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MODEL TESTS OF WIND TURBINES IN WIND TUNNELS

BADANIA MODELOWE TURBIN WIATROWYCH W TUNELACH AERODYNAMICZNYCH

Abstract

This paper describes methods for testing model wind turbines in wind tunnels based on published data and the experience gained by the author through having tested many different wind turbines in wind tunnels at the University of Auckland. Wind tunnels can be used to determine the performance of small wind turbines at full scale, or larger wind turbines at reduced scale. Such experiments need to be done with care as one needs to be aware of issues regarding blockage, the effect of Reynolds number, and being able to control the speed of the turbine so that is power coefficient can be obtained over a suitable range of tip speed ratios. With rotating machinery, it is also important to have a regard to safety, so the models have to be made with care and a stress analysis carried out to ensure that the material properties are not exceeded during the testing. It is found that wind tunnel testing is a useful way of determining experimentally the performance of wind turbines in order to predict the power output, and for obtaining data to validate theoretical or numerical model predictions.

Keywords: wind engineering, wind energy, wind tunnel test, blade aerodynamics, renewable energy, blockage correction

Streszczenie

W poniższym artykule opisano metody testowania modeli turbin wiatrowych w tunelach aerodynamicznych na podstawie opublikowanych danych oraz doświadczenia autora uzyskanego w wyniku badań wielu turbin wiatrowych przeprowadzonych w tunelach aerodynamicznych Uniwersytetu w Auckland. Tunele aerodynamiczne mogą być wykorzystywane do wyznaczania wydajności małych turbin wiatrowych w pełnej skali, albo większych turbin w skali zredukowanej. Takie doświadczenia muszą być przeprowadzane bardzo starannie, ze zwróceniem uwagi na takie problemy, jak efekt blokady, efekt liczby Reynoldsa. Trzeba także mieć możliwość kontrolowania prędkości turbiny, tak aby współczynnik mocy mógł być uzyskany w odpowiednim zakresie współczynnika szybkobieżności. W przypadku maszyn wirnikowych ważne jest zapewnienie bezpieczeństwa, tak aby modele były wykonane z należytą starannością na podstawie przeprowadzonej wcześniej analizy wytrzymałościowej, co pozwala upewnić się, że odpowiednie charakterystyki materiałowe nie zostaną przekroczone w trakcie badań. Stwierdzono, że badania w tunelu aerodynamicznym to użyteczna metoda doświadczalnego wyznaczania wydajności turbin wiatrowych. Pozwalają one przewidzieć moc wyjściową oraz inne dane umożliwiające walidację modeli teoretycznych i numerycznych.

Słowa kluczowe: inżynieria wiatrowa, energia wiatrowa, badania w tunelu aerodynamicznym, aerodynamika łopat turbin, energia odnawialna, korekcja efektu blokady

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1. Introduction

As the population of Earth grows, so does its use of energy. Fossil fuels have provided energy for mankind for centuries, but the remaining coal and oil is harder to extract and thus more expensive. Coupled with this is our knowledge that burning fossil fuels releases carbon dioxide into the atmosphere and this can contribute to global warming, a serious issue that mankind has to face. This background has increased the focus on renewable energies like wind. Wind energy is abundant, free, environmentally friendly and inexhaustible. Consequently it has been one of the largest sources of new electricity generation in many parts of the world in recent times. Further details on wind energy can be found in the World Wind Energy Association reports [28].

Recent rapid growth in wind energy has been driven by advances in turbine technology, which have allowed wind turbine sizes to be increased from 15 m in diameter in the 1980s, to over 150 m today. Turbine capacity has grown from 55 kW to 5 MW, with turbines having diameters of 100 m or more. The world's largest wind turbine called the Sea Titan has a diameter of 190 m, a rotational speed of 10 rpm, and a rated power of 10 MW. It is interesting that its tip speed ratio, $V_t = (10/60)(2\pi)(190/2) = 99.5$ m/s, which is approximately one third of the speed of sound and so the air can be assumed to be incompressible.

Clearly with such a large investment in wind energy there is a need for considerable research on wind turbine performance. The aerodynamics can be explored using theoretical methods, numerical computations, full-scale monitoring as well as wind tunnel testing. It is usual to attack such problems using more than one approach in order to validate and check predictions of performance, loads, dynamics etc. Wind tunnel testing is one of these options and is described in detail in the present paper.

2. Literature Review

The University of Auckland has had a longstanding interest in wind energy, beginning at the time of the rapid increase in the price of oil in the 1970s. Two Darrius wind turbines were built and tested at the Universities of Auckland and Canterbury [5]. At the same time, research was being undertaken by Lindley et al. [18] to measure wind structure at levels relevant to wind turbines. In more recent times, there has been considerable research undertaken at the University of Auckland where the wind tunnel has been an important tool in determining the performance of non-conventional wind turbines, namely a diffuser augmented wind turbine (e.g. [20]), and wind turbine blades with extendable [16].

A perusal of the recent literature on wind tunnel testing of wind turbines shows that it is an active area and that wind tunnel tests are being carried out all over the world to investigate various aspects of wind turbine performance. For example Bottasso et al. [4] describe testing in a very large wind tunnel, which is aeroelastically scaled, and features active individual blade pitch and torque control. The flow simulation took place in a boundary layer wind tunnel.

Wind tunnel testing of wind turbine models to investigate aerodynamics have been reported by, for example, Oku et al. [19], Hand et al. [12], Vermeer et al. [26], Snel et al. [24]

and Schepers and Snel [23]. These and similar studies have produced valuable information and measurements regarding the performance of rotors and the behaviour of airfoils, blades and wakes, which has helped the understanding of the aerodynamics, and has also provided valuable information for validation and calibration of mathematical models.

3. Wind tunnel calibration

It is important when undertaking any measurement in a wind tunnel to measure the reference quantities precisely in order to be able to determine the appropriate coefficients. One of the most important measurements is that of the reference dynamic pressure at the vicinity of the test model. From the dynamic pressure the velocity can be determined. In the case of testing wind turbines, the plane where the model blade plane is to be located should be surveyed with a Pitot-static or other high quality probe, such as a Cobra probe [6, 13] in order to determine the uniformity of the flow field. The average dynamic pressure over this plane can then be related to the reference pressure measuring system using the procedure outlined below.

