

Determination of performance parameters of vertical axis wind turbines in wind tunnel

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Abstract. The paper deals with the determination of the performance parameters of a small vertical axis wind turbines (VAWT), which operate by the utilization of drag forces acting on the blades of the turbine. The performance was evaluated by investigating the electrical power output and torque moment of the wind machine. Measurements were performed on the full-scale model and the experimental data are assessed and compared to other types of wind turbines, with respect to its purpose.

1 Introduction

The energy industry today has increased interest in the use of renewable energy sources, which are more environmentally friendly. Among renewable ecological energy sources are undoubtedly wind turbines [1]. One goal of this article is to determine the power and torques characteristics of a very simple wind turbine with a vertical rotation axis VAWT by measurements in the wind tunnel. This model changes the kinetic energy of airflow into mechanical energy of the generator shaft and then it is converted to electricity. The expected output of this measurement is performance characteristics of the wind turbine depending on the velocity conditions of the wind tunnel.

On the basis of the measured results on the VAWT, characteristics were performed to its dimensionless state and a compared with the value obtain by theoretical assumptions. By applying dimensional analysis, it is possible to subsequently predict performance characteristics of a geometrically similar wind turbine, which will be produced in the desired size. From the results obtained by the measurement, and subsequent conversion to the parameters of the real model, it is possible to determine the power requirements for the connected electrical rotating machine - a generator which converts mechanical energy of VAWT to resulting electrical energy. The generator is an integral part of the entire set of wind turbines [Fig. 2b]. Its output parameters enable us to design and dimension the parameters of other devices connected to VAWT. The evaluation process also included the results of the performance measurement for an air flow velocity in the measurement section of the wind tunnel in a range from 8 m/s to 14 m/s.

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2 The drag type of VAWT

2.2 The principle

VAWT can be classified from many perspectives, e.g. by the working principle of producing forces on the blade of the wind turbine. From this perspective, there are two types of wind engines: lift type (Darrieus) and drag type (Savonius) [2]. The drag type utilizes the differential drag force of a suitably shaped body during bypass of the wind flow around bodies from opposite directions. The typical example is a cup-type wind-speed sensor (anemometer), which is used as wind speed meter. The Fig. 1 illustrates this case - the cup on the right side of the picture produces much less of the drag force than a cup on the left side. The ratio of these drag force at the same wind speed is up to about 1:4 [3].

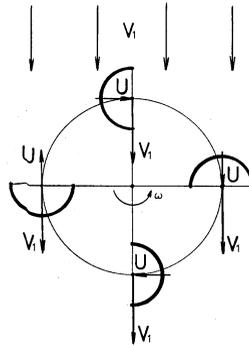


Fig. 1. Cup-type wind-speed sensor / Simple vertical drag type of wind turbine.

The previous kinematic scheme shows that the right cup has a low drag and this effect is further increased because the wind speed V_1 is added to the peripheral speed of rotation U . Also, the left cup generates more drag, because the wind speed is subtracted by the peripheral speed. Therefore, the resulting differential drag force decreases proportionally with the increasing value of angular velocity ω . The circumferential speed must be in all cases smaller than the wind speed in order to produce torque.

The drag of body depends on the square of the relative speed, the drag coefficient, the front surface area of the body and the specific weight (density) of the air. If the circumferential speed is limited, the absolute and differential value of drag force is limited too. Therefore, from the overall energy passing through the rotor, it can process only a few percent (about 5%) and the efficiency of these types of wind turbines is generally very low. The rest of the wind flow energy remains unused or it is transformed into a wake and heat.

