FUNDAMENTALS OF ENERGY EXTRACTION FROM WIND

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Contents

Summary

This Article presents some fundamental principles on how a wind energy conversion system converts the kinetic energy of the wind into mechanical energy and electric energy using airfoils, a drive-train and a generator. Operating characteristics of major rotor type wind turbines are shown. Efficiencies of various types of wind turbines and Betz limit are described. The typical wind turbine energy output versus wind speed is given.

1. Introduction

Wind energy is the kinetic energy of large masses of air moving over the earth. Because the sun heats the earth’s surface and atmosphere unevenly, thermal differences produce air density and pressure differences and drive air masses around the planet. The earth’s rotation also contributes to powerful air currents.

A wind energy conversion system (WECS) converts this kinetic energy into mechanical energy and electrical energy using airfoils, a drive train, and a generator. The conversion process begins as air flows over a blade, called an airfoil that is similar to an airplane wing or propeller.

2. Forces Arising when Wind Flows Over an Airfoil

Airflow over a stationary airfoil produces two forces, a lift force perpendicular to the airflow and a drag force in the direction of airflow, as shown in Figure 1. The air flowing over the top of the airfoil has to speed up because of a greater distance to travel, and this increase in speed causes a slight decrease in pressure. This pressure difference across the airfoil yields the lift force, which is perpendicular to the direction of airflow.

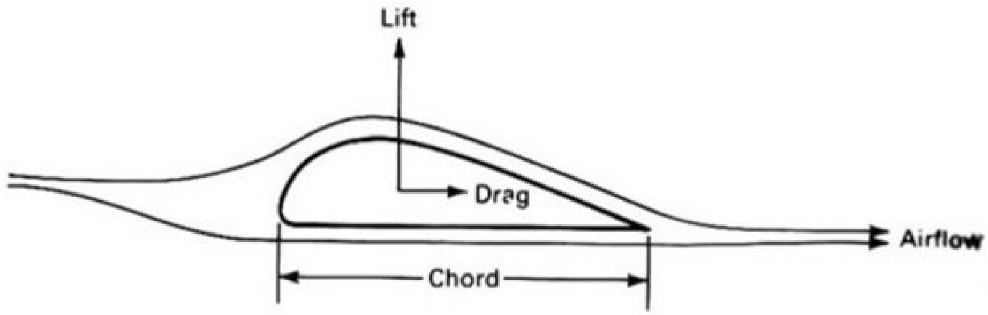

Figure 1. Lift and drag on a stationary airfoil.

The air moving over the airfoil also produces a drag force in the direction of the airflow. This is a loss term and is minimized as much as possible in high performance wind turbines. Both the lift and the drag are proportional to the air density, the area of the airfoil, and the square of the wind speed.

An important parameter of a blade is the pitch angle β, which is the angle between the chord line of the blade and the plane of rotation, as shown in Figure 2. The chord line is the straight line connecting the leading and trailing edges of an airfoil. The plane of rotation is the plane in which the blades lie as they rotate. The blade tips actually trace out a circle that lies on the plane of rotation.

Full power output would normally be obtained when the wind direction is perpendicular to the plane of rotation. The pitch angle is a static angle, depending only on the orientation of the blade. Another important blade parameter is the angle of attack γ, which is the angle between the chord line of the blade and the relative wind velocity or the effective direction of airflow. It is a dynamic angle, depending on both the speed of the blade and the speed of the wind. The blade speed at a distance r from the rotation axis is $r\omega_m$, where ω_m is the angular velocity.

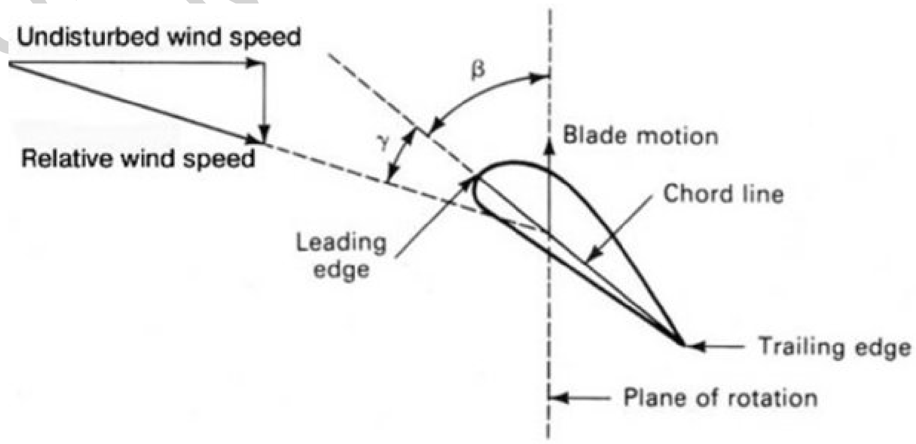

Figure 2. Definition of pitch angle β and angle of attack γ.

A blade without twist will have a variation in angle of attack from hub to tip because of the variation of $r\omega_m$ with distance from the hub. The lift and drag have optimum values for a single angle of attack; so a blade without twist is less efficient than a blade with the proper twist to maintain a nearly constant angle of attack from hub to tip. Even the blades of the old Dutch windmills were twisted to improve the efficiency. Most modern blades are twisted, but some are not for cost reasons. A straight blade is easier and cheaper to build and the cost reduction may more than offset the loss in performance.

When the blade is twisted, the pitch angle will change from hub to tip. In this situation, the pitch angle measured at three-fourths of the distance from the hub to the tip is selected as the reference.

3. Power Carried Over by the Wind and Extracted by the Wind Wheel

The power carried over by the wind through an area *A* perpendicular to the flow is defined for air at standard conditions: pressure 101.3 kPa and temperature 273 K:

$$P_w = 0.5\, A\rho V^3, \qquad (1)$$

where *A*, m^2 is area swept by the wind; ρ, kg m^{-3} is the air density equal at standard conditions 1.294 kg m^{-3}; *V*, m s^{-1} is the wind speed; P_w, W is the power carried over by the wind.

The fraction of power extracted from the wind by a practical wind turbine is usually defined as C_p standing for the power coefficient of the wind wheel.

Using this notation the actual mechanical power output P_m can be written as

$$P_m = C_p\, 0.5 A\rho V^3 = C_p P_w \qquad (2)$$

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Biographical Sketch

Professor Vladimir A. Dobrovolski, Ph.D. was born in Moscow, Russia in 1936. He graduated from Moscow Aviation Institute in 1960 and Ph. D. Degree in 1968.

1960-1963 - test engineer, the USSR Civil Aviation

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