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# DEVELOPMENT OF A TEST RIG FOR THE MEASUREMENT OF SMALL WIND TURBINES IN A WIND TUNNEL

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**Abstract:** This paper describes the development, design and function of a test rig for the measurement of small wind turbines in a wind tunnel and presents the first exemplary measurements of the performance characteristics of various horizontal and vertical rotors. A central part of this test rig is the developed control system with an electronic load, which enables an automated recording of the measured values for the evaluation of the power coefficients ($c_p$) and tip-speed ratio ($\lambda$) values. Another challenge emerges owing to the known differences in the power spectrum, because the power coefficients of drag rotors (<20%) are different from those of buoyancy rotors (<40%). The system was adapted to the different ranges by means of a stepless switching using various resistors. The entire control and regulation unit was compactly implemented using a programmable logic controller (PLC) and dynamically linked to the operating parameters of the wind tunnel. This enables an automated operation of the wind tunnel during the determination of the performance parameters of the investigated wind turbines.

**Key words:** wind tunnel testing, small wind turbine, performance measurement

## 1. INTRODUCTION

The currently anticipated challenges for energy technology in the coming years are enormous. Not only the realisation of the necessary energy transition but also increasing energy demands and geopolitical changes in the current energy supply make it necessary to rethink energy generation. In particular, energy generation by wind power plays an important role in this context. The study of small wind turbines, especially the vertical axis wind turbine (VAWT), is always a subject of research, especially in view of the current energy crisis [1–5].

With this in mind, a test rig was developed that allows investigation of the performances of different small wind turbines. This test rig allows various investigations to be carried out in the wind tunnel at Stralsund University. The size of the small wind turbines or the scaled models is limited by the boundary conditions of the wind tunnel. Wind energy converters with different operating principles and axis positions can be investigated.

This paper describes the development, design and function of the test rig and presents the first exemplary measurements of the performance characteristics of various horizontal and vertical rotors. A central part of this test rig is the developed control system with an electronic load, which enables an automated recording of the measured values for the evaluation of the power coefficients (cp) and tip-speed ratio (λ) values. Another challenge emerges owing to the known differences in the power spectrum, because the power coefficients of drag-type rotors (<20%) are different from those of lift-type rotors (<40%). The system was adapted to the different ranges by means of a stepless switching using various resistors. The entire control and regulation unit was compactly implemented using a programmable logic controller (PLC) and dynamically linked to the operating parameters of the wind tunnel. This enables an automated operation of the wind tunnel during the determination of the performance parameters of the investigated wind turbines.

## 2. THE WIND TUNNEL FACILITY AND THE CONTROL SYSTEM OF PERFORMANCE MEASUREMENTS

The tests to determine the performance characteristics of the small wind turbines were carried out in the subsonic wind tunnel at Stralsund University. The wind tunnel was developed and constructed completely through project work and final theses by students at the university. The control unit for the performance measurement is also the result of a final thesis and provides a strong simplification of the operation of the wind tunnel, as well as the automatic recording of the performance parameters of various rotors of wind turbines.

### 2.1. The wind tunnel facility and test rigs for vertical and horizontal rotors

The wind tunnel is designed as a closed circuit wind tunnel (Göttingen-type) with an open test section (Fig. 1). The external dimensions are approximately 15 m x 2.4 m x 3.6 m (Fig. 1). The wind tunnel is equipped with two nozzle/collector configurations. It can be operated with a measuring cross-section of either 1,000 mm x 1,000 mm or 700 mm x 700 mm, with maximum possible speeds of up to 30 m/s and 60 m/s. The length of the open test section is a maximum of 1.76 m in the case of the nozzle with the large outlet. The axial blower has a power of 45 kW. It produces a maximum flow rate of 90,000 m³/h at a pressure increase of 1,100 Pa (Tab. 1).