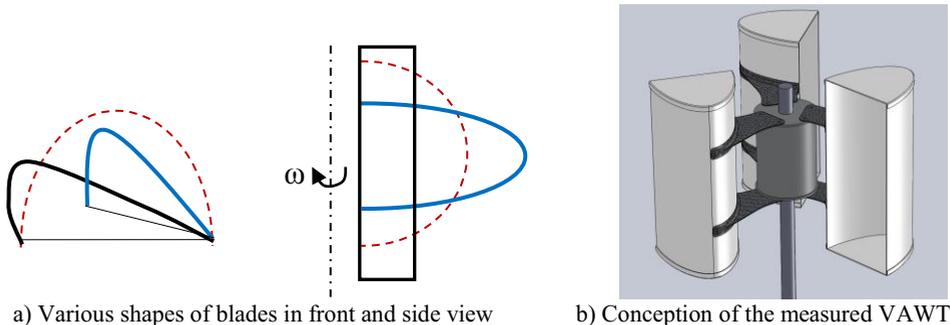


Fig. 2. Construction modification of basic cup type and the measured model.

This disadvantage can be decreased by some special modifications of the construction. In this particular case, the rotor is designed with the various number and aerodynamic shapes of blades. The aim was to confirm and find the most efficient configuration – i.e. find configuration, where the differential value of drag coefficient and frontal area of the left and the right side is largest.

2.2 The mathematical description

Mathematical description of the wind turbine is based on the basic laws of mechanics, laws of conservation of mass, momentum, and energy [4, 5, 6]. The basic idea is that said wind turbine is put into the so-called flow tube, see Fig. 3. The mass air flow along the length of the tube is constant. Far ahead of the wind turbine, the speed of the flow in the tube is equal to the freestream velocity V . Around the wind turbine, it is diminishing and it is noted V_1 . Far behind of the wind turbine the velocity in the flow tube is V_2 .

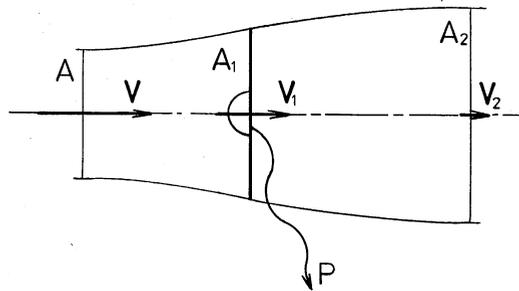


Fig. 3. Power take-off from the stream flow tube.

We selected three cross sections of the flow tube to write an equation describing the law of conservation of mass continuity

$$m_s = \rho \cdot V \cdot A = \rho \cdot V_1 \cdot A_1 = \rho \cdot V_2 \cdot A_2 \quad (1)$$

The density of the air ρ is a constant; A , A_1 , A_2 are cross-sectional areas perpendicular to the axis of flow tube; V , V_1 , V_2 are the air speed in the individual areas.

Ideal performance, which can be taken to the shaft of wind turbine, can be expressed as the difference between input and output power of the fluid flowing through the flow tube

$$P = m_s \cdot \frac{V^2 - V_2^2}{2} \quad (2)$$

The efficiency of the wind turbine is given by the ratio of the power P for the total performance of the fluid at the entrance of the flow tube. After some calculations, it can be shown that the theoretical efficiency η_t can be calculated only from speeds V_1 and V_2 .

$$\eta_t = 1 - \frac{V_2^2}{V^2} = 4 \cdot \left(\frac{V_1}{V} - \frac{V_1^2}{V^2} \right) \quad (3)$$

Maximum efficiency can be achieved in the operating mode of the wind turbine, if V_2 is zero, and the ratio V_1/V is 0.5. In this case, the theoretical efficiency achieves value $\eta_t = 1$. Practically, this value is unachievable, because the air far behind the wind turbine must flow along the flow tube and speed V_2 cannot be zero. Because of the complex calculation

of the actual mass flow, we estimate the maximum efficiency. The true efficiency η can be then calculated by the formula:

$$\eta = \frac{\rho \cdot A_1 \cdot V_1 \left(\frac{V^2 - V_2^2}{V^2} \right)}{\rho \cdot A_1 \cdot V} = 4 \cdot \frac{V_1}{V} \left(\frac{V_1}{V} - \frac{V_1^2}{V^2} \right) \tag{4}$$