The reference dynamic pressure is usually measured with a high quality pressure transducer connected either to pressure taps in the wind tunnel contraction, or to a reference Pitot-static probe located well upstream and away from the test model, so that it is not influenced by the pressure field generated by the model itself. In this example, I will assume that the reference pressure is being measured by contraction pressure taps, as shown in Fig. 1. Sometimes the reference pressure taps at the contraction inlet and outlet are manifolded together from taps on the top, bottom, far and near sides, but this is probably not necessary. The most important thing is that they are installed in a careful and professional manner so that there are no burrs and that the taps are flush with the surface and normal to it.

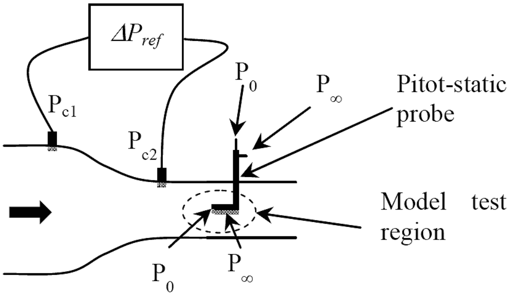

Fig. 1. Schematic diagram of a wind tunnel contraction with pressure taps, and a Pitot-static probe located at the centre of the test region

An empty wind tunnel calibration is done prior to putting the model in the wind tunnel. It is assumed that all pressure differences in the wind tunnel are proportional to each other. The wind tunnel fan is then turned on and the speed varied over the range that will be used for the testing. At the same time, the pressure differences P_{c1} - P_{c2}, P_∞ - P_{c2} and P_0 - P_∞ are measured simultaneously. The pressure differences P_0 - P_∞ and P_∞ - P_{c2} are then plotted against P_{c1} - P_{c2} as shown in Fig. 2 in order to obtain the slopes, $k_{q\infty}$ and $k_{p\infty}$ of straight lines fitted to the data points.

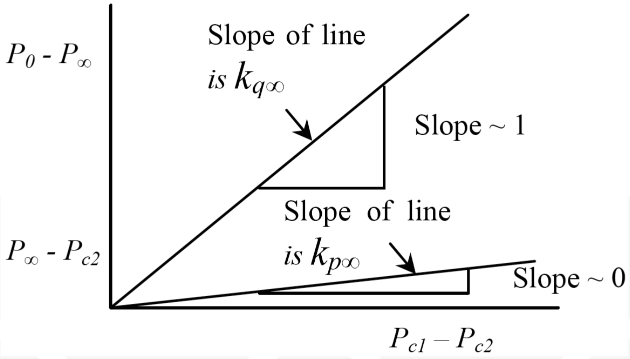

Fig. 2. Plot of wind tunnel pressure measurement data to derive test section calibration data

Referring to Fig. 2, it is evident that

$$k_{q\infty} = \frac{P_0 - P_\infty}{P_{c1} - P_{c2}} \tag{1}$$

and that

$$k_{p\infty} = \frac{P_\infty - P_{c2}}{P_{c1} - P_{c2}} \tag{2}$$

During an actual test a model will be located in the wind tunnel at the location of the Pitot-static probe shown in Fig. 1. However, the dynamic pressure there may be determined by measuring the contraction pressure drop and using Eqn. (1), viz,

$$q_\infty = P_0 - P_\infty = k_{q\infty}\left(P_{c1} - P_{c2}\right) \tag{3}$$

The static pressure at the model location can be determined by rearranging Eqn. (4).

$$P_\infty = P_{c2} + k_{p\infty}\left(P_{c1} - P_{c2}\right) \tag{4}$$

Force coefficients, e.g. thrust on the wind turbine can now be determined from the dynamic pressure resulting from Eqn. (3). For example if the force measured is T, then the coefficient is given by Eqn. (5).

$$C_T = \frac{T}{A_{ref}q_\infty} \tag{5}$$

where A_{ref} is a reference area for coefficients.

Pressure coefficients, e.g. on a wind turbine blade at position “*x*”, may also be determined. An approximate “raw” coefficient may be determined using Eqn. (6).

$$Cp_x^* = \frac{P_x - P_{c2}}{P_{c1} - P_{c2}} \tag{6}$$

A corrected pressure coefficient may be determined using Eqn. (7).

$$Cp_x = \frac{P_x - P_\infty}{P_0 - P_\infty} = \frac{P_x - \left(P_{c2} + k_{p\infty}\left(P_{c1} - P_{c2}\right)\right)}{k_{q\infty}\left(P_{c1} - P_{c2}\right)} \tag{7}$$

Now by expanding Eqn. (7), it can be written in terms of Cp_x^* and the calibration values, as shown below in Eqn. (8).

$$Cp_x = \frac{P_x - P_{c2}}{k_{q\infty}\left(P_{c1} - P_{c2}\right)} - \frac{k_{p\infty}\left(P_{c1} - P_{c2}\right)}{k_{q\infty}\left(P_{c1} - P_{c2}\right)} = \frac{Cp_x^*}{k_{q\infty}} - \frac{k_{p\infty}}{k_{q\infty}} \tag{8}$$

The author has sometimes seen pressure distributions on aerofoils which appear to be shifted on the ordinate. This may have occurred because the reference pressure for the coefficients was offset slightly from the actual pressure P_∞ that existed there.

4. Similarity requirements

The relevant dimensionless quantities for wind turbine testing are considered in this section.

Probably the most important dimensionless quantity is the so-called tip speed ratio, often given the symbol λ, $\lambda = \omega R/V_\infty$ where $\omega R = u_{\mathrm{tip}}$ the blade tip speed, ω is the rotational speed in radians per second, R is the blade radius and is the free-stream wind speed. λ is often around 5-8 for horizontal axis wind turbines. It is important in wind tunnel testing to keep this parameter the same as in full-scale, as it controls the direction of the flow onto the blade.