**Tab. 1.** General technical data of the wind tunnel

| | | |
|---|---|---|
| Dimension of wind tunnel (L/W/H) | 15 m/2.8 m/3.6 m | |
| Air flow rate | 90,000 | m³/h |
| Total pressure increase | 1,120 | Pa |
| Power of axial blower | 45 | kW |
| Blower speed | 1,500 | 1/min |
| Dimension of test section | Small | Big |
| Length | 1.76 m | 1.25 m |
| Cross-section | 1.00 m² | 0.50 m² |
| Maximum velocity | 30 m/s | 60 m/s |

Following the axial blowers, the flow gets into the first diffuser. In the diffuser, the flow velocity is reduced. In order to form a flow with low losses as well as to meet the demand for the imposition of a wall boundary layer, a maximum opening angle of $\varphi \le 7°$ has been considered in the formulation of the design of the diffusers. In the wind channel, a guidance of the flow in the duct bends is necessary. This takes place by means of guide vanes that have been placed in the duct bends. The installation of the guide vanes ensures that flow separation and related losses in the duct bends can be prevented.

Before the flow reaches the test area, it slows down once again in the settling chamber. Here the flow is guided through three fine-mesh grids. Still existing vortices are destroyed inside the fine grid, thus reducing the turbulence intensity. After that, the flow is accelerated in the nozzle and rendered still more uniform, so that at the outlet of the nozzle there forms a uniform velocity profile with a low turbulence intensity.

In order to cover a wide range of investigations, two nozzles with the contraction ratios of $\varepsilon = 4$ and $\varepsilon = 8$ were designed. The calculation of the profile of the nozzle contour is based on a method in which the ratio of the nozzle length of the nozzle outlet, the non-uniformity of the flow profile and the contraction ratio $\varepsilon$ of the nozzle are taken into account. The nozzle with a small outlet has a contraction ratio of $\varepsilon = 8$ and is designed with a specific nozzle length of 1.25 m. This results in a relatively large nozzle length. In order to ensure compliance with the guidelines for the design of the test section, which mandate that the maximum length of the channel should not be in excess of that stipulated, in the case of the large outlet, the nozzle cross section was determined at 1 m², and a contraction ratio of $\varepsilon = 4$ and a ratio of the nozzle length to the nozzle outlet = 1 were reckoned appropriate. Furthermore, the nozzles are equipped with stiffening ribs and a stiffening frame, whereby an oscillation of the sheet metal parts is prevented.

To avoid oscillations of the air, which could result from the outflow of the open jet from the nozzle into the measuring room, small metal strips on the principle of Seiferth-wing [6] are attached to the inner edge of the outlet nozzle. After flowing through the open test section, the core flow is guided into the collector. Then, the air flow in the duct bend is redirected twice and then returned to the axial fans.

For the performance measurement of small wind turbines, a modular test rig has been developed for the measuring plenum, which allows vertical and horizontal rotors to be measured [7, 8]. For the measurement of vertical rotors, the rotor–generator combination is placed vertically in a support rack and positioned about 0.5 m in front of the nozzle opening (Fig. 2, left).

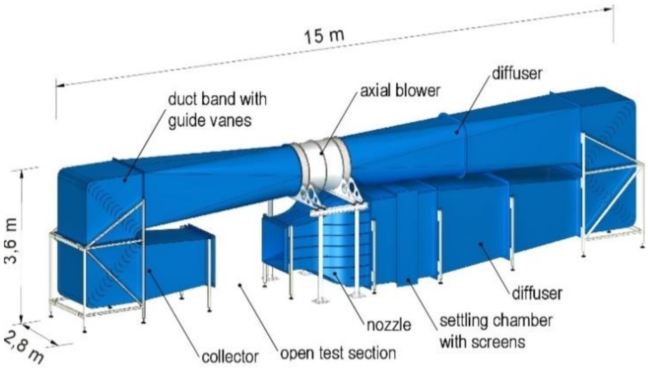


**Fig. 1.** The subsonic wind tunnel at Stralsund University

**Fig. 2.** Test rig for vertical rotors (left) and for horizontal rotors (right subsonic wind tunnel at Stralsund University)

