HYDRO AND EOLIC PLANTS

ESF II project of the University of West Bohemia in Pilsen reg. number: CZ.02.2.69/0.0/0.0/18_056/0013239



EUROPEAN UNION
European Structural and Investment Funds
Operational Programme Research,
Development and Education



Eolic engines

Milan Bělík

Eolic engines

- drag principle
  - farmer wheel (15 – 30 %)
  - rotor Savonius (10 – 20 %)
- lift principle
  - propeller (45 – 48 %)
  - rotor Darrieus (38 – 48 %)
  - wind wheel (20 – 30 %)
  - Halladay turbine (20 – 43 %)
  - turbine Eclipse (25 – 45 %)
  - wind mill (15 – 30 %)









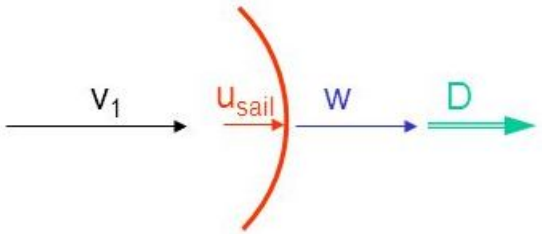


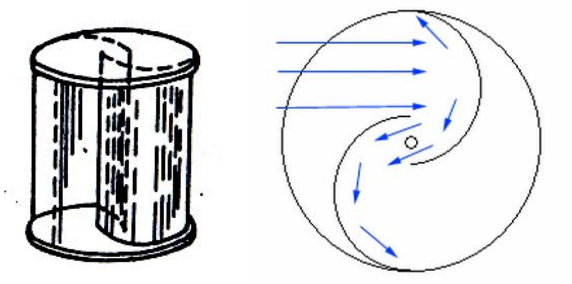
Drag principle

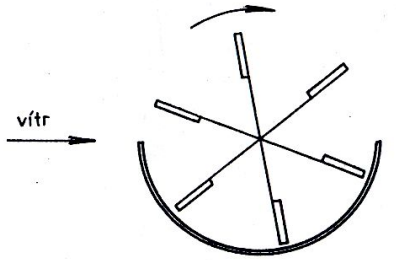
- drag force

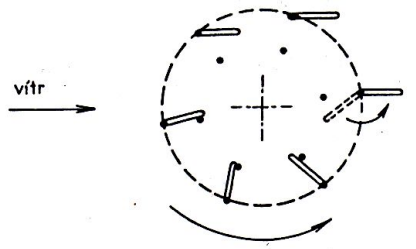
$$F_D = \frac{1}{2}\rho * c_D * A * w^2 \qquad [N]$$