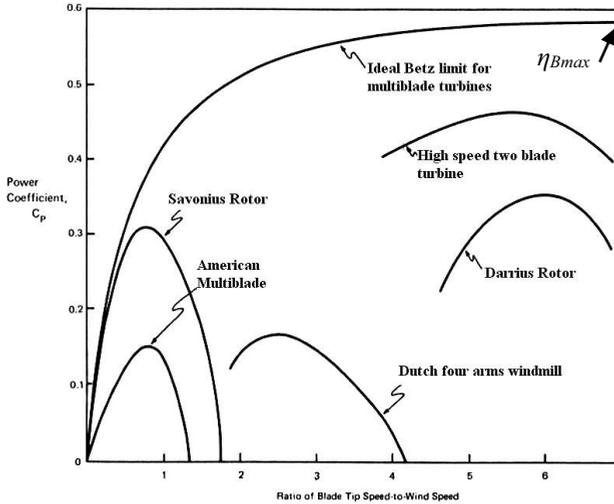


Fig. 4. Typical performances of wind machines. The power coefficient C_p is equal to the true efficiency η [6].

Maximum true efficiency η_{Bmax} , calculated as an ideal Betz limit for multiblade wind turbines, is achieved when the ratio $V_1/V = 2/3$. Its maximum value will be (after substituting $2/3$ for V_1/V in equation (4)):

$$\eta_{Bmax} = 16/27 \approx 0.593 \tag{5}$$

Maximum efficiency from the perspective of design parameters can be achieved with a ratio of tip speed and the wind speed V about 2.5 to 5 and more [6]. The tip speed and angular velocity depend on the product of the number of blades, width of the blades and lift force generated by the blades. The optimal angular velocity is inversely proportional to this product. This is a reason why multi-blade propellers and rotors optimized for lower angular velocity feature high torque, and they generally operate very well in the breeze. Multi-blade propellers are used mostly for water pumping [6].

The performance can be precisely estimated from known area A_l of the turbine and the wind speed V :

$$P = \eta \cdot \rho \cdot A_l \cdot V^3 / 2 \approx 0.3 A_l \cdot V^3 \tag{7}$$

The constant 0.3 in the formula can be achieved if the efficiency η is equal to 0.5 and the air density is $1.2 \text{ kg}\cdot\text{m}^{-3}$, which corresponds to the MSL ISA. This formula is valid for both the propeller and the rotor types of wind machines. The value of the constant 0.3 is the upper possible limit of the wind turbine of propeller type. For rotor type of wind turbine, the limit of efficiency ranges typically from about 0.10 to 0.12 and less [6]. This relation can be observed in the Fig. 4.

3 Test setup

Test equipment used to measure the unsteady aerodynamic characteristics of the wing section is shown in the Fig. 5. Model of VAWT was mounted in the test section of the wind tunnel, which was designed by company ENERGOKLASTR and is based at the University of Defence in Brno. It is a low-speed return-flow wind tunnel with an open test section. The wind flow's velocity is generated by a fan driven by a 260 kW electric motor. The dimension of the outlet nozzle is 2.4×2.4 m and the length of measurement section is 6 m.

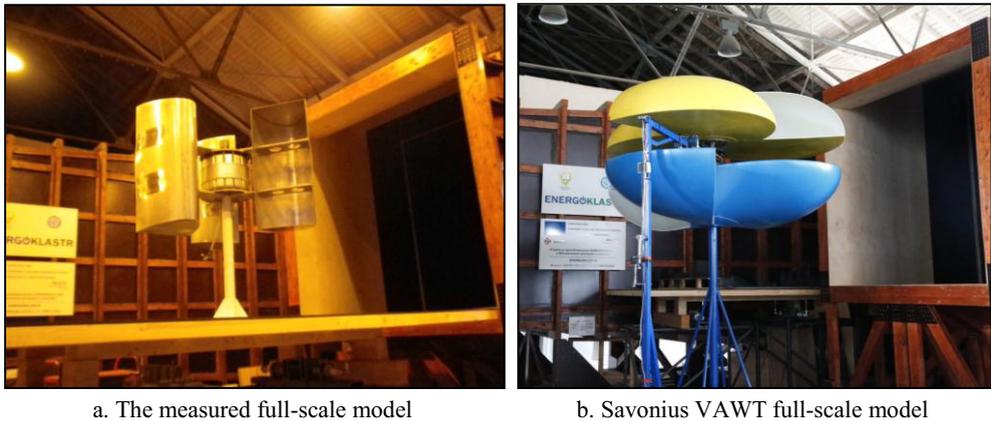


Fig. 5. Placement of VAWT models in the wind tunnel.