The Mach number for a wind turbine can be defined by $\mathrm{M} = u_{\mathrm{tip}}/a$, where $u_{\mathrm{tip}} = \omega R$, a is the speed of sound, and is typically around 340 m/s. As noted in the introduction, the blade tip speed is typically up to around 100 m/s. At this speed $\mathrm{M} = 0.3$, which is low enough for compressibility to be neglected.

The Reynolds number, $\mathrm{Re} = VL/\nu$, where V is reference speed, L is a reference length and ν is the kinematic viscosity of the fluid. In the present case, we may write $V = u_{tip} = \omega R$, and $L = c$, the reference blade chord, which is proportional to R for a geometrically similar blade.

Hence for wind turbine testing the Reynolds number can be written $\mathrm{Re} = \omega R^2/\nu$. For testing in air, the kinematic viscosity is unchanged. The model is reduced in size by the scale factor. Hence if the wind tunnel speed is the same as the full scale speed, the product ωR will also be the same in order keep the same tip speed ratio, and so Re will be lower by approximately the model scale factor.

The model scale factor for a 100 m diameter rotor would be of the order of 50 in order to have a 2 m diameter model, and so Re will reduce by a factor of 50 or so. The full scale Reynolds number will be of the order of $\mathrm{Re} = \omega R^2/\nu = 100 \cdot 3/(15 \cdot 10^{-6}) = 20 \cdot 10^6$ (which is a very high Reynolds number) whereas the model scale Reynolds number would be around 2 to $4 \cdot 10^5$. Since the model scale Reynolds number will be substantially lower than the prototype wind turbine, it is important that during the design of the model for the wind tunnel tests that the lift and drag characteristics as a function of Reynolds number are researched to check that there is no substantial difference in performance at the reduced Reynolds numbers. If it is found that the blade profile is rather sensitive to Re, then perhaps a different profile could be used for the wind turbine model. One would select a profile with properties that are relatively insensitive to Re for the range of values that are anticipated in the tests.

These dimensionless groups are the most important and lead onto the next section, corrections for wind tunnel blockage.

5. Correction for wind tunnel blockage

It is very well known that when a model is placed in a solid wall wind tunnel that an error in the resulting force or other measurements will occur due to the acceleration of the air in the gap between the wall and the model itself. This increase in the dynamic pressure in the gap causes a larger pressure drop than would occur in the "free air", and so the model base pressure drops, thereby causing an increase in the pressure difference between front and rear, and thus an increase in the drag. This phenomenon does not occur from tests in a free jet with a constant pressure boundary condition at the jet boundaries, as the flow is free to expand away from the model and generally the force is underestimated, and the error is of order half or less that which would occur in a solid wall wind tunnel with the same blockage.

Other errors can occur, e.g. for long models in a wind tunnel with a longitudinal static pressure gradient a "buoyancy" correction must be applied. Further details of these and other corrections can be found in Barlow et al [3]. Blockage corrections are also discussed by Wilson et al [27] and by Chen and Liou [7] who carried out an experimental investigation on the effects of blockage.

An elegant theory for the effect of blockage on testing airscrews (propellers) in wind tunnels was worked out by Glauert [11]. This has been illustrated for wind turbine testing in the present paper.

Consider a wind turbine rotor placed in a circular cross-section wind tunnel of area C. Assume that the drag is uniformly distributed over the whole of the swept area and that the axial velocity of the air has a constant value over this disc and over a cross-section of the wake well downstream. This situation is shown schematically in Fig. 3. The stream-tube enveloping the blade-plane expands in area both upstream and behind the blade plane, as the air experiences the resistance of the disc. The air approaches the blade plane at speed V_∞. u is the axial velocity at the blade plane, u_1 is the velocity within the stream-tube well downstream and u_2 is the axial velocity outside the stream-tube well downstream. A_∞ is the upstream area of the stream-tube enveloping the blade-plane, which increases to area A at the blade-plane and increases further to area A_1 well downstream. P_∞ is the static pressure in the wind tunnel well upstream of the blade-plane, and P_1 is the static pressure well downstream.

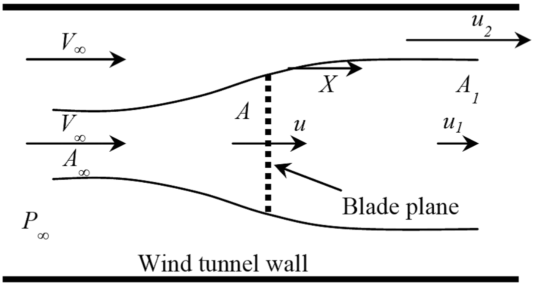

Fig. 3. Schematic diagram of a stream-tube enveloping a wind turbine rotor located centrally in a circular section wind tunnel

Then from the continuity equation, it follows that

$$u_1 A_1 = uA \tag{9}$$

$$u_2 \left(C - A_1\right) = V_\infty C - uA \tag{10}$$

The total pressure of the fluid stream (H_∞) remains constant outside the stream-tube, whereas the total pressure inside the stream-tube reduces to H_1 due to the drag which is applied by the turbine disc.

$$H_\infty = P_\infty + \frac{1}{2}\rho V_\infty^2 = P_1 + \frac{1}{2}\rho u_2^2 \tag{11}$$

$$H_1 = P_1 + \frac{1}{2}\rho u_1^2 \tag{12}$$

Hence from Eqns. (11) and (12) the reduction in total pressure is

$$H_\infty - H_1 = \frac{1}{2}\rho\left(u_2^2 - u_1^2\right) \tag{13}$$

This reduction in total pressure is equal to the static pressure drop across the blade plane, and hence the drag force (T) on the blades is given by Eqn. (14).

$$T = A\frac{1}{2}\rho\left(u_2^2 - u_1^2\right) \tag{14}$$

The momentum equation is now applied to the flow both inside and outside the stream tube, and enables the reduction in pressure in the far wake to be determined.

$$\left(P_\infty - P_1\right)C - T = A_1\rho u_1\left(u_1 - V_\infty\right) + \left(C - A_1\right)\rho u_2\left(u_2 - V_\infty\right) \tag{15}$$