$$w = v_1 - u$$

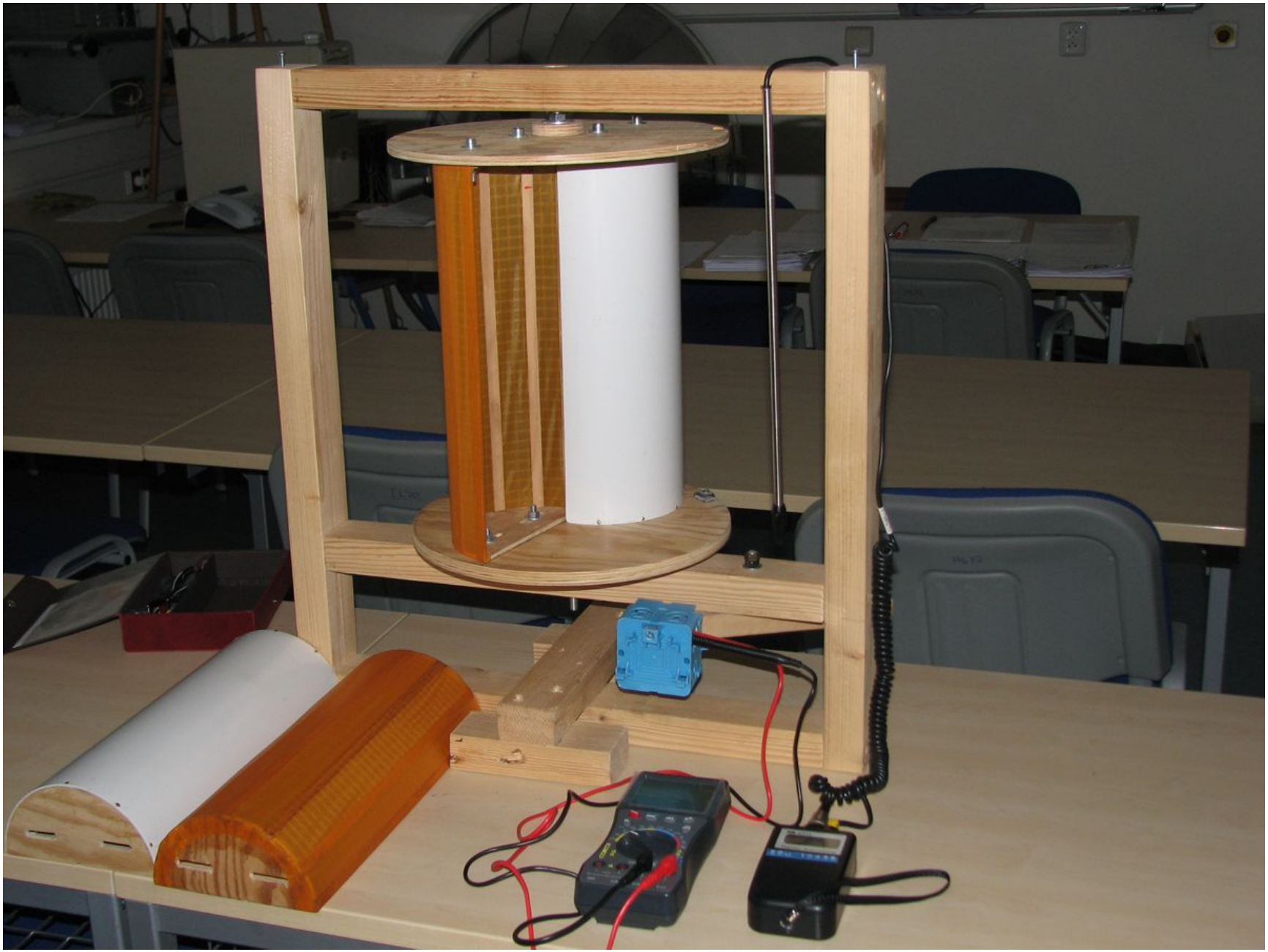








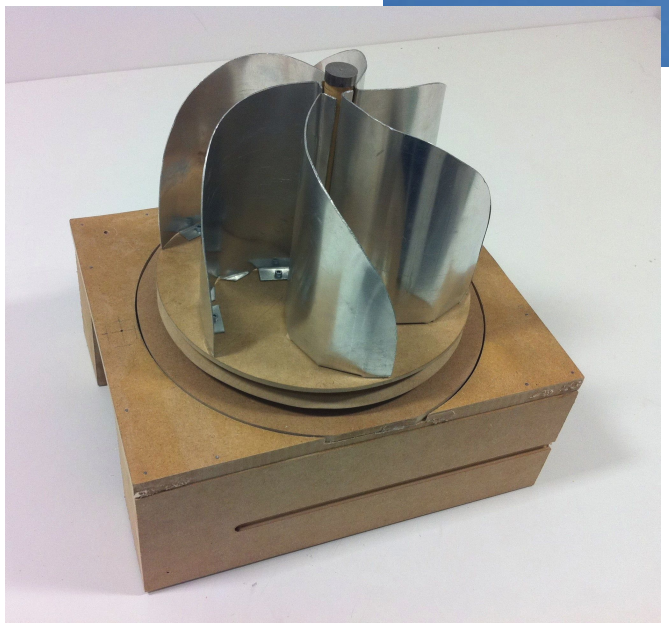
Rotor Savonius







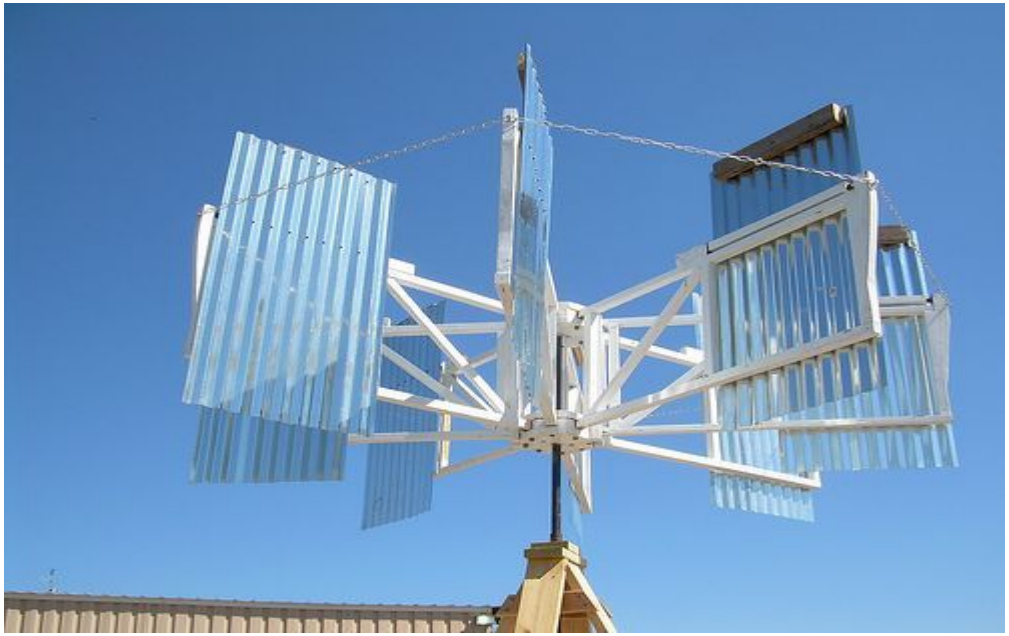













AMG
POWER SOLUTIONS










SATTHON


CARTHAGE'S
SATTHON

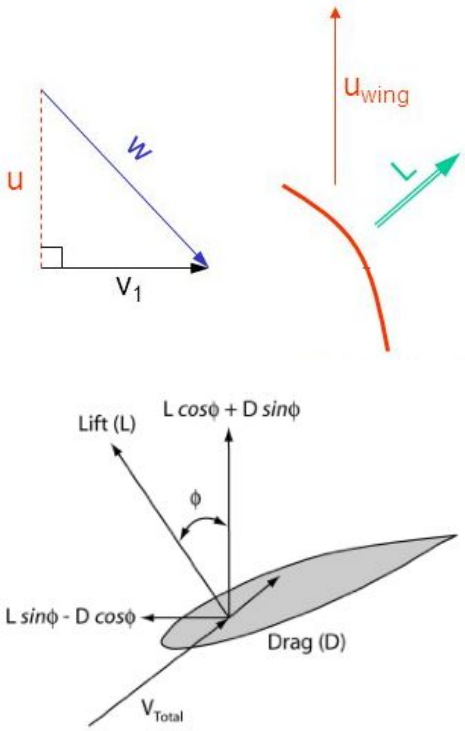
Lift principle

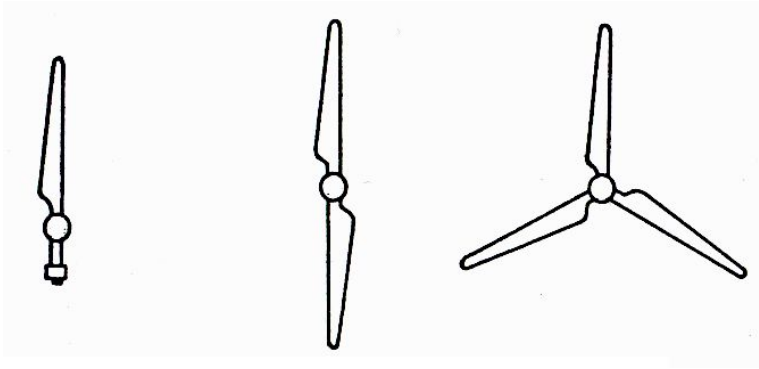
- lift force

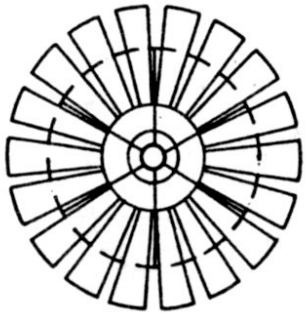
$$F_L = \frac{1}{2}\rho * c_L * A * w^2 \qquad [N]$$

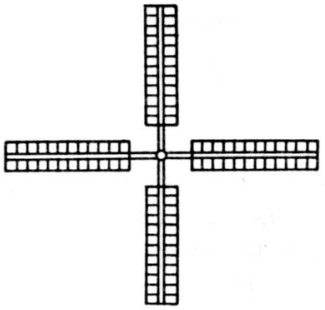
$$w = \sqrt{v_1^2 + u^2}$$

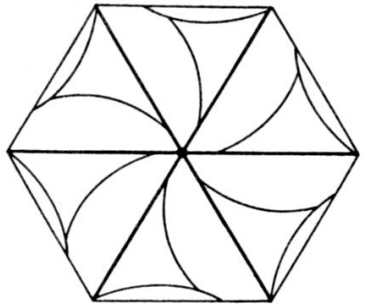
- J. Smeaton (1724-1792)
  - c_L=0,28 (c_p)
  - smeaton coefficient







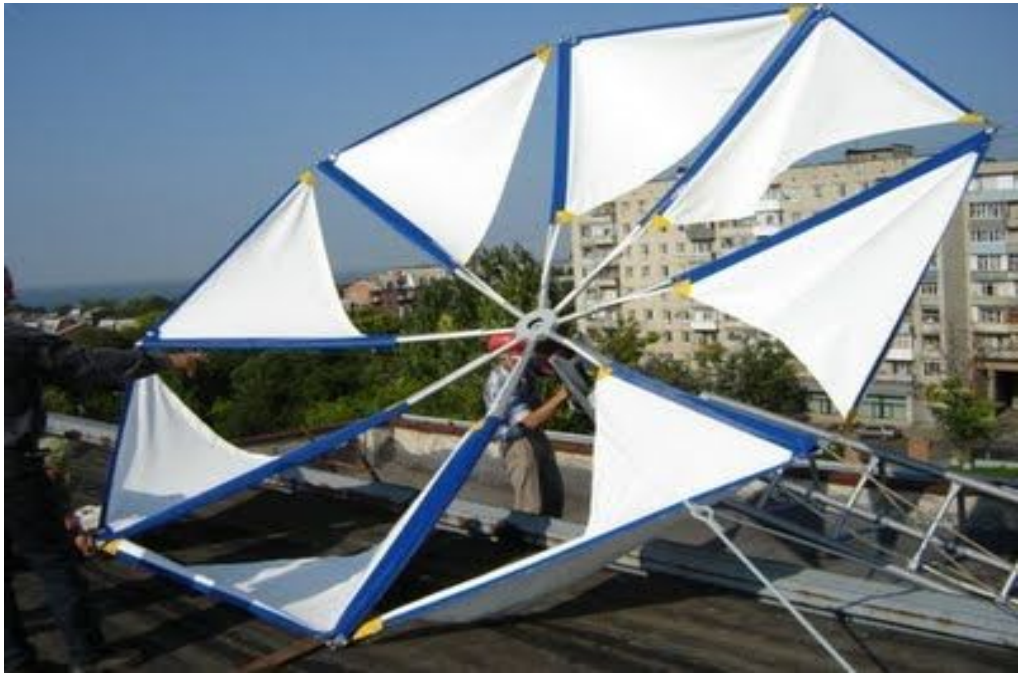




Wind mill







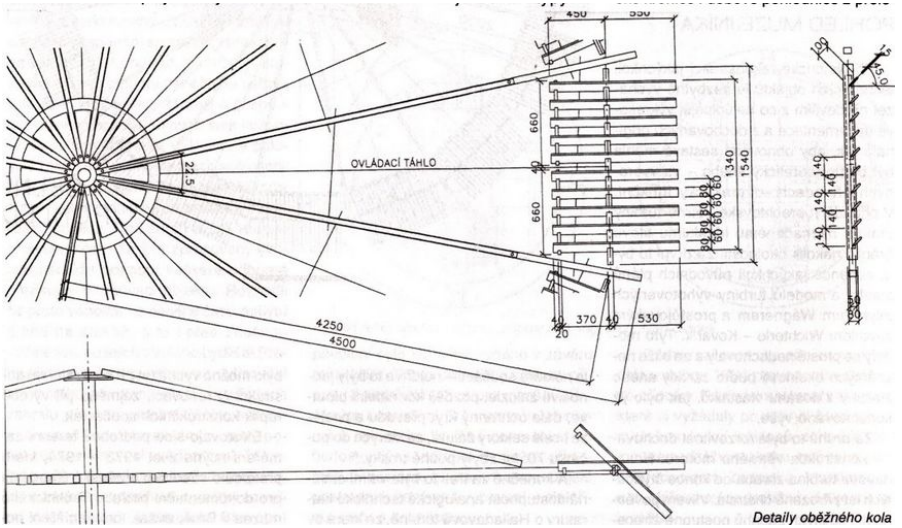


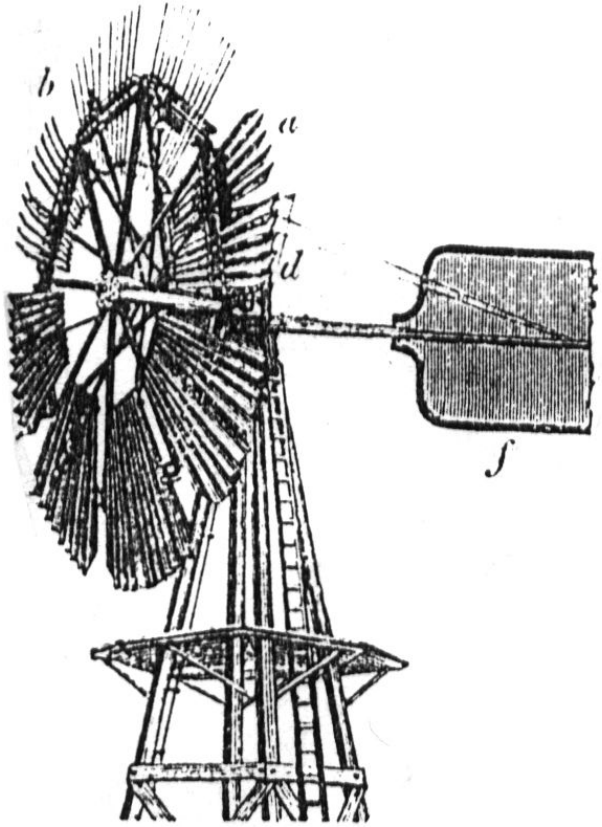


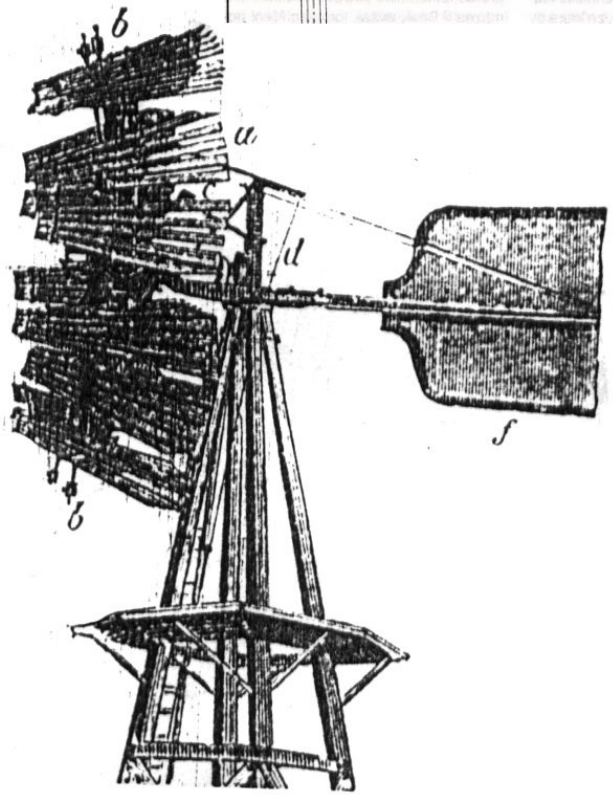


Halladay turbine

1854 – Daniel Halladay (Vermont)