In the test section of the wind tunnel was installed a system, onto which was mounted the measured model (Fig. 5 a.). The mechanical power of the VAWT was transformed into electricity produced by the generator, which was then consumed in a resistor. The investigated parameters were the angular velocity of VAWT, the force on the disc brake, and consumed the electric output of the generator. By changing the resistance of the resistor, the load on the generator changed as well and it was possible to continuously determine the torque of VAWT. In order to convert the measured values into their dimensionless form, it is necessary to know the ambient pressure, temperature, and velocity of the flow in the test section of the tunnel. All measured parameters are converted into electrical quantities, which are then processed and evaluated. The speed of wind flow in test section was gradually increased from 8 m/s to 14 m/s.

4 Results

4.1 The power characteristic

The aim of the test was to determine the performance of the wind turbine for 7 values of the speed of the wind flow. The Fig. 6 presents a measured electrical output power generated by turbines of VAWT versus RPM of its rotor shaft.

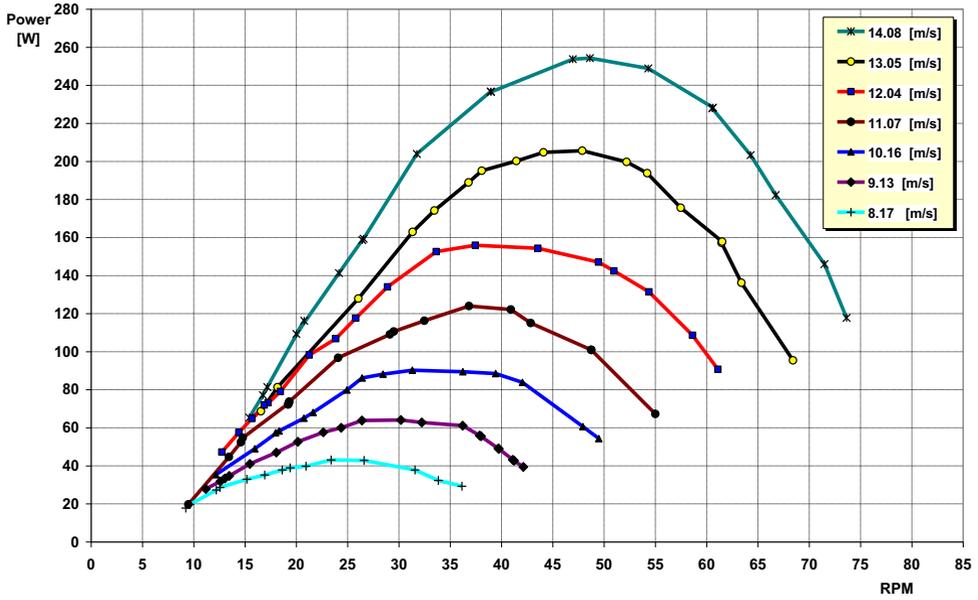


Fig. 6. Output power of the measured VAWT versus RPM.

The performance of the wind turbine is proportional to its size, effectiveness of the rotor and the parameters of the flowing fluid, which flows through the rotor. The measured performance parameters can be converted into dimensionless form accordingly:

$$C_p = \frac{2 \cdot P}{\rho \cdot A_1 \cdot V^3} \tag{8}$$

The aim of this transformation is to eliminate the influence of geometrical dimensions of the turbine, as well as the influence of ambient conditions under which tests were conducted.