From Eqn. (13), the reduction in pressure in the wake is given by Eqn. (16).

$$P_\infty - P_1 = \frac{1}{2}\rho\left(u_2^2 - V_\infty^2\right) \tag{16}$$

The drag coefficient of the disc is now defined as

$$C_T = \frac{T}{A\frac{1}{2}\rho V_\infty^2} \tag{17}$$

Some rather non-trivial algebraic manipulation is then required to simplify the equations into a form that can be used to assess the effects of blockage ratio on the results. The required manipulation has been carried out by Glauert [11] in his development to assess the effect of blockage on propeller testing. For this testing, an “equivalent free air speed V'” has been defined, as the speed which corresponds to the same values of the thrust T and of the axial velocity u as obtained in the wind tunnel with an upstream speed of V. For the case of propellers being tested in a solid wall wind tunnel, Glauert’s correction can be plotted as in Fig. 4. Note here that Glauert’s thrust coefficient τ, is based on double the reference wind tunnel upstream dynamic pressure, i.e. $\tau = T/(A\rho V^2)$. A/C is the ratio of the propeller swept area to the wind tunnel area.

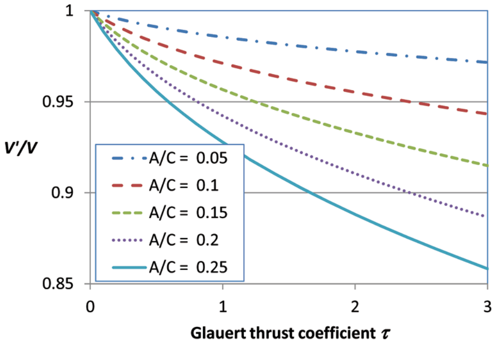

Fig. 4. Ratio of equivalent air speed to reference wind tunnel speed as a function of area blockage and thrust coefficient, for a propeller test

Glauert notes that typical tests are done at blockage ratios of 0.15.

The blockage correction for testing wind turbines in wind tunnels is discussed by Wilson et al [27]. They use the method developed by Glauert and give the resulting correction in a figure which is reproduced here as Fig. 5. The measured coefficient of thrust in Figure 5 is determined using Eqn (17), and then the power coefficient (C_p) correction is applied using the measured ratio of wind tunnel area to wind turbine blade-plane (swept) area.

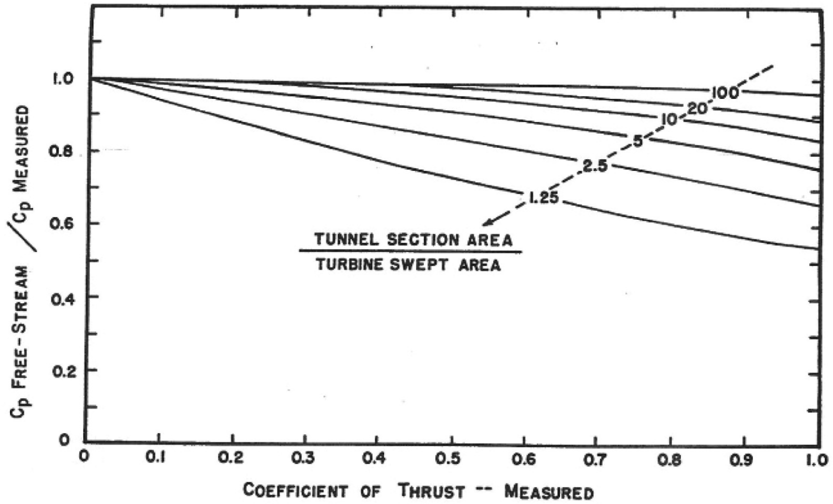

Fig. 5. Blockage correction for wind turbine testing [27]

From the Betz actuator disc theory, it can be shown that the ideal thrust coefficient is 8/9. For this thrust coefficient and for 20% blockage, the ratio of free-stream to measured power coefficient is 0.8, meaning a 25% overestimate, which is quite significant. If the blockage is reduced to 10%, then the overestimate on power coefficient is reduced to 15%.

Testing in an air jet has significant advantages for both propeller and wind turbines. Whereas a solid-wall test section constrains the flow in such a way that the streamlines adjacent to the wall must travel along the wall, the boundary condition for a free jet is a constant pressure. Hence the jet can expand due to the pressure field imposed by a wind turbine rotor. In this case the power coefficient determined in a wind tunnel test can be expected to be smaller than in free air, as the jet will expand more than it should. However, this effect is much smaller that the overestimate provided by a solid wall boundary. Glauret [11] states that in testing propellers with diameter ratios up to about 0.7 (49% area blockage) in a free jet gave interference free results. Hence most of the early testing of propellers at Farnborough was done in open jet wind tunnels.

Some wind tunnel designers have therefore tried to design test sections that are a combination of solid and open walls in order to have a zero blockage effect. This is sometimes called a blockage tolerant test section. A simple example of such a test section is shown in Fig. 6, which is a photograph of a wind tunnel (1.5 m x 1.5 m cross-section) and diffuser augmented wind turbine model at the University of Auckland.

