Wind Power

Wind resources

Earth, the Earth's rotation and seasonal and regional fluctuations of the solar

air pressure differentials

Table 5.1 *Wind Speed Classification of the Beaufort Wind Scale*

Bf	*v in m/s*	*Description*	*Effects*
0	0–0.2	Calm	Smoke rises vertically
1	0.3–1.5	Light air	Smoke moves slightly and shows direction of wind
2	1.6–3.3	Light breeze	Wind can be felt. Leaves start to rustle
3	3.4–5.4	Gentle breeze	Small branches start to sway. Wind extends light flags
4	5.5–7.9	Moderate breeze	Larger branches sway. Loose dust on ground moves
5	8.0–10.7	Fresh breeze	Small trees sway
6	10.8–13.8	Strong breeze	Trees begin to bend, whistling in wires
7	13.9–17.1	Moderate gale	Large trees sway
8	17.2–20.7	Fresh gale	Twigs break from trees
9	20.8–24.4	Strong gale	Branches break from trees, minor damage to buildings
10	24.5–28.4	Full gale/storm	Trees are uprooted
11	28.5–32.6	Violent storm	Widespread damage
12	$\geqslant$ 32.7	Hurricane	Structural damage

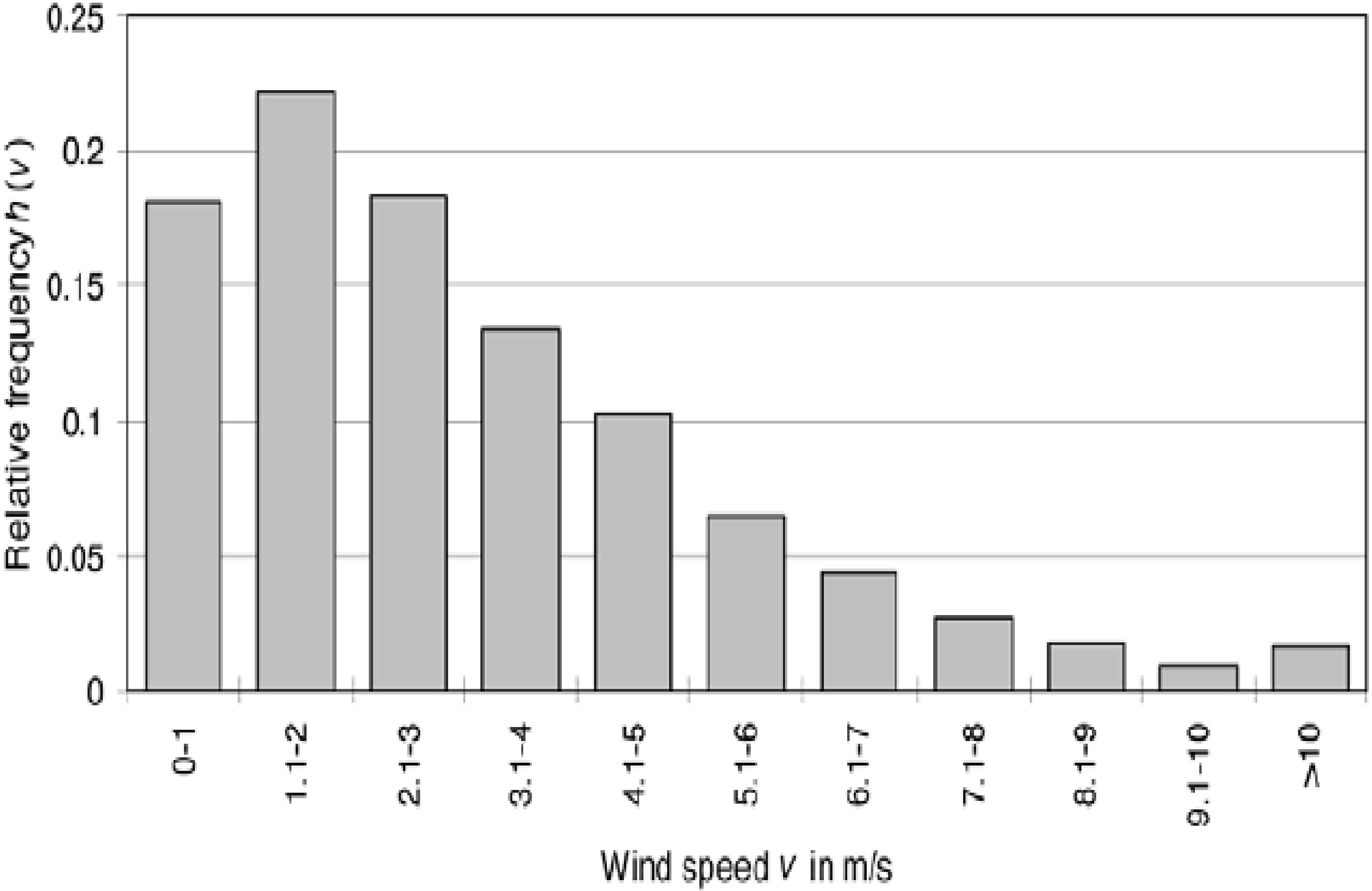


Figure 5.1 *Wind Speed Distribution for Karlsruhe in Inland Germany in 1991/1992*

Location	*k*	*a*	*v in m/s*	*Location*	*k*	*a*	*v in m/s*
Berlin	1.85	4.4	3.9	Munich	1.32	3.2	2.9
Hamburg	1.87	4.6	4.1	Nuremberg	1.36	2.9	2.7
Hannover	1.78	4.1	3.7	Saarbrücken	1.76	3.7	3.3
