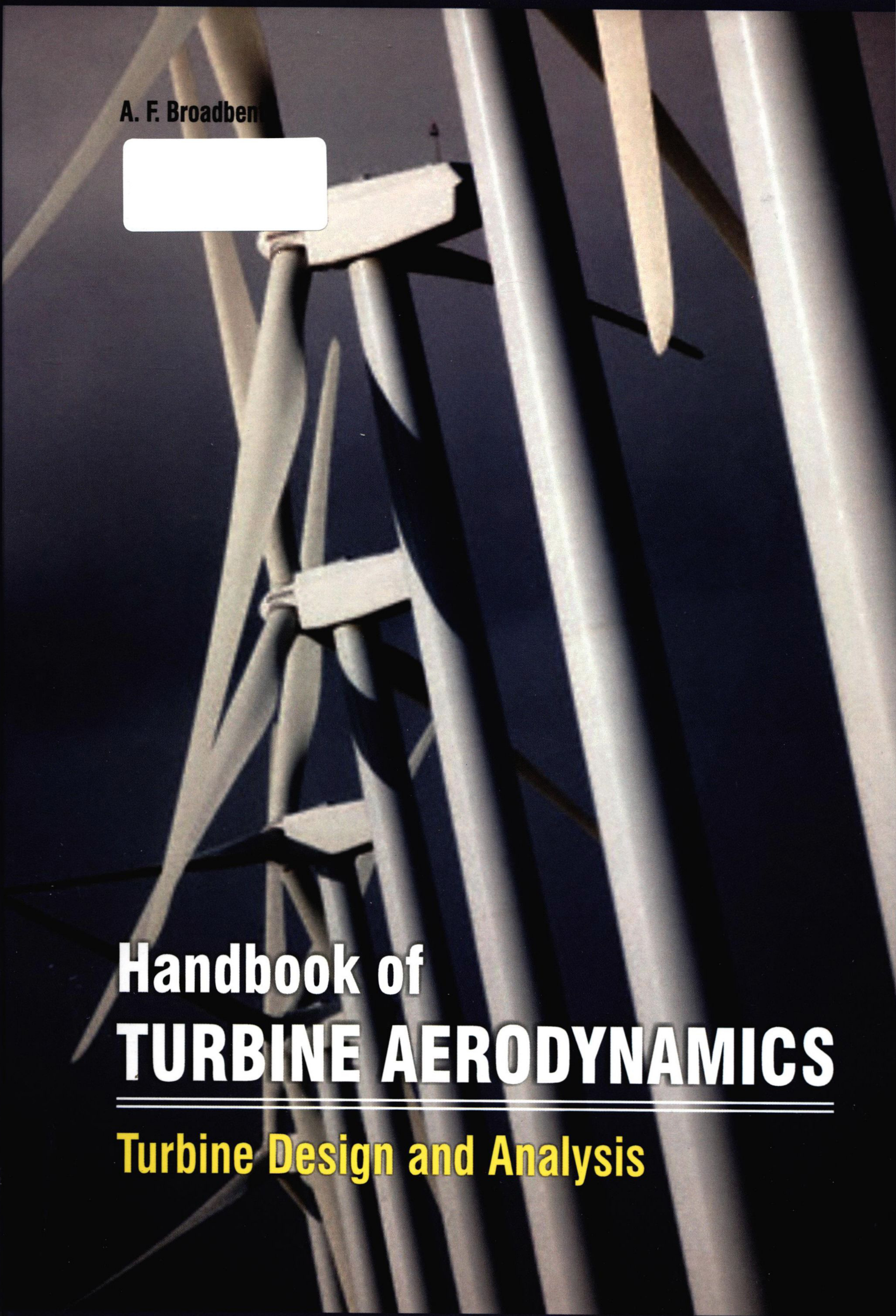

A. F. Broadben

Handbook of TURBINE AERODYNAMICS

Turbine Design and Analysis

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TURBINE AERODYNAMICS
Turbine Design and Analysis

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Preface

It has become almost a ritual to preface a book. But this preface is much more than a ritual. It is a direct interaction with the readers of this book.