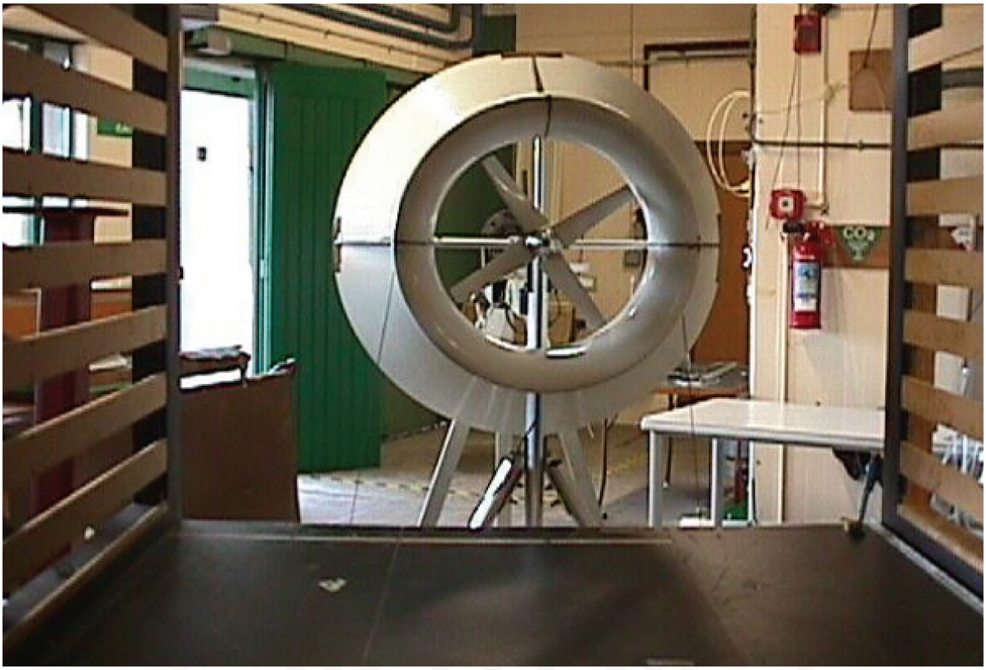

Fig. 6. Photograph of wind turbine model positioned downstream of a slotted wall wind tunnel designed to reduce blockage corrections

6. Examples of wind tunnel tests

Some recommendations on how to carry out wind tunnel tests on model wind turbines are now discussed and are based on testing that has been carried out in the writer's laboratory.

6.1. Wind tunnel testing diffuser augmented wind turbines

The author was asked to assist a company that had begun to build a diffuser augmented wind turbine, based on work done by researchers at Grumman [10]. A 7 m diameter prototype was built near Auckland, and is shown in Fig. 7.

The performance of the wind turbine was less than predicted and so a programme of work was carried out to try to ascertain why this was the case. A PhD student was recruited to work on the project. Investigations took place using CFD and wind tunnel experiments, as well as measurements on site using pressure transducers with self-orientating Pitot-static tubes, as well as other instrumentation. Several of the following figures were used from the thesis that resulted from this research [21].

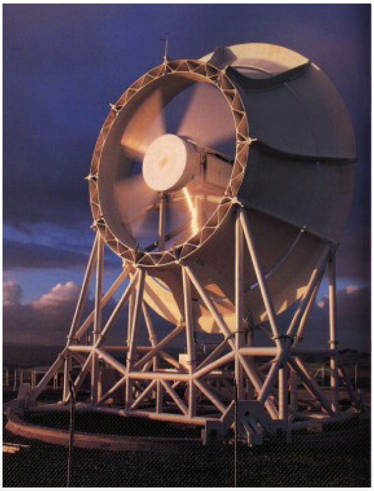

Fig. 7. The Vortec 7 diffuser augmented wind turbine at Waikaretu, New Zealand

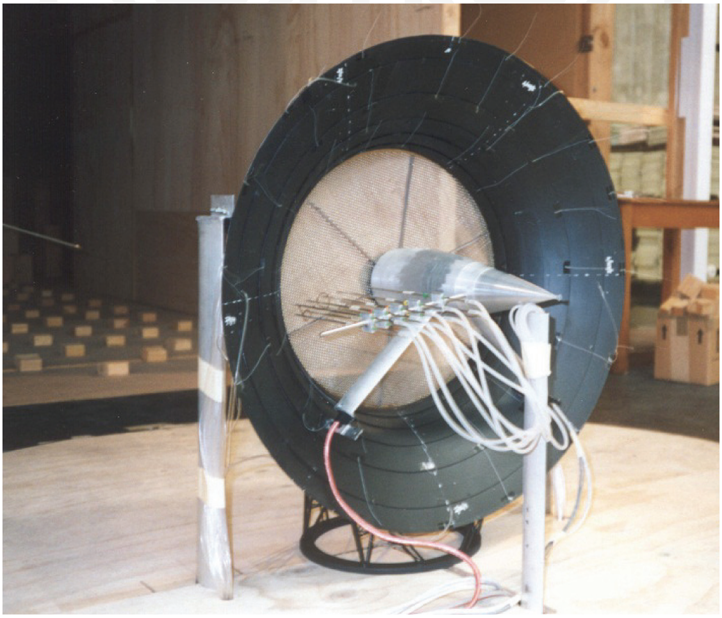

Fig. 8. Wind tunnel model of a diffuser augmented wind turbine with a wire mesh screen to simulate the blades, and with a rack of Pitot tubes to measure the pressure drop and flow speed through the blade-plane

In order to find out if the blade loading was matched to the diffuser, a model scale Vortec 7 wind turbine was constructed and then tested in the University of Auckland's large 7 m x 3.5 m wind tunnel. Fig. 8 shows the model in the wind tunnel. The blades have been replaced by wire mesh screens of suitable pressure drop coefficient. Screens are very convenient to use for testing and can give a good indication of potential output of wind turbines. In the present design, it is important to match the resistance at the blade plane to the diffuser area ratio. An estimate of the power output can be made by measuring both the flow speed through the mesh, u, as well as the pressure drop, ΔP. Then the power is

$$\dot{W} = Au\Delta P \tag{17}$$

where the pressure drop is

$$\Delta P = k_s \frac{1}{2}\rho u^2 \tag{18}$$

Hence,

$$\dot{W} = Ak_s \frac{1}{2}\rho u^3 \tag{19}$$

It is much more challenging to build model wind turbines with small blades. Notwithstanding the lack of Reynolds number similarity, it is difficult practically to build small blades. However, this was necessary in the Vortec project and after the optimum pressure drop was determined from tests using a range of screen pressure drop coefficients in preliminary tests, blades were designed in such a way that their pressure drop (or drag) coefficient was the required value.

A wind tunnel model equipped with blades can be seen in Fig. 9.