Helgoland	2.13	8.0	7.1	Stuttgart	1.23	2.6	2.4
Cologne	1.77	3.6	3.2	Wasserkuppe	1.98	6.8	6.0

Table 5.3 *Roughness Lengths z_0 for Different Ground Classes*

Ground class	*Roughness length z_0 in m*	*Description*
1 – Sea	0.0002	Open sea
2 – Smooth	0.005	Mud flats
3 – Open	0.03	Open flat terrain, pasture
4 – Open to rough	0.1	Agricultural land with a low population
5 – Rough	0.25	Agricultural land with a high population
6 – Very rough	0.5	Park landscape with bushes and trees
7 – Closed	1	Regular obstacles (woods, village, suburb)
8 – Inner city	2	Centres of big cities with low and high buildings

Power content of wind

kinetic energy E

$$E = \frac{1}{2} \cdot m \cdot v^2$$

power P

$$P = \dot{E} = \frac{1}{2} \cdot \dot{m} \cdot v^2$$

$$m = \rho \cdot V$$

air mass flow:

$$\dot{m} = \rho \cdot \dot{V} = \rho \cdot A \cdot \dot{s} = \rho \cdot A \cdot v$$

$$P = \frac{1}{2} \cdot \rho \cdot A \cdot v^3$$

$$\dot{m} = \rho \cdot \dot{V} = \rho \cdot A_1 \cdot v_1 = \rho \cdot A \cdot v = \rho \cdot A_2 \cdot v_2 = const.$$

The wind speed

$$v = \frac{1}{2} \cdot (v_1 + v_2)$$

$$P_T = \frac{1}{2} \cdot \dot{m} \cdot (v_1^2 - v_2^2) \quad .$$

With $\dot{m} = \rho \bullet A \bullet v = \rho \bullet A \bullet \frac{1}{2} \bullet (v_1 + v_2)$, the expression becomes:

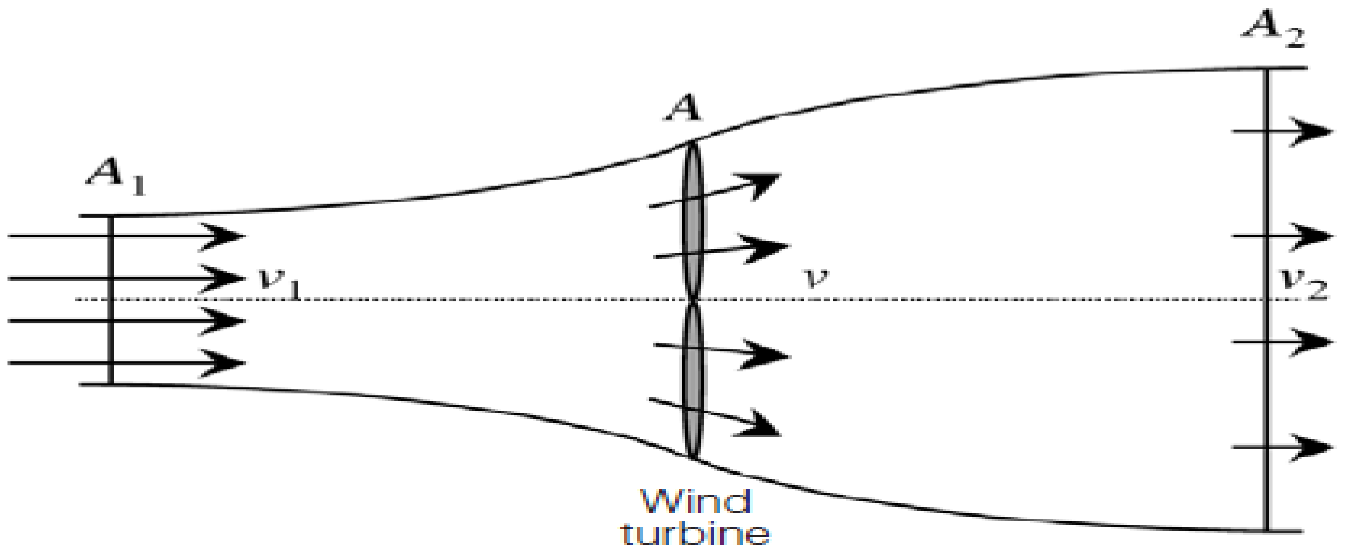


Figure 5.4 *Idealized Change of Wind Speed at a Wind Turbine*

$$P_T = \frac{1}{4} \cdot \rho \cdot A \cdot (v_1 + v_2) \cdot (v_1^2 - v_2^2)$$

The power P_0 of the wind through the area A without the influence of the wind turbine is:

$$P_0 = \frac{1}{2} \cdot \rho \cdot A \cdot v_1^3 \quad . \tag{5.17}$$

: *power coefficient* c_P

$$c_P = \frac{P_T}{P_0} = \frac{(v_1 + v_2) \cdot (v_1^2 - v_2^2)}{2 \cdot v_1^3} = \frac{1}{2} \cdot (1 + \frac{v_2}{v_1}) \cdot (1 - \frac{v_2^2}{v_1^2})$$

Betz power coefficient $c_{P,Betz}$

With $\zeta = \frac{v_2}{v_1}$ and $\frac{d c_P}{d\zeta} = \frac{d\left(\frac{1}{2} \cdot (1+\zeta) \cdot (1-\zeta^2)\right)}{d\zeta} = -\frac{3}{2} \cdot \zeta^2 - \zeta + \frac{1}{2} = 0$,

$$\zeta_{id} = \frac{v_2}{v_1} = \frac{1}{3} \quad .$$

$$\eta = \frac{P_T}{P_{id}} = \frac{P_T}{P_0 \cdot c_{P,Betz}} = \frac{P_T}{\frac{1}{2} \cdot \rho \cdot A \cdot v_1^3 \cdot c_{P,Betz}} = \frac{c_P}{c_{P,Betz}}$$

Drag devices

If an object is set up perpendicularly to the wind, the wind exerts a force F_D on the object. The wind speed v, the effective object area A and the *drag coefficient* c_D, which depends on the object shape, define the drag force:

$$F_D = c_D \cdot \frac{1}{2} \cdot \rho \cdot A \cdot v^2$$

$$P_D = c_D \cdot \frac{1}{2} \cdot \rho \cdot A \cdot v^3$$

$$F_D = c_D \cdot \frac{1}{2} \cdot \rho \cdot A \cdot (v - u)^2$$

$$P_T = c_D \cdot \frac{1}{2} \cdot \rho \cdot A \cdot (v - u)^2 \cdot u$$ object moves with speed u