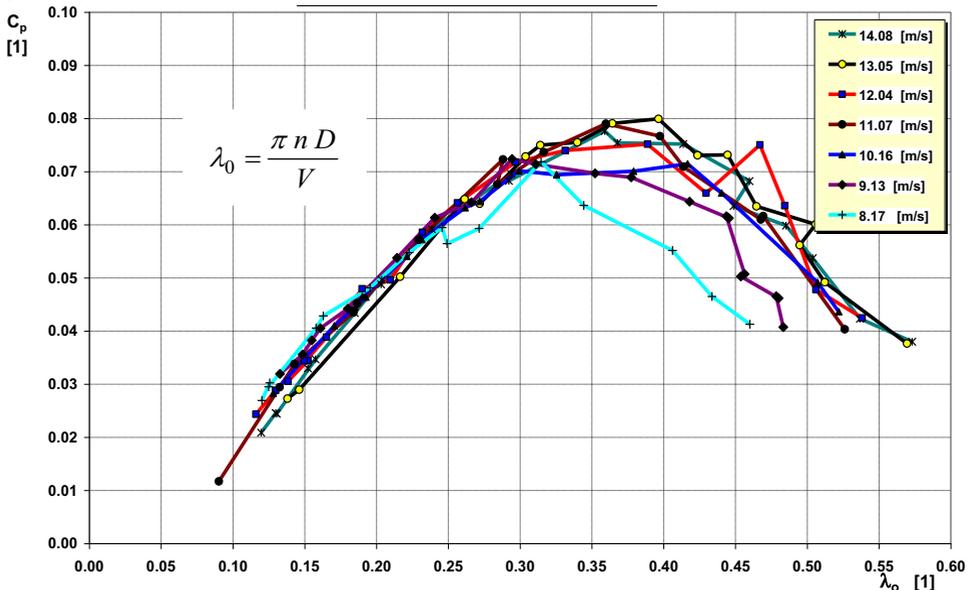


Fig. 7. Power coefficient of the measured VAWT versus tip speed ratio.

The value of dimensionless performance coefficient C_p versus dimensionless speed (tip speed ratio λ_o) allows us to perform a qualitative assessment of the VAWT. Graphical diagrams evaluating the dimensionless coefficients of VAWT are plotted in Fig. 7 and Fig. 9.

4.2 The power characteristic

The torque moment M_k of VAWT can be calculated from the measured output power and revolutions.

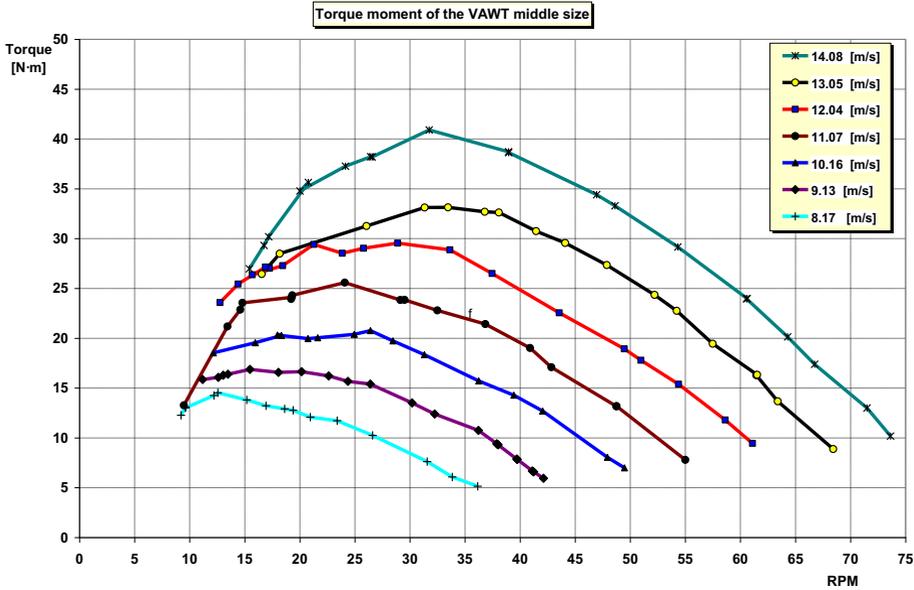


Fig. 8. Output torque moment of the VAWT versus RPM.