Mlýn Ruprechtov

1873 – wind wheel

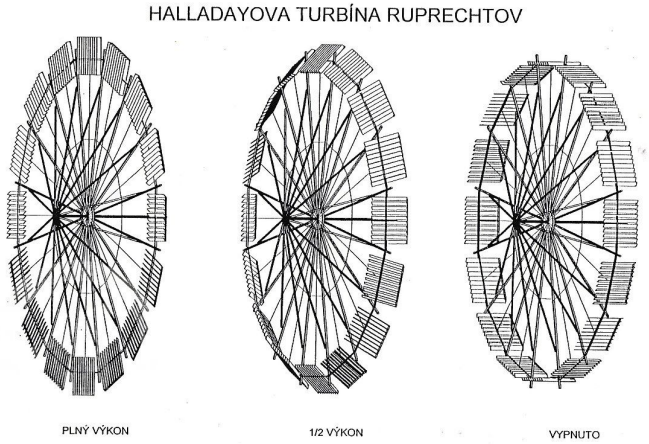
Wágner, Čtvrtníček, Gottwald

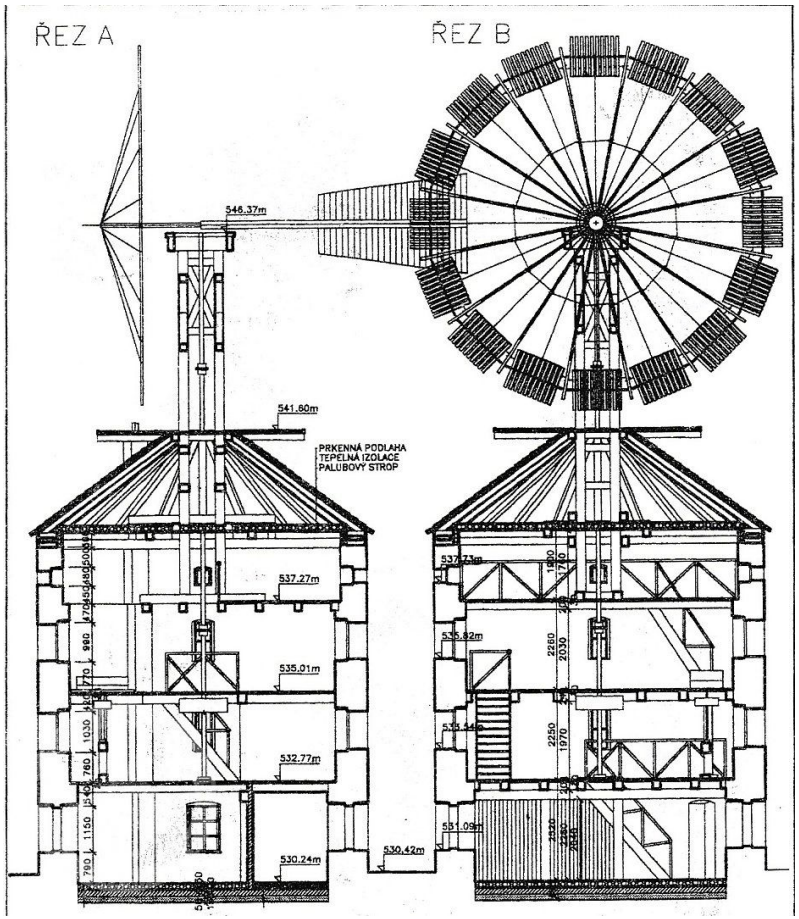
1884 – Halladay turbine

Wágner

1995 - renovation







Farmer wheel



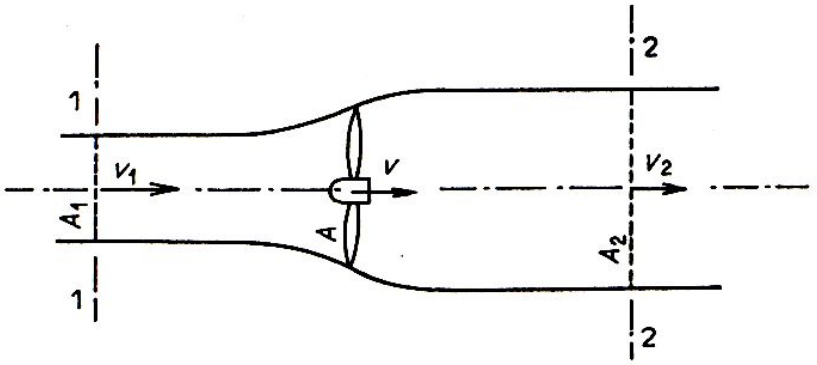
n-blade propeller











$$v_1 A_1 = vA = v_2 A_2$$

$$F_a = \rho A v (v_1 - v_2)$$

$$P = F_a v = \rho A v^2 (v_1 - v_2) \qquad P = \frac{\Delta E_k}{t} = \frac{1}{2}\rho A v \left(v_1^2 - v_2^2\right)$$

$$v = \frac{v_1 + v_2}{2}$$

$$F_a = \frac{1}{2}\rho A \left(v_1^2 - v_2^2\right)$$

$$P = \frac{1}{4}\rho A \left(v_1^2 - v_2^2\right)(v_1 + v_2) \qquad P = \frac{\Delta E_k}{t} = \frac{1}{2}\rho A v^3$$

$$\eta_i = \frac{P_{vrtule}}{P_{větru}}$$

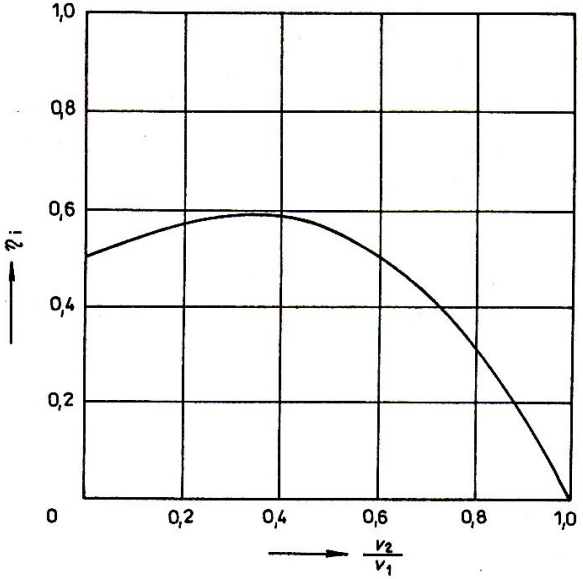
$$\eta_i = \frac{\left(v_1^2 - v_2^2\right)(v_1 + v_2)}{2v_1^3}$$

$v_2/v_1 = 1/3 \quad \eta_i = \frac{16}{27} = 0{,}592\,6$

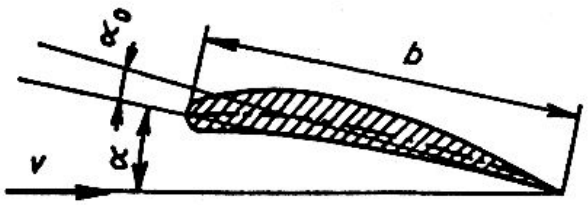
$u = v/3 \quad \eta_{i\,max} = 1/3$

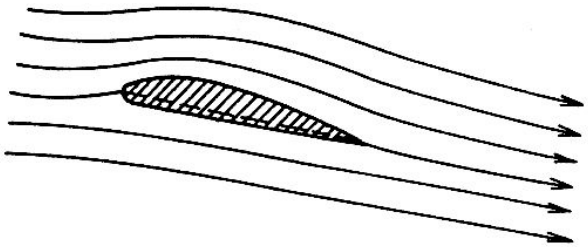
$v_2/v_1 = 0{,}414 \quad \eta_i = 0{,}687$