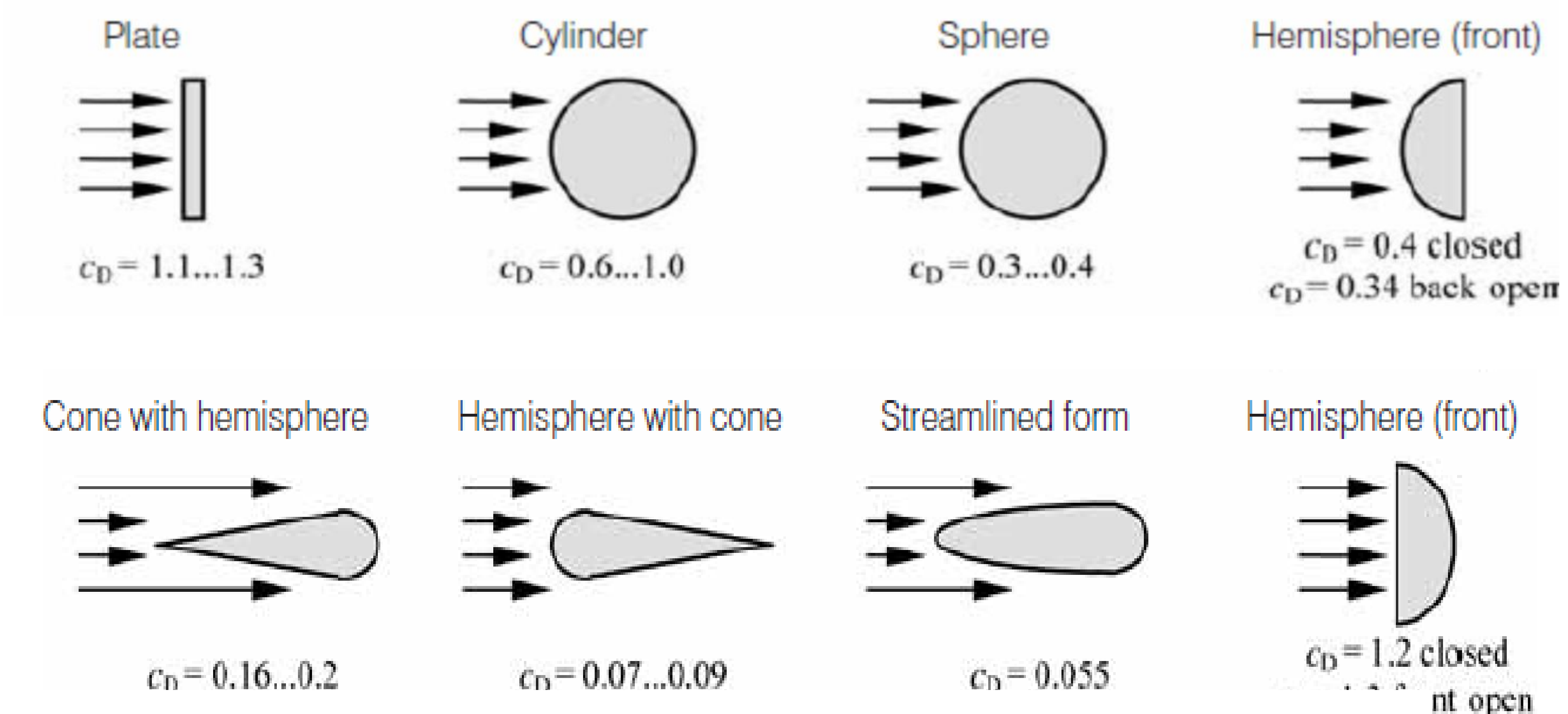


Figure 5.5 Drag Coefficients for Various Shapes

Tower, Foundations, Gearbox, Nacelle and Generator

The *tower* is one of the most important parts of the wind power plant. It must hold the nacelle and the rotor blades. Higher tower heights can increase the wind generator output because the wind speed rises with height. Early in their

Modern towers can reach heights up to 100 m and even more.

The following example calculates approximately the used power of a cup anemometer that is used for the measurement of the wind speed v. It consists of two open hemispherical cups that rotate around a common axis. The wind impacts the front of the first cup and the back of the second cup (Figure 5.6).