The readers of this book will have comprehensive knowledge on design and analyses of wind turbines and various aspects of aerodynamics related to wing turbines and gas turbines. Wind turbines use the same aerodynamics principals as aircrafts. Basic design principles and mechanical aspects of wind turbines are covered on Chapters 1 to 24. Aerodynamics principles of gas turbines have been covered in 4 chapters (No. 25-28).

Chapters 1 and 2 : Covers general consideration of aerodynamics related to wind turbines.

Chapter 3 : Cover aspects related to wind turbine blade aerodynamics.

Chapters 4, 5, 6, 7, 8 and 9 : Cover mechanical aspects related to wind turbines and wind power.

Chapters 10 and 11 : Cover electrical power generation system from a wind turbine.

Chapters 12 to 18 : Covers control methods on wind energy conversion system.

Chapters 19 to 25 : Cover basic principles of aerodynamics and various theories related to wind turbines.

Chapters 26 to 28 : Cover basic concepts of gas turbines and aerodynamics consideration.

I finally believe that there is always scope for improvement. Suggestion and comment from readers would be gratefully received and duly acknowledged.

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Contents

Chapter 1

WIND TURBINE AERODYNAMICS

1.1 INTRODUCTION

Wind turbine extracts energy from wind. Hence, the aerodynamics is a very important aspect of wind turbines. Like many machines, there are many different types all based on different energy extraction concepts. Similarly, there is great difference between the aerodynamics of one wind turbine to others.

The details of the aerodynamics depend very much on the topology. Some fundamental concepts apply to all turbines. Every topology has a maximum power for a given flow, and some topologies are better than others. The method used to extract power has a strong influence on this. In general all turbines can be grouped as being lift based, or drag based with the former being more efficient. The difference between these groups is the aerodynamic force that is used to extract the energy.

The horizontal-axis wind turbine (HAWT) is the most common topology. It is a lift-based wind turbine with very good performance, accordingly it is popular for commercial applications and much research has been applied to this turbine. In the latter part of the 20th century. The Darrieus wind turbine was another popular lift-based alternative but is rarely used today. The Savonius wind turbine is the most common drag-type turbine, which is robust and simple to build. It is used despite its low efficiency.

Fig. 1.1 Wind turbine blades awaiting installation in laydown yard

1.2 COMMON CONSIDERATIONS FOR AERODYNAMICS

The governing equation for power extraction is given below:

$$P = \vec{F} \cdot \vec{v} \tag{1}$$

(where: P is the power, F is the force vector, and v is the velocity of the moving wind turbine part.

The force F is generated by the wind interacting with the blade. The primary focus of wind turbine aerodynamics is the magnitude and distribution of this force. The most familiar type of aerodynamic force is drag. The direction of the drag force is parallel to the relative wind. Typically, the wind turbine parts are moving, altering the flow around the part. An example of relative wind is the wind one would feel cycling on a calm day.

The turbine part must move in the direction of the net force for power extraction. In the drag force case, the relative wind speed decreases subsequently, and so does the drag force. The relative wind aspect dramatically limits the maximum power that can be extracted by a drag based wind turbine. Lift based wind turbine typically have lifting surfaces moving perpendicular to the flow. Here, the relative wind will not decrease in fact it increases with rotor speed. Thus the maximum power limits of these machines is much higher than drag-based machines.

1.3 CHARACTERISTIC PARAMETERS OF WIND TURBINE AERODYNAMICS

There are various sizes of wind turbines. Then once the wind turbine is operating it will experience a wide range of conditions. This variability complicates the comparison of different types of turbines. To deal with this, nondimensionalization is applied to various qualities. One of the qualities of nondimensionalization is that when geometrically similar turbines will produce the same non-dimensional results, while because of other factors (difference in scale, wind properties) produce very different dimensional properties. This allows one to make comparisons between different turbines, while eliminating the effect of things like size and wind conditions from the comparison.

The coefficient of power is the most important variable in wind turbine aerodynamics. Buckingham π theorem which is a key theorem in dimensional analysis can be applied to show that non-dimensional variable for power is given by the equation below. This equation is similar to efficiency, so values between 0 and less than one are typical. However, this is not the exactly the same as efficiency so in practice, some turbines can exhibit greater than unity power coefficients. In these circumstances, one cannot conclude, that the first law of thermodynamics is violated that because this is not an efficiency term by the strict definition of efficiency.

$$C_p = \frac{P}{\frac{1}{2}\rho A V^3} \tag{CP}$$

where: C_p is the coefficient of power, ρ is the air density, A is the area of the wind turbine, finally V is the wind speed.