**Fig. 3.** Vertical rotors: Standard-Savonius rotor (left), J-blade rotor (middle) and Benesh-V Rotor (right)

**Fig. 4.** Horizontal rotors: drag-type rotor (left) and lift-type rotor (right)

For the measurement of vertical rotors, three models (Standard-Savonius rotor, J-blade rotor and a variation of a Benesh rotor) are used as examples (Fig. 3), which mainly work according to the drag principle. All three vertical rotors have the same inflow

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area (0.3 m x 0.25 m) of 0.075 m². The blockage ratio defines the relationship between the cross-section of the nozzle outlet and the model and should not exceed 10%–20%. With a nozzle cross-section of 1 m², the area blocked by the rotor is within the tolerable range at 7.5%.

For the measurement of horizontal rotors, the rotor–generator combination is supported by an additional vertical column approximately in the middle of the measurement plenum (Fig. 2, right) [8]. For the measurement of horizontal rotors, two models are used as examples. One rotor works according to the drag principle (Fig. 4) and the other uses the lift principle (Fig. 5). Both rotors can be equipped with two, three or six rotor blades. The cross-section of 0.4 m² (drag-type rotor) is about four times larger than that of the vertical rotors and therefore not quite optimal for the flow in the measurement plenum, which could lead to a slight deviation of the measurement results.

## 2.2. The control system of performance measurements

A major part of this work is the development and implementation of a control and measurement system to measure the output power of small wind energy converters [7]. This system should enable accurate measurement of the power curve of variable rotors.

The frequency inverter provides the power for the wind tunnel. It is activated and controlled externally via the central control. A PLC of the type LOGO 8 from Siemens is to be used as the central control.

The measured data are recorded on a memory card. The central control unit (Fig. 5) is the main component of the test rig. For example, the rotor parameters are entered and the speed profile for measurement is defined. Additionally, the remote control provides the user with a visualisation of the measurement data. Both of these systems were individually programmed with the software LOGO! (Soft Comfort V8.2 and TIA-Portal v.12.1, respectively) from Siemens. The mechanical power of the rotors is converted in a specially designed permanently excited synchronous generator. The range of rotational speeds to be expected is relatively large, as both different axis orientations and rotors with different operating principles (resistance and lift principles) are to be measured. With the relatively low speeds of the rotors operating according to the resistance principle, the tip-speed ratios are $\lambda$ <1. Contrastingly, the tip-speed ratios for the lift rotors are approx. $\lambda$ = 4–6.

An electronic load serves as a load for the generator or the rotors, which has a power of 300 W in the first expansion stage and works in combination with a measuring and braking resistor. This assembly is a very important component of the test rig, as it allows the output power of the rotors to be controlled in very small steps. Additionally, the load and the resistor prevent the rotor from overspeeding during no-load operation by regulating the speed of the rotor.

The measurement of the electric current is carried out by means of the measuring resistor. This has a constant resistance value of 5 Ω in the operating range. Thus, the current can be easily determined by measuring the voltage drop at the resistor. This results in a voltage drop of 7.5 V over the measuring resistor with a current flow of 1.5 A. The measuring resistor with a power consumption of up to 500 W can easily absorb the converted power loss of 11.25 W. Since the controller has an analogue measuring range of 0–10 V with a resolution of 10 bits, the measured values are recorded with 10V/1,000 = 0.01 V steps. Divided by the constant resistance value of 5 Ω, this results in a current value of 2 mA and thus allows a very good measurement resolution. The measured output power in comparison to the mechanical power directly at the rotor is influenced by the losses on the complete path of energy transmission.