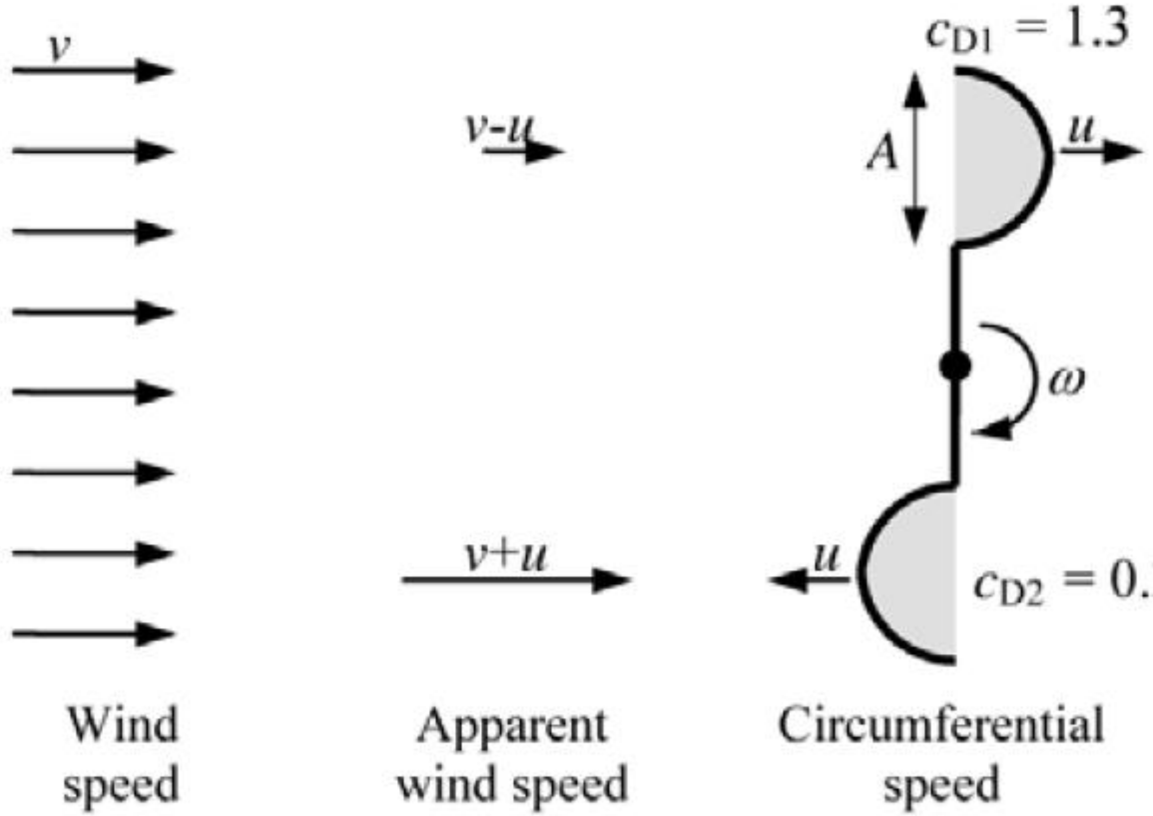
The resulting force F consists of a driving and a decelerating component (Gasch and Twele, 2002):

$$F = c_{D1} \cdot \tfrac{1}{2} \cdot \rho \cdot A \cdot (v - u)^2 - c_{D2} \cdot \tfrac{1}{2} \cdot \rho \cdot A \cdot (v + u)^2 \tag{5.25}$$

$$P_T = \tfrac{1}{2} \cdot \rho \cdot A \cdot \left(c_{D1} \cdot (v - u)^2 - c_{D2} \cdot (v + u)^2 \right) \cdot u$$

$$\lambda = \frac{u}{v}$$

The ratio of the circumferential speed u to the wind speed v is called the tip speed ratio λ:



$$c_P = \frac{P_T}{P_0} = \frac{P_T}{\frac{1}{2} \cdot \rho \cdot A \cdot v^3} = \lambda \cdot \left(c_{D1} \cdot (1-\lambda)^2 - c_{D2} \cdot (1+\lambda)^2 \right)$$