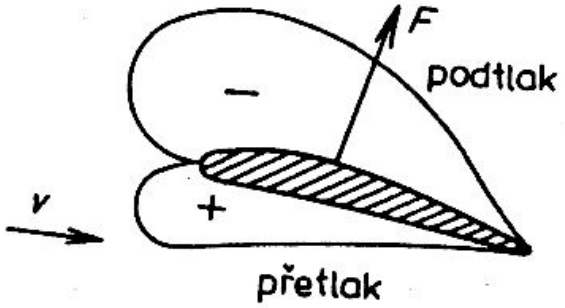
$\eta_i = 0{,}63$



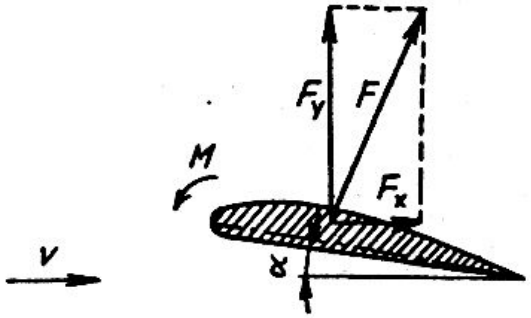
Rotating wing







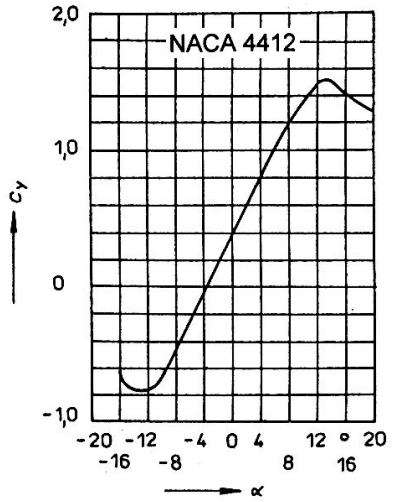
Aerodynamical forces

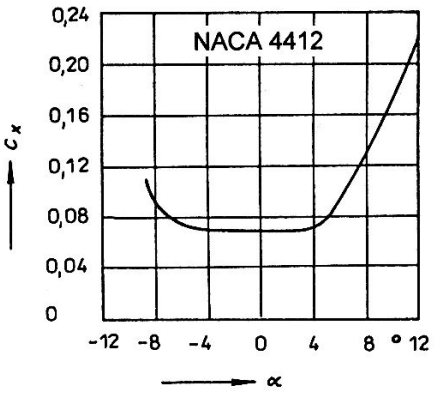


$$F_y = \frac{1}{2}\rho c_y A v^2 \qquad F_x = \frac{1}{2}\rho c_x A v^2$$

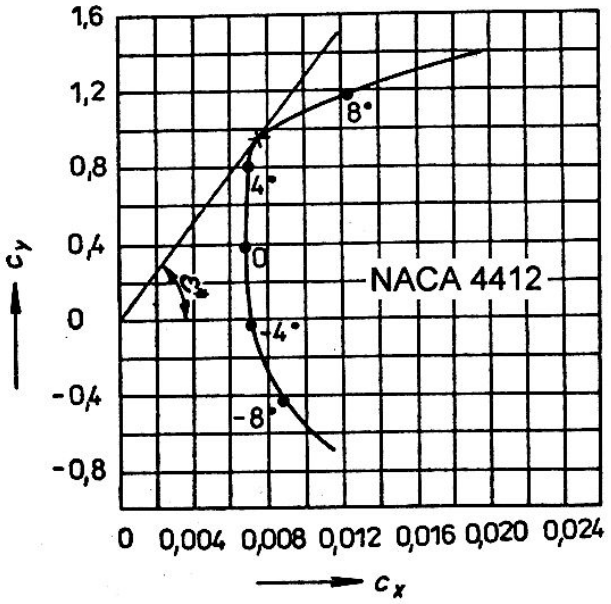
$$F = \sqrt{F_x^2 + F_y^2}$$

$$M = \frac{1}{2}\rho c_M A b v^2$$





Optimal values - profile



NACA 4412 $c_y = 0{,}95$

$c_x = 0{,}0073$

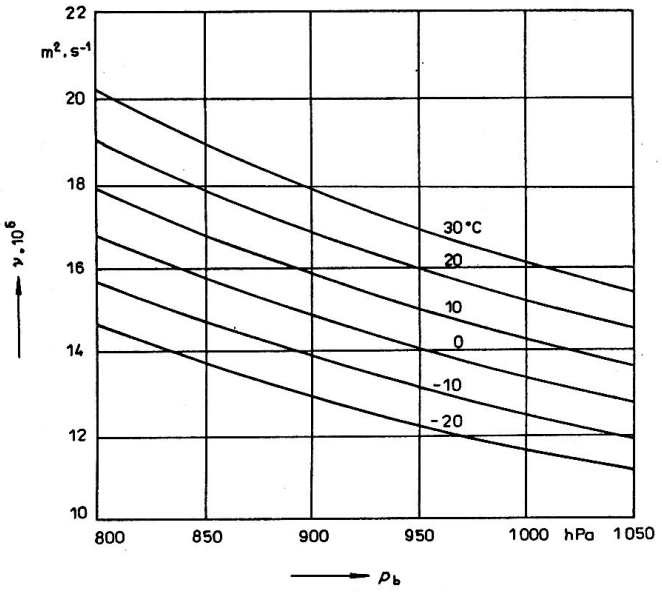
$c_y/c_x = 130$

Aerodynamical similarity

$$Re = \frac{vl}{\nu}$$

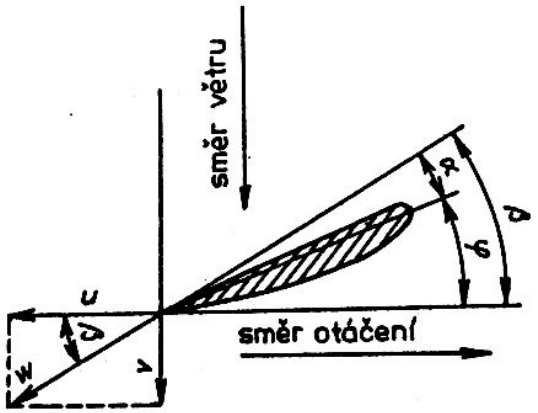
$$\nu = \frac{\mu}{\rho}$$

$$\mu = 1,503.10^{6}.\frac{T^{1,5}}{T+123,6}$$



$$\nu = 15.10^{-6}\,m^2.s^{-1}$$

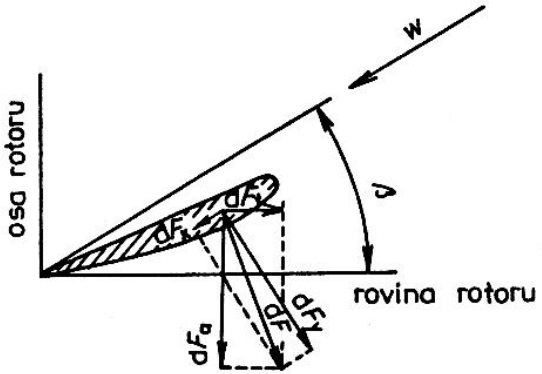
Blade element



$$u = \frac{\pi n}{30} r$$

$$w = \sqrt{v^2 + u^2}$$

$$\operatorname{tg}\beta = \frac{v}{u}$$



$$dF = \sqrt{dF_x^2 + dF_y^2} = \sqrt{dF_a^2 + dF_t^2}$$

$$\mathrm{d}M = \mathrm{d}F_t r$$

$$u = v\,\operatorname{ctg}\beta$$

$$w^2 = v^2(1 + \operatorname{cotg}^2\beta)$$

$$\operatorname{cotg}\beta = \frac{u}{v} = \lambda \qquad \text{pro } r = R$$

Forces of propeller

- axial force

$$dF_a = \frac{\rho}{2} v^2 dA(1 + \mathrm{cotg}^2\beta)(c_y \cos\beta + c_x \sin\beta)$$

- tangential force

$$dF_t = \frac{\rho}{2} v^2 dA(1 + \mathrm{cotg}^2\beta)(c_y \sin\beta + c_x \cos\beta)$$

$$dM = \frac{\rho}{2} v^2 r dA(1 + \mathrm{cotg}^2\beta)(c_y \sin\beta + c_x \cos\beta)$$

$$dP = dM\omega = \frac{\rho}{2} v^3 dA \,\mathrm{cotg}\,\beta(1 + \mathrm{cotg}^2\beta)(c_y \sin\beta - c_x \cos\beta)$$

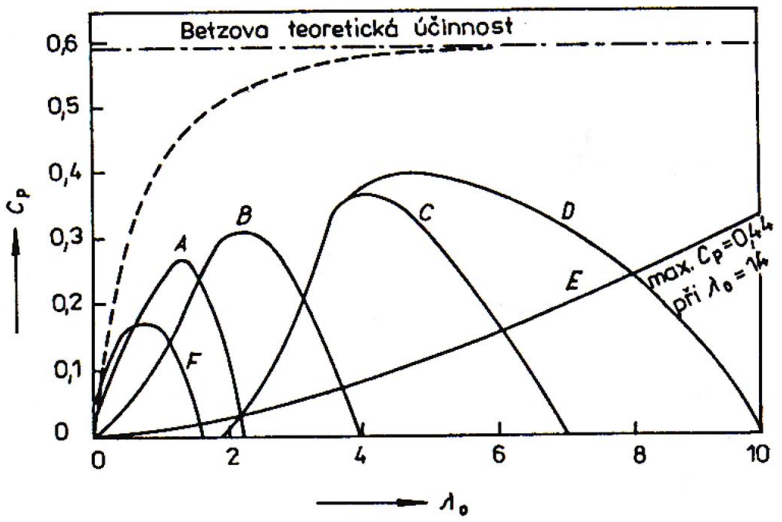
Recalculations and similarity

$$C_{F_a} = \frac{2F_a}{\rho A v^2} \qquad A = \pi R^2$$

$$C_M = \frac{2M}{\rho A v^2 R} \qquad A = \pi R^2$$

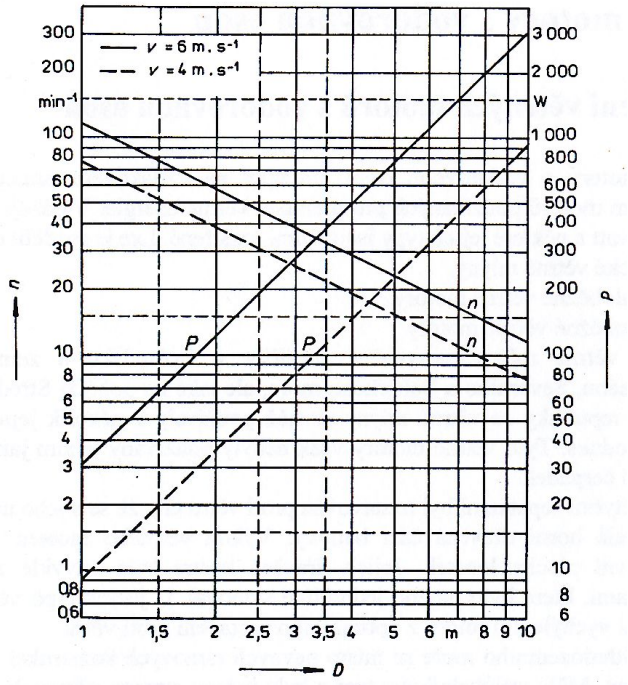
$$C_P = \frac{2P}{\rho A v^3} \qquad A = \pi R^2$$