Equation (1) shows two important dependents. The first one is the speed (U) that the machine is going at. The speed at the tip of the blade is usually used for this purpose, and is written as the product of the blade radius and the rotational speed of the wind (U = omega*r, where omega = rotational velocity in radians/second). This variable is nondimensionalized by the wind speed, to get the speed ratio:

$$\lambda = \frac{U}{V} \qquad \text{(Speed ratio)}$$

The force vector is not straightforward, as stated earlier there are two types of aerodynamic forces lift and drag. Accordingly there are two non-dimensional parameters. However, both variables are non-dimensionalized in a similar way. The formula for lift is given below, the formula for drag is given after:

$$C_L = \frac{L}{\frac{1}{2}\rho A W^2} \qquad \text{(CL)}$$

$$C_D = \frac{D}{\frac{1}{2}\rho A W^2} \qquad \text{(CD)}$$

where: C_L is the lift coefficient, C_D is the drag coefficient, W is the relative wind as experienced by the wind turbine blade, A is the area but may not be the same area as used in the power non-dimensionalization of power.

The aerodynamic forces have a dependency on W, this speed is the relative speed and it is given by the equation below. Note that this is a vector subtraction.

$$\vec{W} = \vec{V} - \vec{U} \qquad \text{(Relative speed)}$$

1.4 MAXIMUM POWER OF A DRAG BASED WIND TURBINE

Starting point for deriving power of a drag based turbine is equation 1. Equation (CD) is used to define the force, and equation (**Relative Speed**) is used for the relative speed. These substitutions give the following formula for power.

$$P = \frac{1}{2}\rho A C_D\,(UV^2 - 2VU^2 + U^3) \qquad \text{(Drag Power)}$$

The formulae (**CP**) and (**Speed Ratio**) are applied to express (**Drag Power**) in nondimensional form:

$$C_P = C_D\,(\lambda - 2\lambda^2 - \lambda^3) \qquad \text{(Drag CP)}$$

With the help of calculus it can be shown that equation (**Drag CP**) achieves a maximum at $\lambda = 1/3$. By inspection one can see that equation (**Drag Power**) will achieve larger values for $\lambda > 1$. In these circumstances, the scalar product in equation (**1**) makes the result negative. Thus, one can conclude that the maximum power is given by:

$$C_P = \frac{4}{27} C_D$$

Experimentally it has been determined that a large C_D is 1.2, thus the maximum C_P is approximately 0.1778.

1.5 MAXIMUM POWER OF A LIFT-BASED WIND TURBINE

Maximum power of a lift-based machine can be derived in similarly way but with some modifications. First we must recognize that drag is always present, thus cannot be ignored. It will be shown that neglecting drag leads to a final solution of infinite power. This result is clearly invalid, hence we will proceed with drag. As before, equations (**1**), (**CD**) and (**Relative Speed**) will be used along with (**CL**) to define the power given in expression.

$$P = \frac{1}{2} \rho A \sqrt{U^2 + V^2} (C_L UV - C_D U^2) \qquad \text{(Lift Power)}$$

Similarly, this is non-dimensionalized with equations (**CP**) and (**Speed Ratio**). However, in this derivation the parameter $\gamma = C_D / C_L$ is also used

$$C_P = C_L \sqrt{1 + \lambda^2} (\lambda - \gamma \lambda^2) \qquad \text{(Lift CP)}$$

Solving the optimal speed ratio is complicated by the dependency on γ and the fact that the optimal speed ratio is a solution to a cubic polynomial. Numerical methods can then be applied to determine this solution and the corresponding C_P solution for a range of γ results. Some sample solutions are given in the table below.