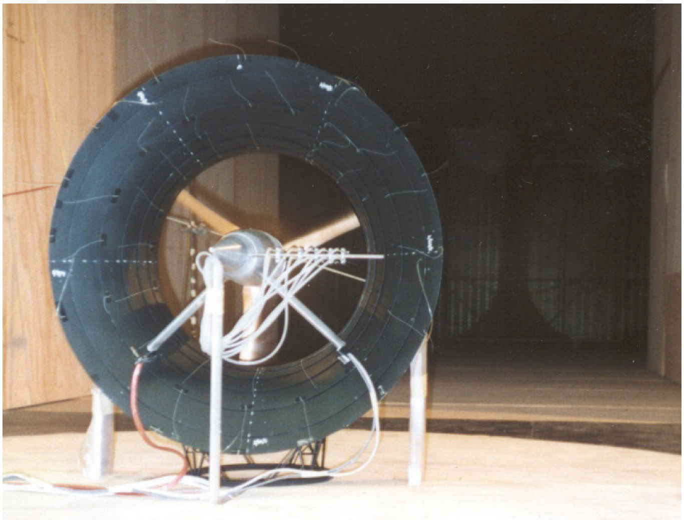

Fig. 9. Wind tunnel model equipped with blades and a Pitot tube rack to measure pressures and speeds

Typical results from wind tunnel test with screens and blades can be seen in Fig. 10.

Fig. 10 shows a range of results from the blade tests for different blade loadings. The axial drag from the blades was altered by changing the pitch angle as well as the tip speed. The screen loading was changed by using screens of differing porosities. The results from the blade tests are rather impressive and were obtained by using a special hub, which measured the thrust and torque to a motor/generator whose rotational speed could be set remotely. Thus by changing the motor speed, the required tip speed ratios for an individual test could essentially be dialled up. This is also illustrated in Fig. 11. The excellent spread of results illustrates that this feature is powerful in carrying out such wind tunnel tests. It should be noted that the augmentation is larger when the blades are used instead of the wire mesh screens. It is believed that this is because of the turbulence and swirl that is generated by the blades that travels downstream and makes the diffuser perform more efficiently.

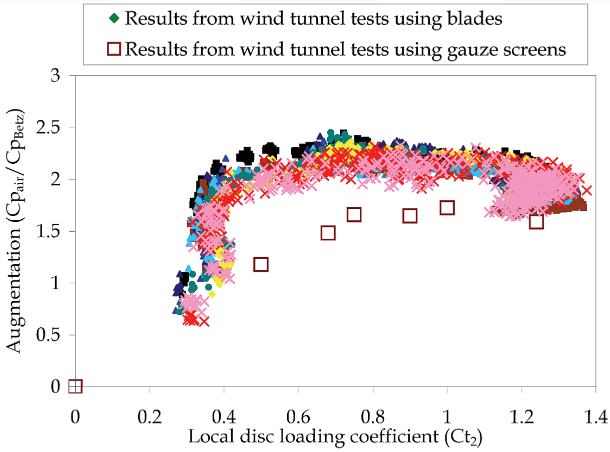

Fig. 10. Typical results from the wind tunnel comparing performance with a screen with that of blades

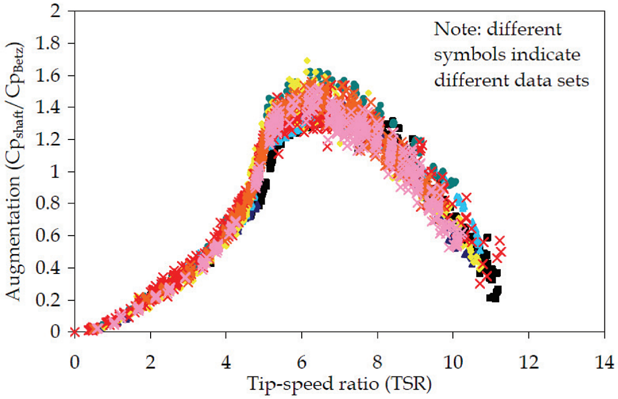

Fig. 11. Augmentation of wind turbine for a wide range of tip speed ratios that could be set by the motor/generator wind turbine load

6.2. Wind tunnel tests of telescoping blade wind turbine

Another interesting study on wind turbines was carried out by a former PhD student, Imraan [14], and concerned increasing the output of wind turbines by using telescoping blades. Further details on this research project can be found in Imraan et al. [15].

A significant aspect of this research resulted from careful wind tunnel tests using various blades. The same instrumented hub was used for this research as for the earlier work by Phillips [21]. The hub and rotor with three blades attached is shown in Fig. 12. Note its streamlined shape. A close-up photograph of the hub is shown in Fig. 13. As explained above, the hub contains a variable speed motor/generator. Although it is not very clear in Fig. 13, the motor/generator system is attached to ground via strain-gauged links that enable both the torque and thrust to be measured. A small l.e.d. is evident at the top of Fig. 13. This led is used to measure the rotational speed.

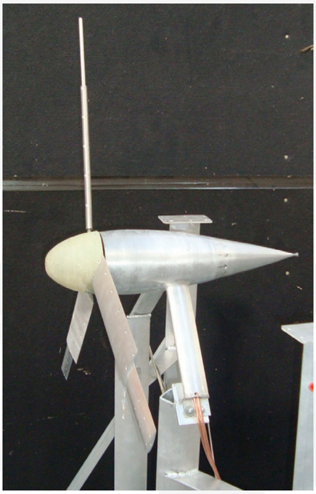

Fig. 12. Photograph of wind turbine model with stepped blades mounted on the instrumented hub

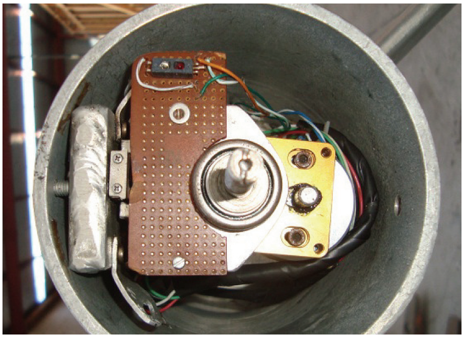

Fig. 13. Close up front view of the instrumented hub

The step in the blades mounted on the hub is clearly evident in Fig. 12. However, here the blades are rather small and thus the Reynolds number was low. It is often useful to know more about the details of the loading in wind turbine investigations, and in this case a larger pressure tapped stepped blade was built for test, and is shown in Fig. 14. The black marks on the blade at the numbering for the pressure taps. These pressure taps were connected to a multi-channel pressure system that can sample up to 1000 Hz. It can be seen in Fig. 15.