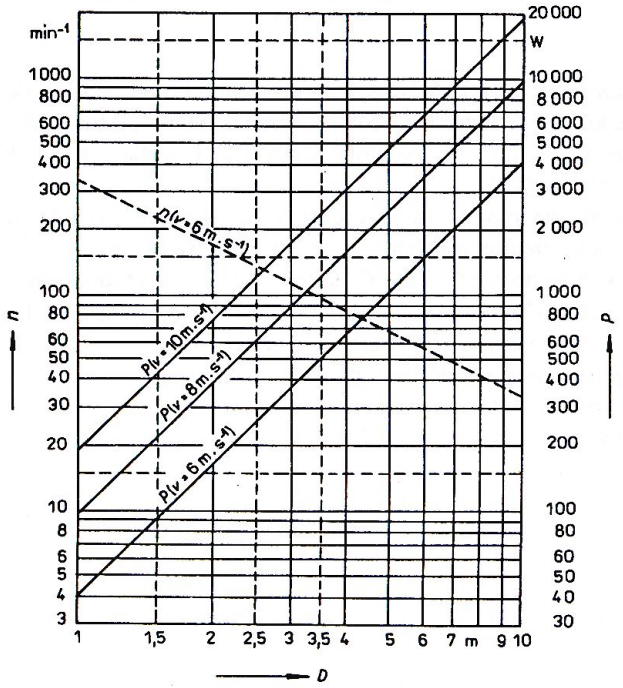
$$\lambda_0 = \frac{u_R}{v} = \frac{2\pi R n}{60 v}$$

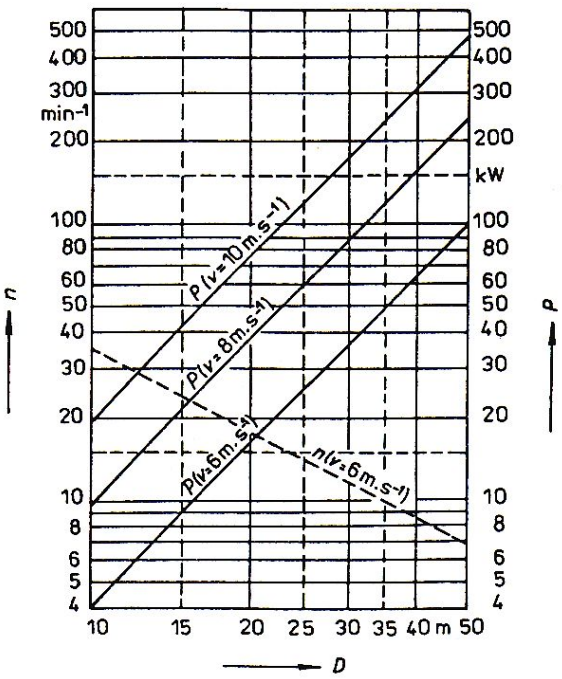


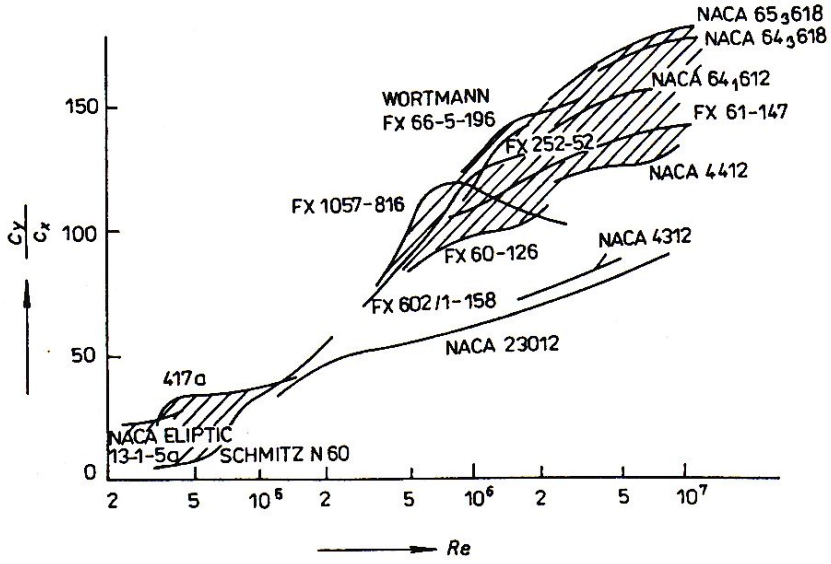
A - pomaloběžný mnoholopatkový rotor, B - čtyřlopatkový tradiční holandský větrný mlýn, C - rotor Darrieus se svislou osou, D - větrný motor s vodorovnou osou s dvoulistou vrtulí, E - větrný motor Hütter 100 kW s rychloběžnou dvoulistou vrtulí, F - rotor Savonius; ---- vypočtený průběh C_P pro nekonečný počet lopatek a nulový profilový odpor; -·-·- maximální teoretická účinnost Betzova

Profile features









Blade calculations

$$v = \frac{2}{3}v_1$$

$$u_r = \lambda_0 v_1 \frac{r}{R}$$

$$dF_a = \rho dV(v_1 - v_2) \qquad dF_a = \frac{\rho}{2}v^2 zb dr(1 + \mathrm{cotg}^2\beta)c_y \cos\beta$$

$$dV = 2\pi r dr.v = 2\pi r dr\frac{v_1+v_2}{2}$$

$$\rho 2\pi r dr(v_1 - v_2)\frac{v_1+v_2}{2} = \frac{\rho}{2}\left(\frac{v_1+v_2}{2}\right)^2 zb dr(1 + \mathrm{cotg}^2\beta)c_y \cos\beta$$

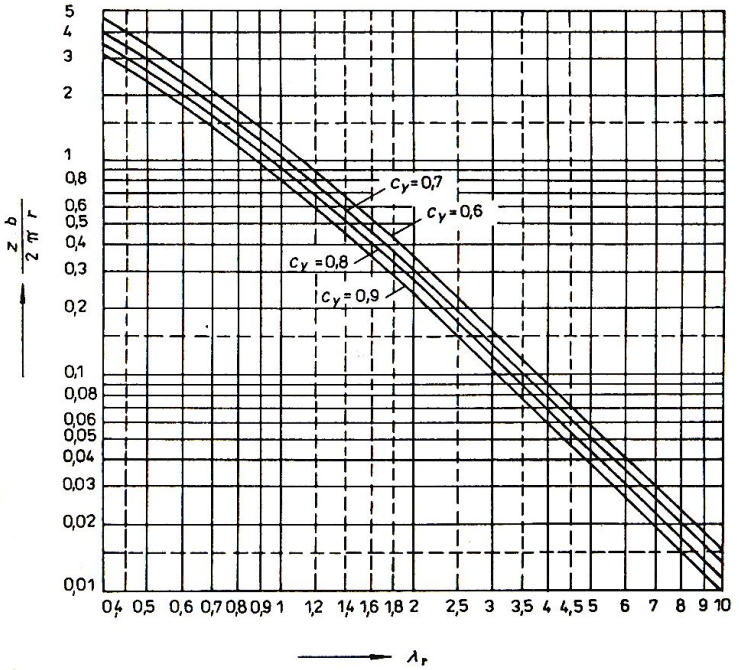
$$\frac{zb}{2\pi r} = \frac{2}{c_y\left(1+\mathrm{ctg}^2\beta\right)\cos\beta}$$

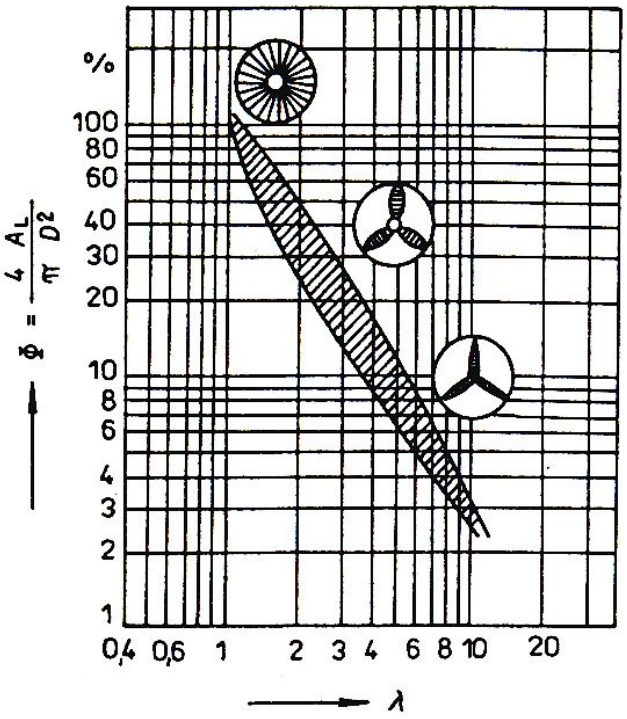
$$\lambda_r = \frac{u_r}{v_1} = \frac{r\omega}{v_1} = \frac{r}{R}\lambda_0$$

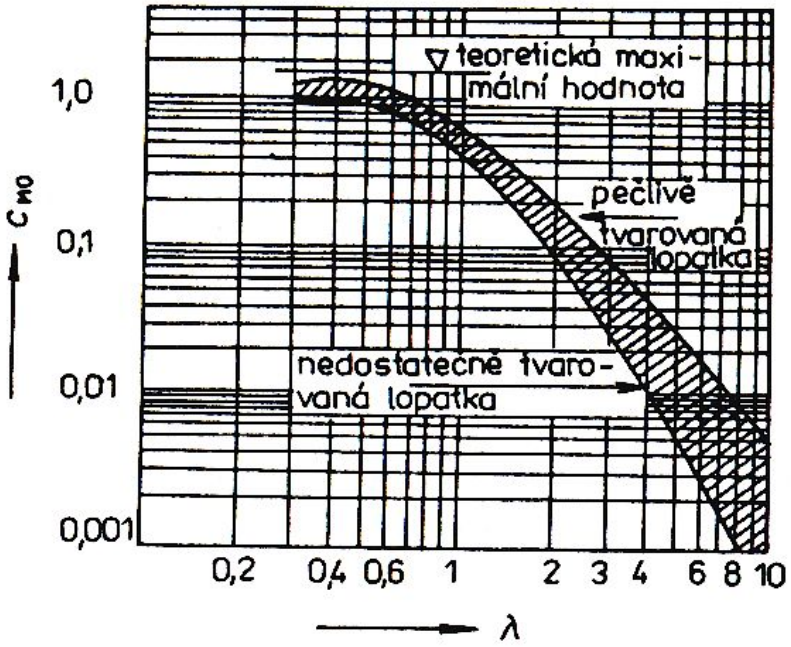
$$\mathrm{cotg}\,\beta = \frac{3}{2}\lambda$$

$$\cos\beta = \sqrt{\frac{9\lambda_r^2}{9\lambda_r^2+4}}$$

$$\frac{zb}{2\pi r} = \frac{8\sqrt{4+9\lambda_r^2}}{\left(12\lambda_r+27\lambda_r^3\right)c_y}$$