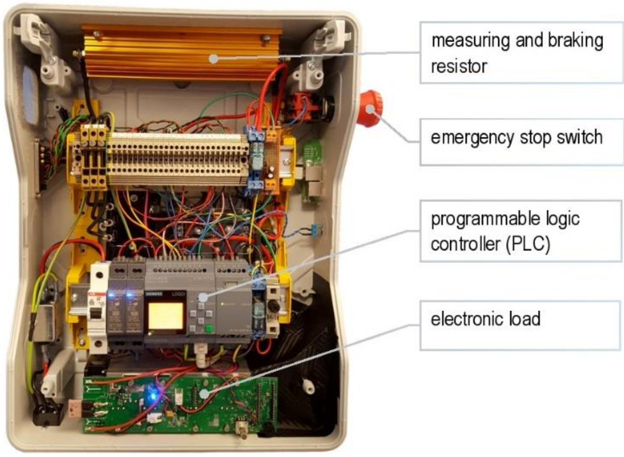


**Fig. 5.** Central control unit

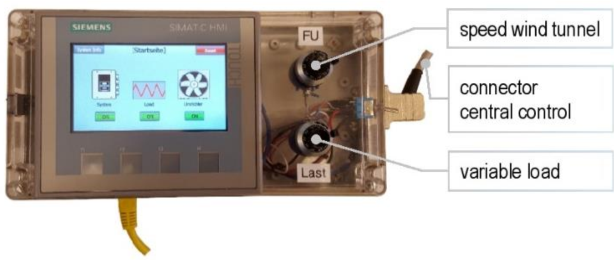


**Fig. 6.** Remote control of wind tunnel and central control unit

The total power loss results from losses in the bridge rectifier, Ohmic losses in the supply lines, losses in the generator coils and the friction losses in the bearings. The fractions of the power losses can be easily estimated as a function of the rotational speed and are taken into account in the calculation of the final power coefficient.

# 3. MEASUREMENT OF PERFORMANCE CHARACTERISTICS OF VERTICAL ROTORS

In order to measure the rotors, the test rig was configured so that the wind tunnel can be automatically controlled from 6 m/s to 20 m/s in seven steps of speed. The load profile is run through in each step. The rotor speed is controlled from 50 rpm to 600 rpm in steps of 50 rpm. The aim is to determine the optimum tip-speed ratio of the rotor in order to subsequently record a performance curve in this range in high resolution. Approximately 100–150 measurements were carried out at each operating point in order to obtain a statistically reliable value. Software procedures are used to evaluate and calculate the performance parameters [7].

The optimum tip-speed ratio of the Standard-Savonius rotor could be determined from the measured values, e.g. at a rotational speed of 500 1/min (Fig. 7), which corresponds to a tip-speed ratio of $\lambda$ = 0.65. This tip-speed ratio is independent of the speed

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steps. The calculated power coefficient takes into account all losses, electrical as well as mechanical, in the bearings. It has been shown that the given Standard-Savonius achieves a power coefficient of $c_p$ = 0.12. Furthermore, a vertical rotor with a shape similar to a Benesh rotor was measured. However, the geometry is not optimally designed, so that the rotor only has a power coefficient of $c_p$ = 0.11 with a tip-speed ratio of λ = 0.45. Among the three tested models, the one ascertained as being the most optimal was the vertical rotor with the J-blade design. It achieves a power coefficient of $c_p$ = 0.15 with a tip-speed ratio of λ = 0.6. It can be clearly seen that the last two rotors have very good start-up behaviour. This generally characterises the vertical rotors, which develop a strong torque at low speeds, a phenomenon that finds good corroboration in the literature [5, 9].