Fig. 14. Photograph of larger pressure tapped model stepped blade in the wind tunnel

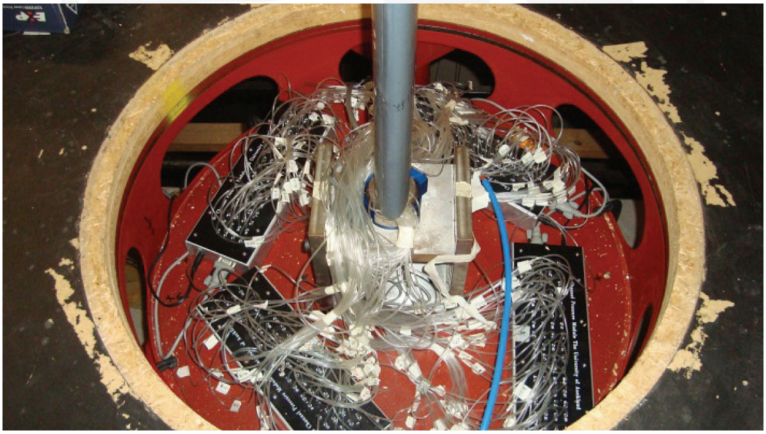

Fig. 15. Photograph of wing mounted on turntable. Tubing from pressure taps leaves the wing at the base and connects to the multi-channel pressure transducer boxes

6.3. Wind tunnel tests on a vertical axis wind turbine

It has been found at The University of Auckland that it is very practical to use an open jet wind tunnel of large size, where the models can be placed on the floor either in a location with side walls, or further downstream without sidewalls. A recent study carried out by an undergraduate student, which is now continuing into a master's project, concerned a vertical axis wind turbine [8]. This wind turbine was fitted with a Voith-Schneider linkage system which enabled the blades to be rotated to different angles of attack with respect to the circumferential direction. The model wind turbine is shown in Fig. 16. The important point of this modelling is that to conveniently build the Voith Schneider linkage, the model could not be too small. The model shown in Fig. 16 has blades that are 1.5 m long and the diameter of the wind turbine was 2 m. The wind tunnel outlet is 3.5 m x 3.5 m in cross-section. At this large size, the linkage mechanism was relatively straightforward to build.

In order to assess the performance of this wind turbine, the reference wind tunnel air speed, the wind turbine rotational speed, and the generator power were measured for a range of settings of the Voith Schneider system. This required the use of a computer based measuring system which sampled the data at 1000 Hz.

Fig. 16. Vertical axis wind turbine set up in open circuit wind tunnel

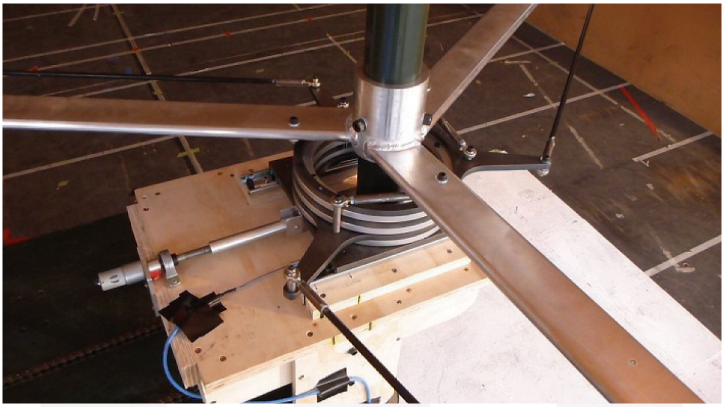

Fig. 17. Voith Schneider linkage system used to alter the angle of attack of the blades during each rotation

7. Conclusions

The paper has shown that in order to undertake successful measurements of wind turbine models in wind tunnels, it is necessary to have an excellent instrumentation setup that can measure the reference quantities of barometric pressure, temperature and pressure accurately. It is also important that the wind tunnel is calibrated so that the dynamic and static pressures measured by the reference measuring system can be transferred to the location of the model.

The paper has discussed blockage corrections and reproduced a procedure originally put forward by Wilson et al [27] who based it on work of Glauert [11], which can be used to correct wind turbine power coefficient measurement from the interference of the walls. It has also been pointed out that much higher blockage ratios can be tolerated in an open jet test, which may be preferable in cases where the available wind tunnels are small, and there is a desire to build as large a model as possible.

Some lessons learnt from testing at the University of Auckland have been discussed by referring to previous research on wind turbines. It has been pointed out that it may be possible to undertake initial testing using porous mesh screens to simulate the pressure drop of rotating blades, which can be hard to manufacture at a small size, and will always operate at a Reynolds number that is at least the model scale ratio lower than full scale Reynolds number.

A suitably equipped hub is needed in order to measure the output from the model wind turbine. The outputs normally needed are thrust, torque and rotational speed. Power produced is also useful but not essential. The load from the motor/generator in the hub should be able to be controlled remotely to enable it to be set to suitable values to enable data to be acquired for the desired range of tip speed ratios. Such a system can be built by mounting the motor/generator with strain-gauged supports.

Additional information on the performance of wind turbines, such as the effect of step changes in the blade can be found by pressure-tapping the blade in the region of interest and testing a larger non-rotating model in a wind tunnel.

For some tests, particularly where there are complicated mechanisms to be built, it is wise to build the model as large as possible to simplify the manufacturing process.

Overall, it is clearly evident that wind tunnel testing is an important tool to make progress in research on wind turbine performance, and the aerodynamics of wind turbine blades.

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References

[1] Blocken B., Carmeliet J., Stathopoulos T., *CFD evaluation of wind speed conditions in passages between parallel buildings - effect of wall-function roughness modifications for the atmospheric boundary layer flow*. Journal of Wind Engineering and Industrial Aerodynamics, Vol. 95(9-11), 2007, 941-962.