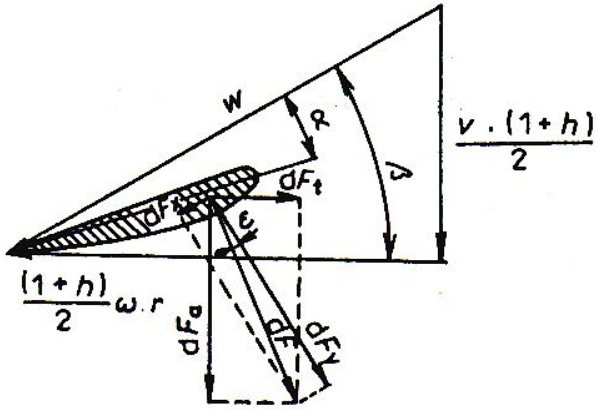




λ_0	1	2	3	4	5
z	8 až 24	6 až 12	3 až 6	2 až 4	2 až 3

$$\operatorname{tg}\varepsilon = \frac{\mathrm{d}F_x}{\mathrm{d}F_y} = \frac{c_x}{c_y}$$

$$\eta_a = \frac{\mathrm{d}P_l}{\mathrm{d}P_a} = \frac{\omega \mathrm{d}M_l}{v\mathrm{d}F_a} = \frac{u\mathrm{d}F_l}{v\mathrm{d}F_u}$$



$$dF_a = dF_y\cos\beta + dF_x\sin\beta = \tfrac{1}{2}\rho b w^2 dr(c_y\cos\beta + c_x\sin\beta)$$

$$dF_t = dF_y\sin\beta + dF_x\cos\beta = \tfrac{1}{2}\rho b w^2 dr(c_y\sin\beta + c_x\cos\beta)$$

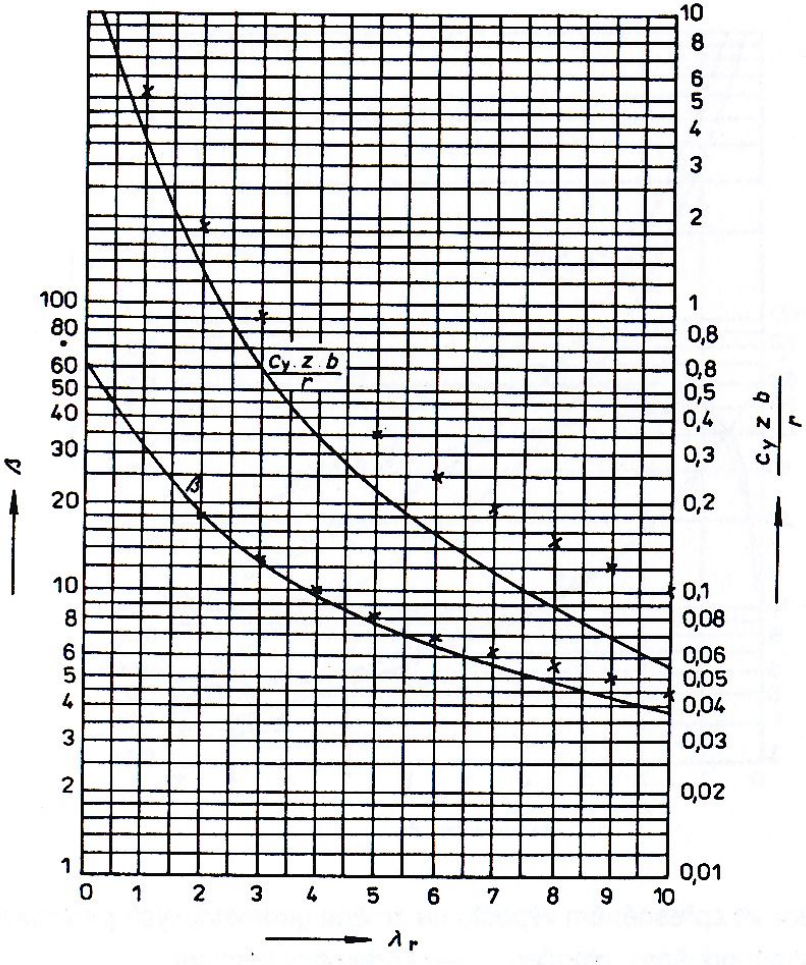
$$\mathrm{tg}\varepsilon = c_x/c_y$$

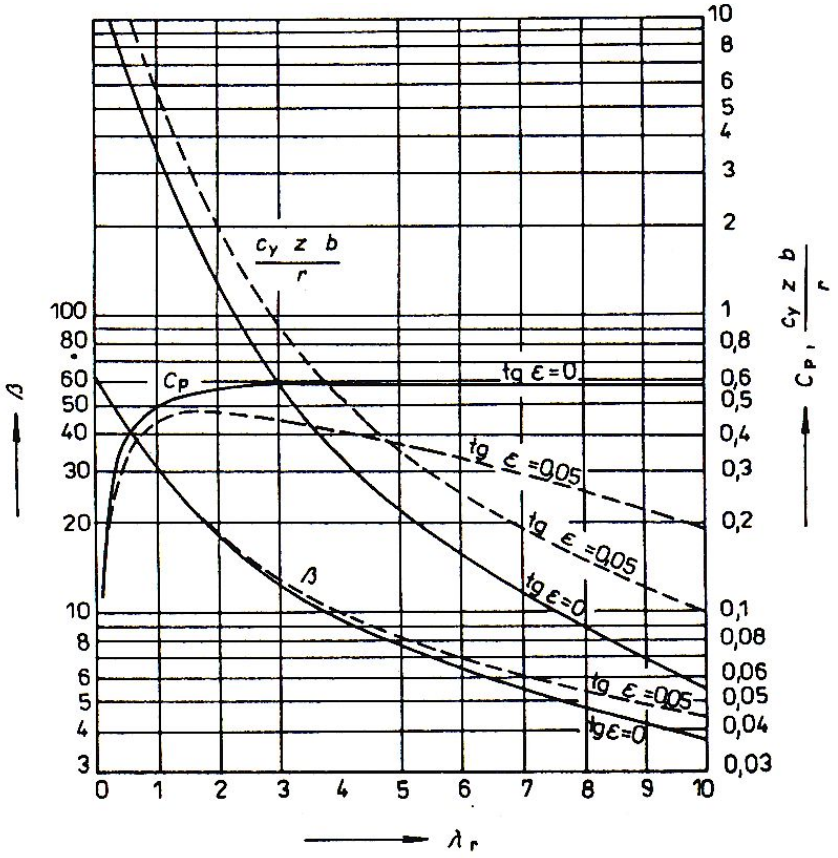
$$dF_a = \tfrac{1}{2}\rho b w^2 c_y \frac{\cos(\beta-\varepsilon)}{\cos\varepsilon} dr$$

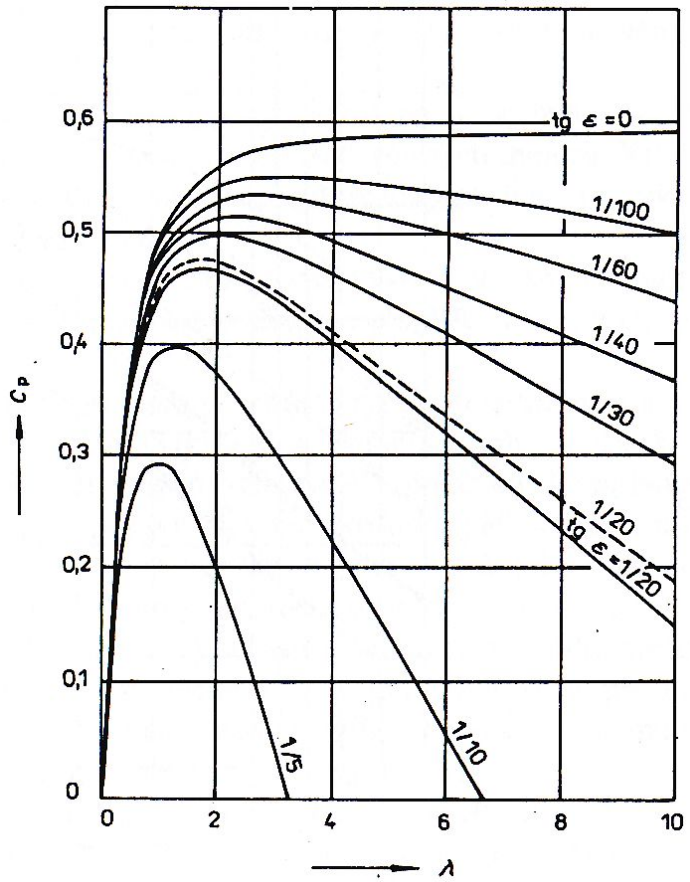
$$dF_t = \tfrac{1}{2}\rho b w^2 c_y \frac{\sin(\beta-\varepsilon)}{\cos\varepsilon} dr$$