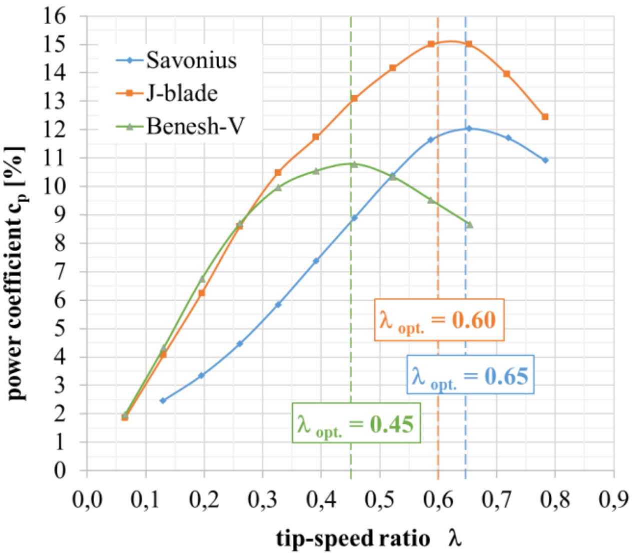


**Fig. 7.** Performance characteristics of vertical drag-type rotor (25°C)

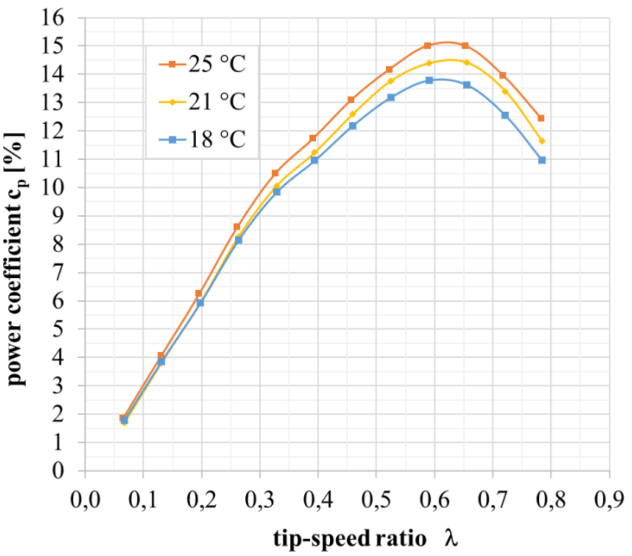


**Fig. 8.** Influence of temperature-dependent bearing friction on performance, e.g. J-blade rotor

A major problem with vertical rotors used in the low-power range of small wind turbines is the bearing friction of the rotors, which was also identified by Ricci et al. [10] in their research. Power loss in the bearings can be of a magnitude that dominates in relation to the harvested wind power, especially in relation to the small inflow area of the rotors. An increase in the power coefficient is seen with increasing temperature, resulting in an increase of 2% for a temperature difference of just 7 K (Fig. 8). Friction in the bearings, which is strongly determined by the operating temperature of the rotors, is a factor that should not be neglected in relation to the relatively low wind power output. This effect is especially amplified if the small wind turbines are to be used reliably and effectively in different climatic zones or even in winter operation.

## 4. MEASUREMENT OF PERFORMANCE CHARACTERISTICS OF HORIZONTAL ROTORS

For the measurements of the horizontal rotors, a self-built low-cost drag-type rotor was made from a commercially available plastic pipe (DN 110). An existing model was chosen as an example for a lift-type horizontal rotor. Since the two horizontal rotor types have different through-flow surfaces, a direct comparison is not possible. Nevertheless, the evaluation of the performance characteristics provides a very good insight into the behaviour of the rotors with the two different operating principles.

The measurements generally show a dependence of the number of rotor blades on the tip-speed ratio and the power coefficient. Especially for the drag-type rotors, an increase in the number of blades from two to three leads to a strong increase in the power coefficient by approx. 40% to $c_p$ = 12.3 (Fig. 9). The tip-speed ratio is reduced from λ = 2.41 to λ = 2.20, as more surface is now available for harvesting the wind power.