Table 1.1. Optimal speed ration and corresponding C_P solution for a range of γ results

γ	**Optimal λ**	**Optimal C_P**
0.5	1.23	0.75 C_L
0.2	3.29	3.87 C_L
0.1	6.64	14.98 C_L
0.05	13.32	59.43 C_L
0.04	16.66	92.76 C_L
0.03	22.2	164.78 C_L
0.02	33.3	370.54 C_L
0.01	66.7	1481.65 C_L
0.007	95.23	3023.6 C_L

Experiments have shown that it is not unreasonable to achieve a drag ratio (γ) of approximately 0.01 at a lift coefficient of 0.6. This would give a C_P of about

889. This is substantially better than the best drag based machine, hence why lift-based machines are superior.

In the analysis given here, there is an inconsistency compared to typical wind turbine non-dimensionalization. As stated in the preceding section the A in the C_p non-dimensionalization is not always the same as the A in the force equations (**CL**) and (**CD**). Typically for C_p the A is the area swept by the rotor blade in its motion. For C_L and C_D A is the area of the turbine wing section. For drag based machines, these two areas are almost identical so there is little difference. To make the lift-based results comparable to the drag results, the area of the wing section was used to non-dimensionalize the power. The results here could be interpreted as power per unit of material. Given that the material represents the cost (wind is free), this is a better variable for comparison.

Applying conventional non-dimensionalization, more information on the motion of the blade would be required. However, the discussion on Horizontal Axis Wind Turbines will show that the maximum C_p there is 16/27. Thus, even by conventional non-dimensional analysis lift-based machines are superior to drag based machines.

The analysis has many idealizations. In any lift-based machine (aircraft included) with finite wings, there is a wake that affects the incoming flow and creates induced drag. This phenomenon exists in wind turbines and was neglected in this analysis. Including induced drag requires information specific to the topology. We can expect that both the optimal speed ratio and the optimal C_p would be less. The analysis is focused on the aerodynamic potential, but neglected on structural aspects. In reality, most optimal wind turbine design becomes a compromise between optimal aerodynamic design, and optimal structural design.

IN SUMMARY

- The horizontal-axis wind turbine (HAWT) is the most common topology which is a lift-based wind turbine with very good performance.
- The coefficient of power is the most important variable in wind turbine aerodynamics.
- The derivation for a the maximum power of a lift-based machine is similar with some modifications.
- In any lift-based machine (aircraft included) with finite wings, there is a wake that affects the incoming flow and creates induced drag.

Chapter 2

HORIZONTAL AXIS WIND TURBINES

1. INTRODUCTION

A wind turbine is a device that extracts kinetic energy from the wind and converts it into mechanical energy. Therefore wind turbine power production depends on the interaction between the rotor and the wind. So the major aspects of wind turbine performance like power output and loads are determined by the aerodynamic forces generated by the wind. These can only be understood with a deep comprehension of the aerodynamics of steady state operation. Accordingly, this chapter focuses primarily on steady state aerodynamics.

2.1. Aerodynamics of Horizontal Axis Wind Turbine (HAWTs)

The majority of the chapter details the classical analytical approach for the analysis of horizontal axis wind turbines and the performance prediction of these machines. The analysis of the aerodynamic behaviour of wind turbines can be started without any specific turbine design just by considering the energy extraction process. A simple model, known as actuator disc model, can be used to calculate the power output of an ideal turbine rotor and the wind thrust on the rotor. Additionally more advanced methods including momentum theory, blade element theory and finally blade element momentum (BEM) theory are introduced. BEM theory is used to determine the optimum blade shape and also to predict the performance parameters of the rotor for ideal, steady operating conditions. Blade element momentum theory combines two methods to analyze the aerodynamic performance of a wind turbine. These are momentum theory and blade-element theory which are used to outline the governing equations for the aerodynamic design and power prediction of a HAWT rotor. Momentum theory analyses the momentum balance on a rotating annular stream tube passing through a turbine and blade-element theory examines the forces generated by the aerofoil lift and drag coefficients at various sections along the blade. Combining these theories gives a series of equations that can be solved iteratively.

2.2.1 Actuator Disc Model

The analysis of the aerodynamic behaviour of wind turbines can be started without any specific turbine design just by considering the energy extraction process. The simplest model of a wind turbine is the so-called actuator disc model where the turbine is replaced by a circular disc through which the airstream flows with