loads is based upon the codified approach described in BS EN 61400 (Ref[3]), coupled with a dynamic magnification factor.

This abstract presents theoretical expressions of aerodynamic performance, and shows how wind tunnel measurements can be used to estimate the mean and fluctuating forces generated by a wind microturbine.

1 Introduction
A commercially available three-bladed microturbine (shown in Figure 1) was tested at the blow-down outlet of a wind tunnel located at BRE. The microturbine has a diameter of 1.2m, and generates a maximum power output of about 300W. Within the rotor hub are springs which are attached by a linkage mechanism to the blade roots. These springs are designed to cause the blades to furl (i.e. change their angle of incidence) at a critical wind velocity, thus limiting the power output from the turbine. Measured power and the rotational characteristics of the microturbine are also shown on Figure 1.
Work undertaken at BRE has demonstrated that a microwind turbine mounted on a pole acts as a one degree of freedom (1-DOF) dynamic system. As shown below the wind tunnel results can be combined with measurements of the dynamic loads acting on the mounting pole. This combination produces results and expressions which allows the mean and peak loads generated by wind microturbines to be predicted.

2 Static Results

The efficiency of a turbine system is defined by

\[ \eta = \frac{P}{\frac{1}{2} \rho A V^3} \]  \hspace{1cm} (1)

where \( P \) is the power generated by the turbine, \( A \) is the swept area of the turbine rotor (m\(^2\)), \( \eta \) is the overall efficiency of the turbine and its associated electrical equipment (i.e. the overall efficiency of the system), \( V \) is the windspeed (m/s) and \( \rho \) is the air density (kg/m\(^3\)).

The electrical power output was measured in the wind tunnel at a range of speed settings. This information was used to calculate the overall efficiency of the wind microturbine system (\( \eta \)); the results are shown as the black trace of Figure 2. It can be seen that the maximum efficiency measured occurs at about 11m/s which is the speed at which the blade furling starts to occur. Below this
threshold velocity it can be seen that the efficiency is reasonably independent of windspeed, and varies between 16 and 20%.

The overall efficiency of the system $\eta$ can be expressed as the product of the electrical and aerodynamic efficiencies ($\eta_e$ and $\eta_a$ respectively), viz: $\eta = \eta_e \times \eta_a$.

$\eta_a$ accounts for the aerodynamic efficiency of the rotor. It is therefore the difference between unity and the ratio between the non-recoverable aerodynamic pressure losses (caused by drag, flow swirl, and turbulence), and the total dynamic pressure ($\frac{1}{2} \rho V^2$) of the approaching flow.

$\eta_e$ accounts for electrical losses. Therefore $\eta_e$ is the difference between unity and the ratio between the sum of i) the electrical power losses of the AC 3-phase generator and cabling losses, and ii) the 3-phase to DC rectification losses, and the overall power $P$ generated by the turbine.

The non-dimensional thrust coefficient, $C_T$ has also been plotted as the red trace of Figure 2. This coefficient is defined by

$$C_T = \frac{P^2}{\left(\frac{1}{2} \rho V^2\right)^2 \times A \times V^2 \times B(cR)} \quad (2)$$

where $B$ is the number of turbine blades ($B = 3$), $R$ is the turbine blade radius ($R = 0.6m$) and $c$ is the average turbine blade chord ($c = 0.082m$).

It can be shown that the thrust coefficient is related to the force coefficient $C_{F(turb)}$ by

$$C_T = \eta_e \times C_{F(turb)} \quad (3)$$

where $\eta_e$ is the aforementioned electrical efficiency of the turbine generation system. Figure 2 shows that $C_T$ varies systematically over the windspeed range tested. However, this variation is not large and the average value over the range of windspeeds tested (between 3-19m/s) is 0.28. If the efficiency of the electrical system is reasonably constant over the range of power being generated (which does not seem an unreasonable assumption) then Equation (3) shows that $C_{F(turb)}$ must also be relatively insensitive to changes of windspeed.

![Figure 2 Variation of Efficiency and Thrust Coefficient With Windspeed](image-url)
Dynamic Results

For a 1-DOF wind microturbine and pole mounting system vibrating at resonance, the amplitude of the pole mounting forces, $F_0$, is given by

$$F_0 = \frac{\frac{1}{2} \rho V^2}{2L \zeta_s + \zeta_b + \zeta_a} \left[ B(cR)C_{F(turb)} + (Ld)C_D \right] = \frac{\frac{1}{2} \rho V^2}{2\left[ \zeta_s + \zeta_b + \zeta_a \right]} \left[ B(cR)C_{F(turb)} + (Ld)C_D \right]$$

(4)

Where $L$ is the exposed length (m), $d$ is the diameter (m) and $C_D$ is the drag coefficient of the mounting pole, $\zeta_s$, $\zeta_b$ and $\zeta_a$ are respectively the critical damping coefficients of the structure, the turning blades and the static blades, $f_0$ is the fundamental natural frequency of the system, and $EI$ is the structural rigidity of the mounting pole (Nm$^2$). With the wind tunnel not running, the structural damping ratio ($\zeta_s$) was determined by measuring the logarithmic decay of the pole oscillations.

From equation (4) it can be seen that

$$\zeta_a = \frac{2\sigma f_0}{2} \times V \times \left( \frac{L^3}{3EI} \right) \times \left[ B(cR) \times \left( \frac{C_T}{\eta_e} \right) + (Ld)C_D \right]$$

(5)

Note that $\zeta_a$ is not proportional to $V$, since $C_T$ varies with $V$ as shown in Figure 2. For the test arrangement shown in Figure 1, $f_0 = 2.6$ Hz, $EI = 2.898 \times 10^3$ Nm$^2$, $L = 2.38$ m, $d = 0.0482$ m, $C_D = 1.2$.

For a given wind tunnel speed, the damping ratio of the turbine system ($\zeta_b$) was obtained using theoretical curves fitted to the power spectra of the measured dynamic force. Values of the aerodynamic damping ($\zeta_a$) were calculated using Equation (5) for a range of electrical efficiency ($\eta_e$) values.

For a range of wind tunnel speeds the amplitudes of the fluctuating forces acting on the turbine pole ($F_0$) were measured using a force balance, and the results are shown on Figure 3. The black line shown on this figure was calculated using Equation (4), with an electrical efficiency ($\eta_e$) of 0.324 (32.4%); this electrical efficiency gave the best fit with the experimentally measured data. It can be seen that, for all practical purposes, the amplitudes of the fluctuating forces are proportional to the approaching wind speed, $V$.  

![Graph showing fluctuating forces vs wind speed](image-url)
With the wind tunnel running it was observed that the amplitude of the force acting on the turbine pole varied in time. The variation of the force amplitude was quantified by measuring its standard deviation, $\sigma_f$. The variation of $\sigma_f$ with windspeed is shown in Figure 4; it can be seen that this parameter increases with the square of the speed.

Using a peak factor approach the peak wind load produced by the microturbine can be estimated using Equation (4), and the empirical expression shown on Figure 4.

3 References


Breeze G. *Static and Dynamic Wind Loads on Building-Mounted Microwind Turbines*. BRE Information Paper IP 14/12, BRE 2012