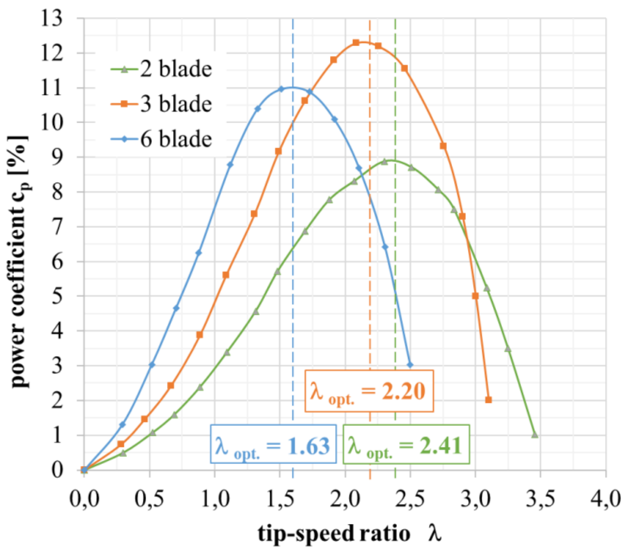


**Fig. 9.** Performance characteristics of horizontal drag-type rotor (average of speeds, 20°C)

The measurements of the drag-type model indicate that the investigated rotor with tip-speed ratio λ >1 is not a pure drag rotor. This rotor has the characteristics of both drag and lift rotors, due to the special shape of the rotor blades. With a lower number of rotor blades, the characteristics of a lift rotor became more evident. Nevertheless, the characteristics of a drag rotor predominated due to the rotor blade geometry and the relatively low power

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coefficients. This low power coefficient is due to the non-optimal blade geometry, which in part negatively influences a good outflow of air at higher speeds. However, the horizontal drag-type rotor has very good start-up behaviour. Even in the lower speed range, relatively high torques are achieved, as can be seen from the strong gradient of the power coefficient.

The lift-type rotors also show an increase in the power coefficients with an increase in the number of blades from two to three. The increase of approx. 20% is significantly lower than that with the drag-type rotor (Fig. 10). With three blades, the optimum in the number of blades is also reached here, and a maximum power coefficient of $c_p$ = 0.28 with a tip-speed ratio of $\lambda$ = 6.12 is achieved.

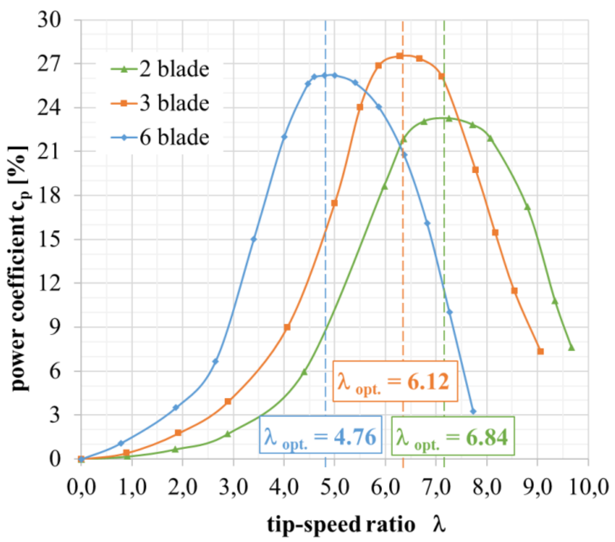


**Fig. 10.** Performance characteristics of horizontal lift-type rotor (average of speeds, 20°C)

Furthermore, the investigations show good agreement with the findings reported in the literature [9], in which a further increase in the number of blades (six blades) leads to a reduction in the power coefficient. This effect is due to negative flow phenomena between the blades.

## 5. CONCLUSIONS

This paper described the development, construction and function of the test rig used in the measurement plenum of the wind tunnel, and presented the first exemplary measurements of the performance characteristics of various horizontal and vertical rotors for small wind turbines.

With the developed automatic control system, the rotor test rig enables the measurement of the rotors with precisely specified parameters. The automated acquisition of the entire power spectrum is carried out systematically, very precisely and comprehensively. This developed control unit with the implemented data acquisition significantly simplifies the measurement processes for recording the performance parameters.

The measurement results of the rotors in the rotor test rig have shown that the energetic use of rotors in the drag-type rotor configuration, especially vertical rotors, offers technically usable potential, but that compared to lift rotors they have a relatively low power output. In particular, the friction in the bearings of the rotors have a strong influence on the total performance of the small wind turbine in this low power range. Nevertheless, the use of these turbines in the form of small, decentralised systems could make sense. While the Savonius-type rotors are characterised by a low power coefficient, this limitation of theirs presents a strong contrast to several advantages that have been observed in them. The rotors have a low tip-speed ratio with a relatively high torque in the lower speed range. They are very robust and not sensitive to changes in wind direction, and pose only a very low risk to wildlife when used in sensitive landscape regions.

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