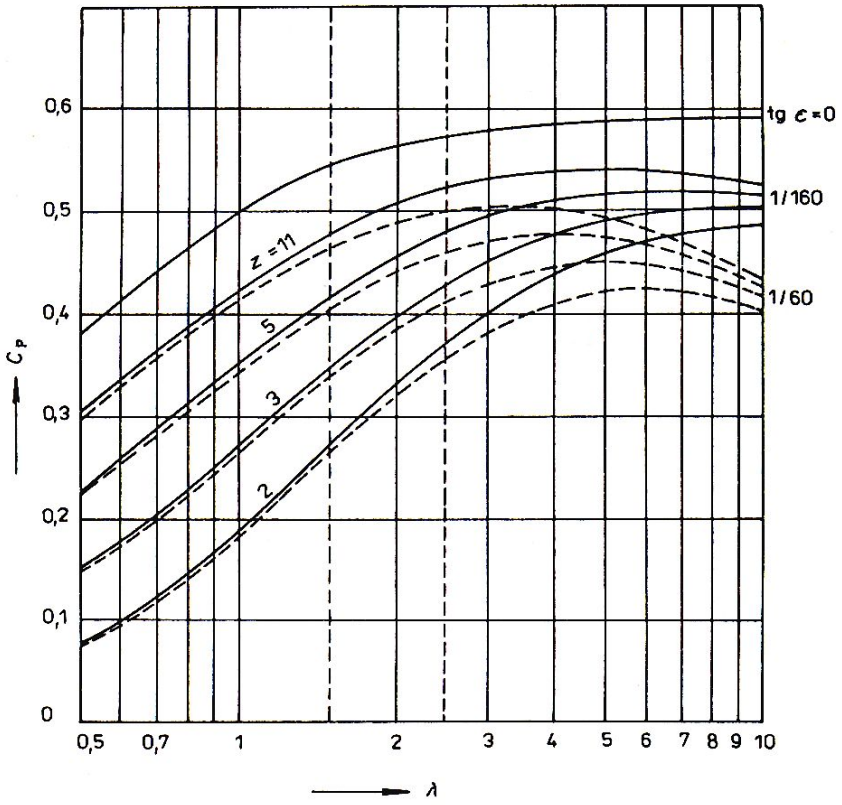
$$dF = z dF_a = \tfrac{1}{2}\rho z b w^2 c_y \frac{\cos(\beta-\varepsilon)}{\cos\varepsilon} dr$$

$$dM = r z dF_t = \tfrac{1}{2}\rho z b r w^2 c_y \frac{\sin(\beta-\varepsilon)}{\cos\varepsilon} dr$$


β
$\frac{c_y\ z\ b}{r}$
λ_r

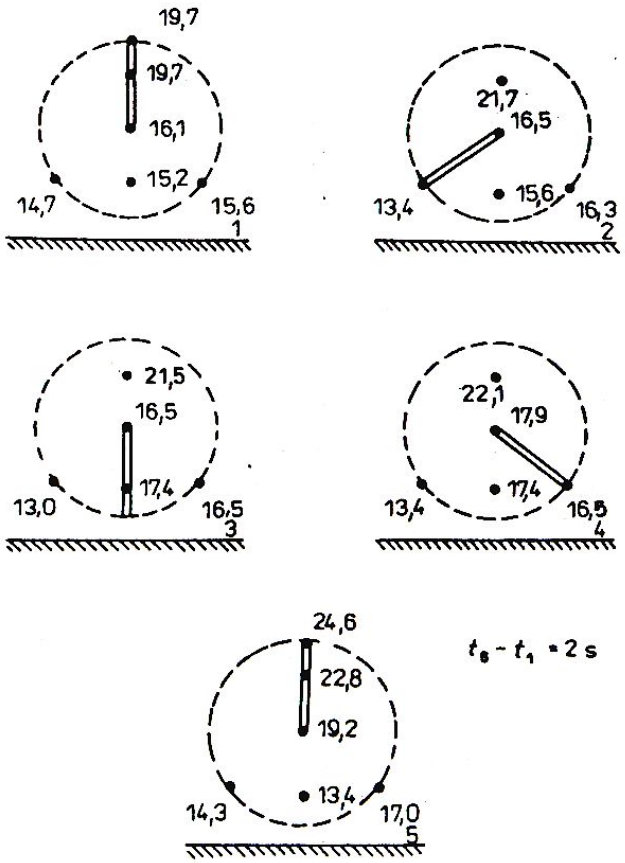

β
$\frac{c_y\ z\ b}{r}$
c_p
tg ε=0
tg ε=0,05
tg ε=0,05
tg ε=0
tg ε=0,05
tgε=0
λ_r


0,6
0,5
0,4
0,3
0,2
0,1
0
c_p
tg ε =0
1/100
1/60
1/40
1/30
1/20
tg ε =1/20
1/10
1/5
0
2
4
6
8
10
λ

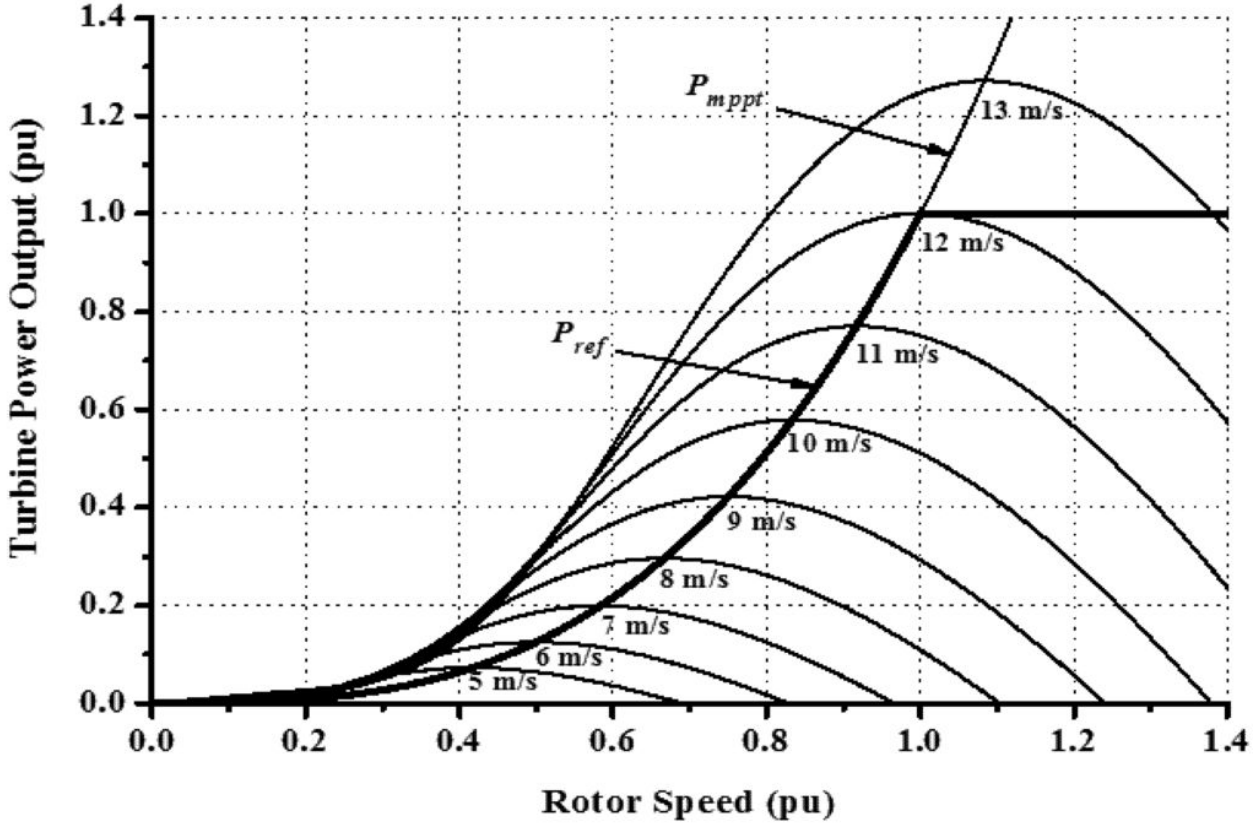

0,6
0,5
0,4
0,3
0,2
0,1
0
c_p
tg ε =0
1/160
1/60
z =11
5
3
2
0,5
0,7
1
2
3
4
5
6
7
8
9
10
λ

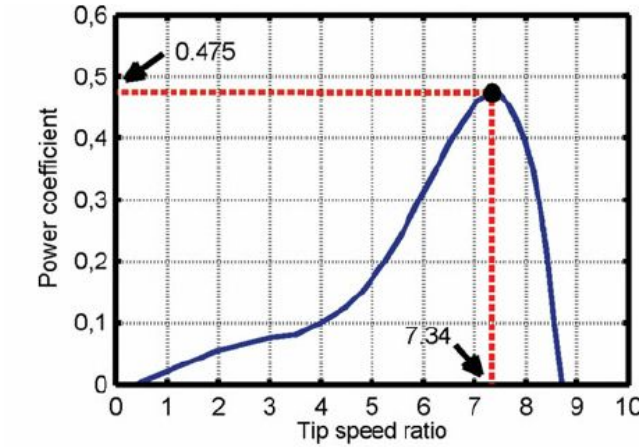

HALTE SANTÉ
CAPUCINS



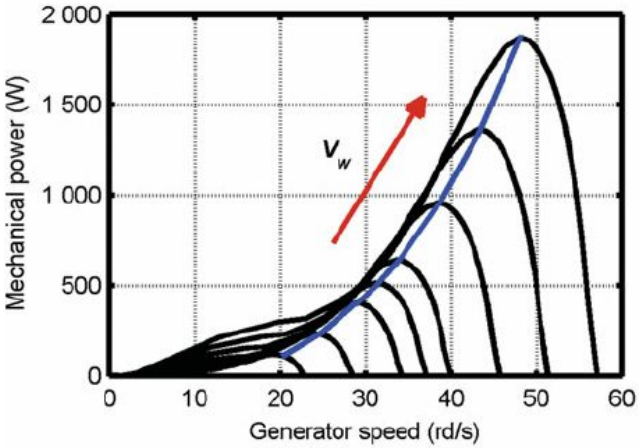

19,7
19,7
16,1
15,2
14,7
15,6
1
21,7
16,5
13,4
15,6
16,3
2
21,5
16,5
17,4
13,0
16,5
3
22,1
17,9
17,4
13,4
16,5
4
24,6
22,8
19,2
13,4
14,3
17,0
5
$t_5 - t_1 = 2$ s