The values of dimensionless performance coefficients C_m can be converted into dimensionless form (9).

$$C_m = \frac{4 \cdot M_k}{\rho \cdot D \cdot A_1 \cdot V^2} \tag{9}$$

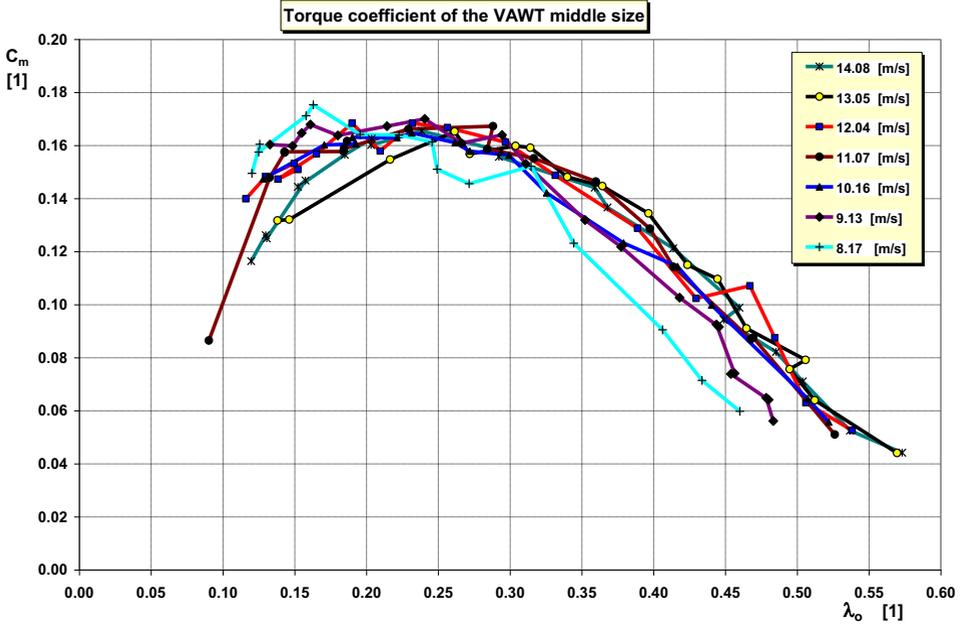


Fig. 9. Torque coefficient of the VAWT versus tip speed ratio.

5 Discussion

The performance parameters observed were the power and the torque moment generated by the VAWT and corresponding dimensionless coefficients, such as C_p and C_m . These coefficients can be used to precisely compare different types of wind turbines and assess their performance in different atmospheric conditions.

The obtained data show that the maximum coefficient of performance C_p is relatively low and corresponds to the theoretical predictions. If we only evaluated the mechanical performance of the VAWT without the generator, the investigated efficiency would be for about 20% higher. The efficiency of the generator, which is a part of the structure of VAWT, reached in the measured operating range of rpm and load about 80%. The measured characteristics differ with the velocity of the wind flow, as seen in Fig. 7 and Fig. 9. The efficiency of the generator is not constant. The revolutions of the generator are proportional to the wind velocity and with the increase of the velocity in the operating range, its efficiency grows to 80%. This effects the entire wind machine, which operates at a lower efficiency if its revolutions are lower. The measured results contain other factors such as mechanical losses in bearings of VAWT, thermal processes in the generator.

The advantage of this type of wind turbine is its high torque moment generated in relatively small revolutions – the maximum torque achieved is actually when the wind turbine is not rotating at all. However, the generator produces zero power if it is not rotating. The actual electrical power output generated by the VAWT, therefore, depends also on the type of the generator used. It is necessary to measure both the characteristics of the VAWT and the generator and they have to be tuned together. Coupling the generator with its maximum efficiency achieved in high revolutions with VAWT type of wind turbine can turn the wind machine extremely inefficient.

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