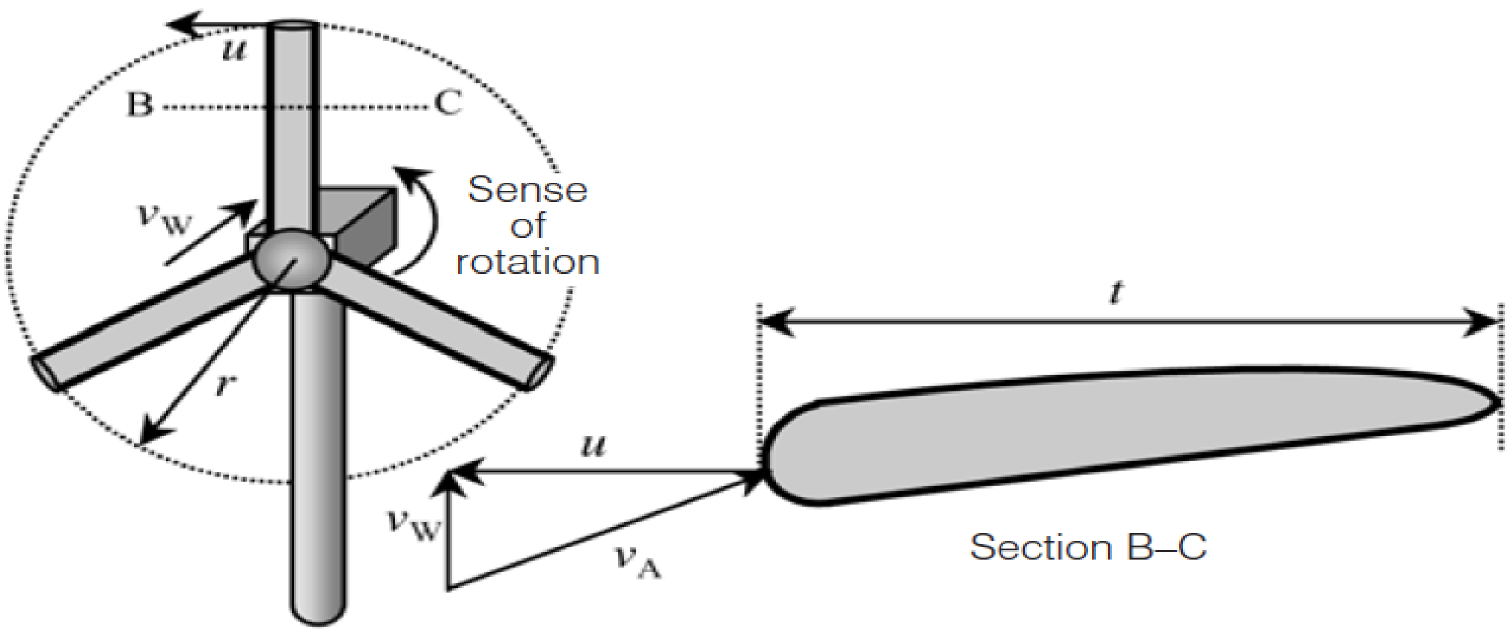
Lift devices

If wind, which circulates around a body, develops higher flow speeds along the upper surface than along the lower, an overpressure emerges at the upper surface and an underpressure at the lower. The result is a *buoyancy force*, according to Bernoulli:

$$F_L = c_L \cdot \tfrac{1}{2} \cdot \rho \cdot A_P \cdot v_A^2$$

lift coefficient c_L,

the apparent wind speed v_A and the projected body area A_P.



Drag forces,

$$F_D = c_D \cdot \tfrac{1}{2} \cdot \rho \cdot A_P \cdot v_A^2$$

lift-drag ratio ε:

$$\varepsilon = \frac{F_L}{F_D} = \frac{c_L}{c_D}$$

$$F_R = F_D + F_L$$

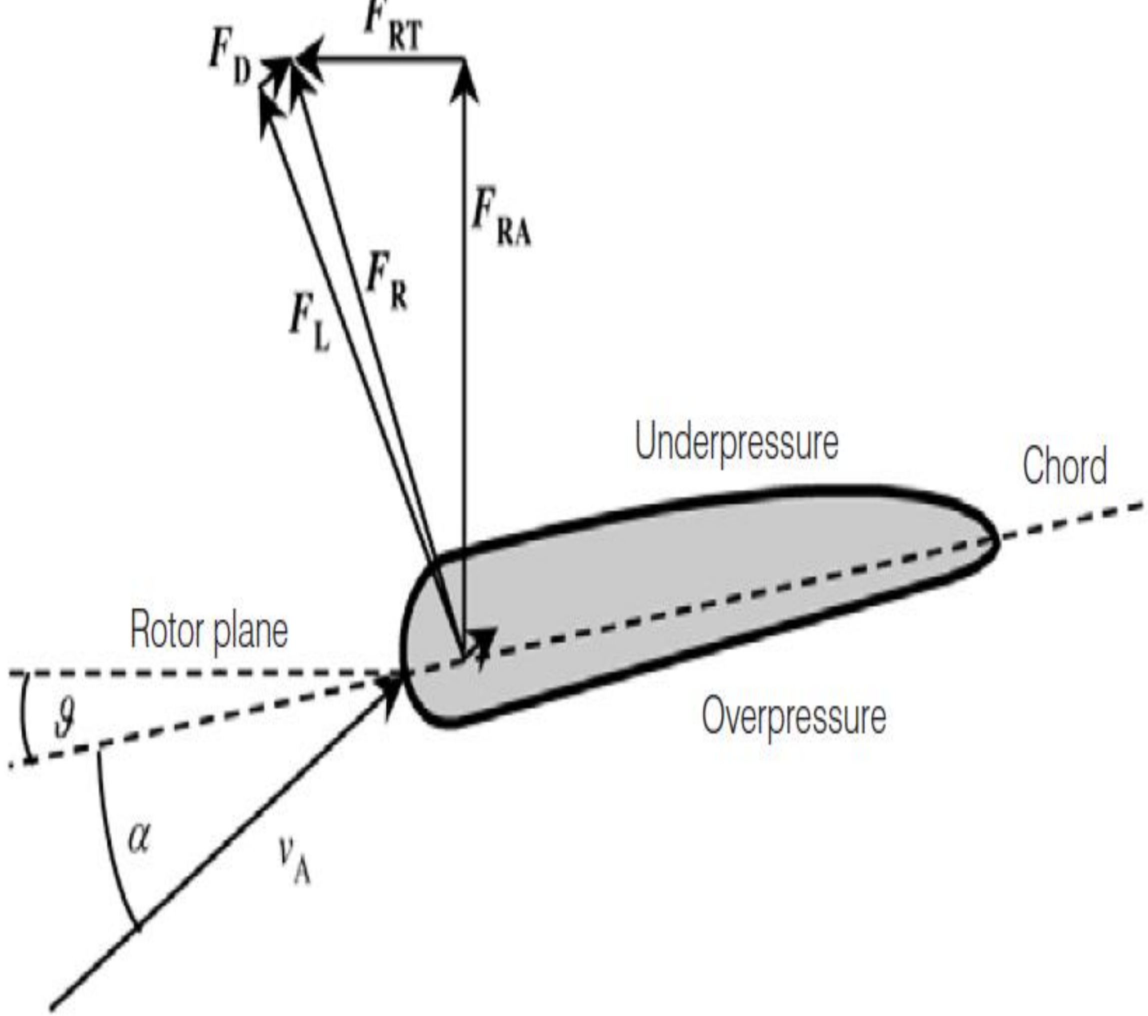


Figure 5.8 *Ratio of the Forces for a Lift Device*

Figure 5.8 shows the ratio of the drag force F_D to the buoyancy force F_L. Vector addition of both forces provides the resultant force:

The nacelle of the wind power plants carries the rotor bearings, the *gearbox* and the electric generator. Since most generator designs need high rotational speed, a gearbox must adapt the rotor speed to the generator speed. However, a gearbox has a lot of disadvantages: it causes higher costs, friction losses, noise pollution and higher maintenance efforts. Gearless wind power plant concepts with specially designed generators try to avoid these disadvantages. These generators must have a high number of magnetic poles so that the generator can also produce electricity at low rotor speeds. However, a high number of poles enlarge the generator significantly and therefore increase its cost.