[2] Builtjes P.J.H., Milborrow D.J., *Modelling of wind turbine arrays*. Proc. 3rd International Symposium Wind Energy Systems, Denmark, Copenhagen 1980.

[3] Barlow J.B., Rae W.J., Pope A., *Low speed wind tunnel testing*, Wiley-Interscience, John Wiley and Sons, USA 1999.

[4] Bottasso C.L., Campagnolo F., Petrovi V., *Wind tunnel testing of scaled wind turbine models: Beyond aerodynamics*, Journal of Wind Engineering and Industrial Aerodynamics, Vol. 127, 2014, 11-28.

[5] Chasteau V.A.L., *Operational experience with a 5 m Darrieus wind turbine*, Proc. 6th Australasian Hydraulics and Fluid Mechanics Conference, Australia, Adelaide, 5-9 December 1977.

[6] Chen J., Fletcher D.F., Haynes B.S., *Validation of the cobra probe using turbulence measurements in a fully developed pipe flow*. Proc. 13th Australasian Fluid Mechanics Conference, 13-18 Dec, eds. M. C. Thompson & K. Hourigan, Monash University, Melbourne, Australia, 1998, Vol. 1, 385-388.

[7] Chen T.Y., Liou L.R., *Blockage corrections in wind tunnel tests of small horizontal-axis wind turbines*. Experimental Thermal and Fluid Science, Vol. 35(3), 2011, 565-569.

[8] Corkery S., *Vertical axis wind turbine with new variable pitch blades*, Project Report 2013-ME18, October 2013.

[9] Fitzgerald R., *Wind tunnel blockage corrections for propellers*, Master Thesis, University of Maryland, 2007.

[10] Gilbert B.L., Foreman K.M., *Experimental demonstration of the diffuser-augmented wind turbine concept*, Journal of Energy, Vol. 3(4), 1979, 235-240.

[11] Glauert H., Durand W.F. (Ed.), *Aerodynamic theory*, "*Airplane propellers*", Vol. IV, Division I, Chapter VII, Section 4, Julius Springer, Berlin 1935, 169-360.

[12] Hand M.M., Simms D.A., Fingersh L.J., Jager D.W., Cotrell J.R., Schreck S., Larwood S.M., *Unsteady aerodynamics experiment phase VI: wind tunnel test configurations and available data campaigns*, Technical Report NREL/TP-500-29955, NREL National Renewable Energy Laboratory, USA 2001.

[13] Hooper J.D., Musgrove A.R., *Multi-hole pressure probes for the determination of the total velocity vector in turbulent single-phase flow*, Proc. 4th International Symposium on Transport Phenomena in Heat and Mass Transfer, ed. J. A. Reizes, Pacific Centre of Thermal-Fluids Engineering, Sydney, Australia 1991, Vol. 4, 1364.

[14] Imraan M. *Aerodynamic analysis of a wind turbine with telescopic blades*, PhD thesis, Mechanical Engineering Department, The University of Auckland, New Zealand, 2013.

[15] Imraan M., Sharma R.N., Flay R.G.J., *Wind tunnel testing of a wind turbine with telescopic blades: The influence of blade extension*, Energy, Vol. 53, 2013, 22-32.

[16] Imraan M, Sharma, R.N., Flay, R.G.J. *Wind tunnel testing of a wind turbine with telescopic blades*, Proc. 13th International Conference on Wind Engineering, Amsterdam, The Netherlands, July 10-15, 2011.

[17] Sorensen J.N., Wen Zhong Shen, Mikkelsen R., *Wall correction model for wind tunnels with open test section*, AIAA Journal, Vol. 44(8), 2006, 1890-1894.

[18] Lindley D., Flay R.G.J., Bowen A.J., *Field measurements of the characteristics of a rural boundary-layer near the ground: Part I; The measured data*, Proc. 6th Australasian Conference on Hydraulics and Fluid Mechanics, Adelaide, Australia, Vol. 1, 1977, 182-185.

[19] Whale J., Papadopoulos K.H., Anderson C.G., Helmis C.G., Skyner D.J., *A study of the near wake structure of a wind turbine comparing measurements from laboratory and full-scale experiments*, Solar Energy, Vol. 56, 1996, 621-633.

[20] Phillips D.G., Richards P.J., Flay R.G.J., *CFD Modelling and the development of the diffuser augmented wind turbine*, Wind and Structures, Vol. 5(2-4), 2002, 267-276.

[21] Phillips D.G., *An investigation on diffuser augmented wind turbine design*, PhD thesis, School of Engineering, The University of Auckland, New Zealand 2003.

[21] Ross I.J., *Wind tunnel blockage corrections: an application to vertical-axis wind turbines*. MSc Thesis, University of Dayton, Dayton, Ohio, May 2010.

[22] Ross I.J., Altman A., *Wind tunnel blockage corrections: Review and application to Savonius vertical-axis wind turbines*, Journal of Wind Engineering and Industrial Aerodynamics, Vol. 99, 2011, 523-538.

[23] Schepers J.G., Snel H., *Model experiments in controlled conditions – final report*. Technical Report, ECN-E-07-042, ECN Wind Energy, The Netherlands 2007.

[24] Snel H., Schepers J.G., Montgomerie B., *The MEXICO projec (Model EXperiments In Controlled cOnditions): the data base and first results of data processing and interpretation*, Journal of Physics: Conference Series, Vol. 75, 2007.

[25] Tamura Y., Kareem A. (Eds.), *Advanced structural wind engineering*, Springer, Japan 2013.

[26] Vermeer L.J., Sørensen J.N., Crespo A., *Wind turbine wake aerodynamics*, Progress in Aerospace Sciences, Vol. 39, 2003, 467-510.

[27] Wilson R.E., Lissaman P.B.S., Walker S.N., *Aerodynamic performance of wind turbines – Final report*, Report ERDA/NSF/04014-76/1, Department of Mechanical Engineering, Oregon State University, Corvallis, Oregon. Available from NTIS, U.S. Department of Commerce, Springfield, Virginia 22161, USA.

[28] World Wind Energy Association, WWEA., World Wind Energy Half Year Report, 2014, http://www.wwindea.org/home/index.php 2014.