Power characteristics

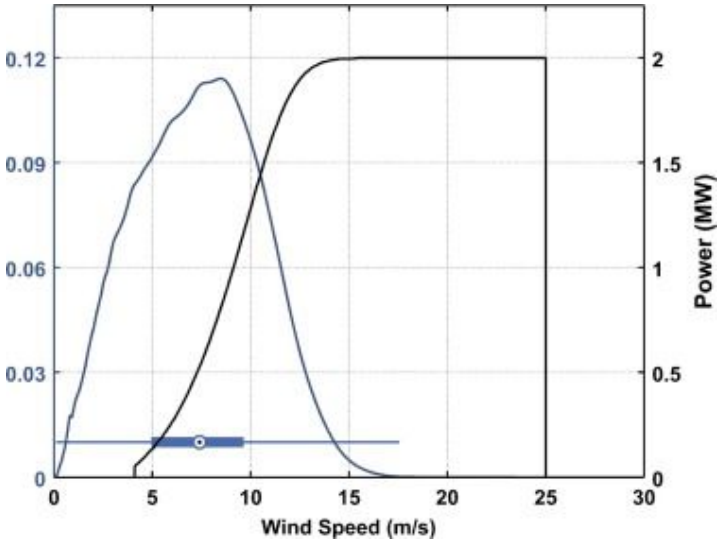


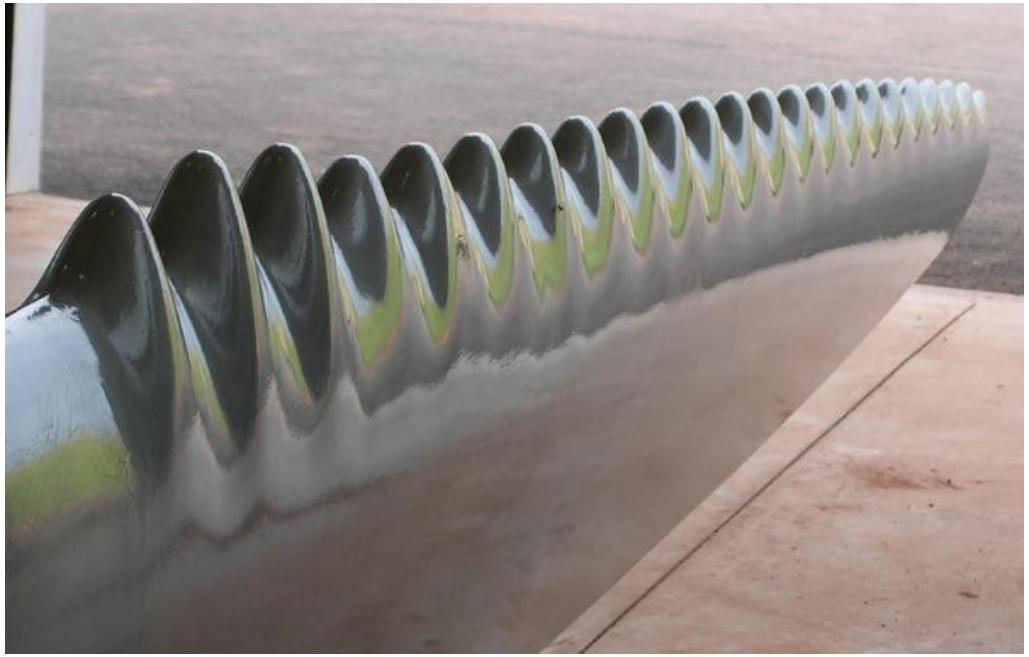

0,6
0,5
0,4
0,3
0,2
0,1
0
0.475
7.34
Power coefficient
0 1 2 3 4 5 6 7 8 9 10
Tip speed ratio

(a)

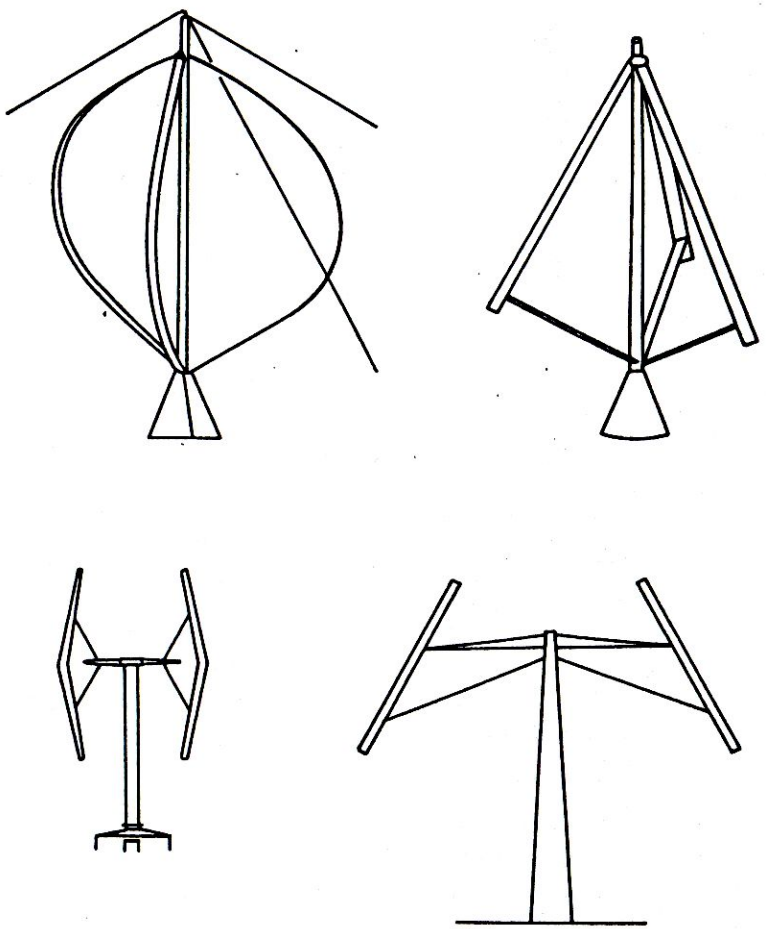

2 000
1 500
1 000
500
0
v_w
Mechanical power (W)
0 10 20 30 40 50 60
Generator speed (rd/s)

(b)


0.12
0.09
0.06
0.03
0
2
1.5
1
0.5
0
Power (MW)
0 5 10 15 20 25 30
Wind Speed (m/s)



Rotor Darrieus





EOLE VAWT

Cap Chat, QC
coast of St. Lawrence gulf

project 4,2 MW
Supposed production 15 GWh/rok
Axor Ltd.



finished:
1987 - 4,2 MW





EOLE 4,2 MW

vertical axis - type Darrieus
auxiliary start
height 110m
diameter 60m
basement 10m
rigging cables
DC generator
DC/AC inverter

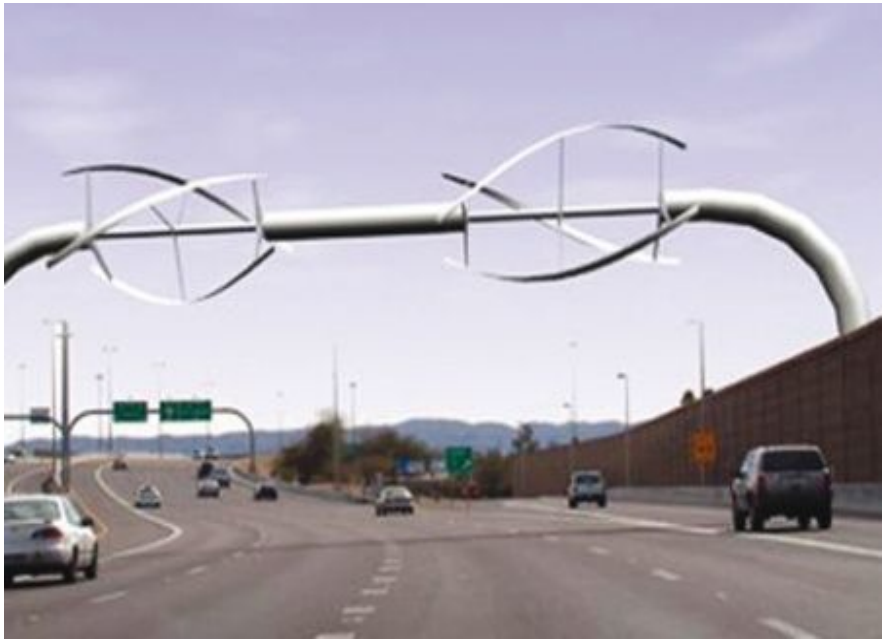
1. multi MW
1. without gearbox
1. variable speed
1. with invereter











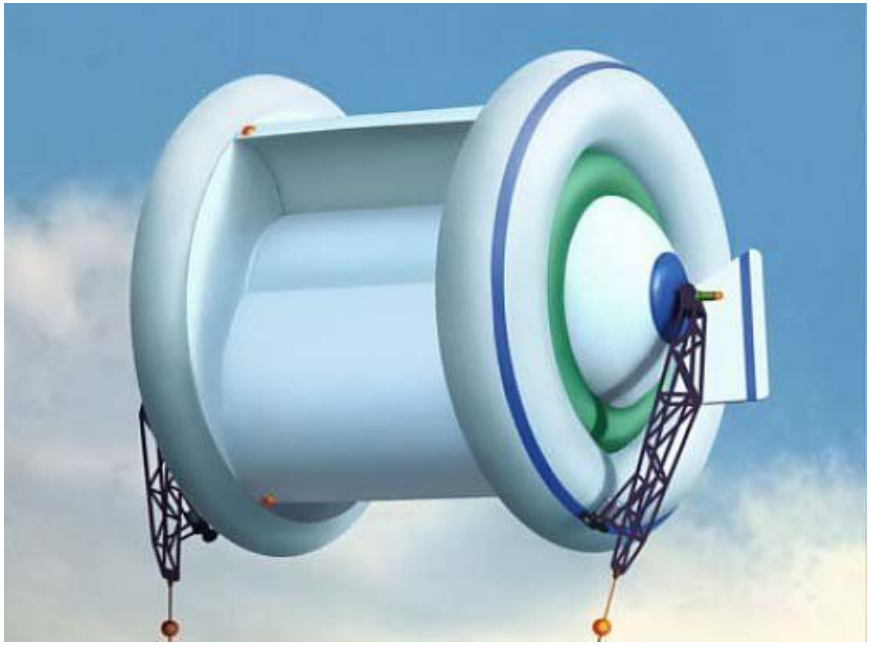






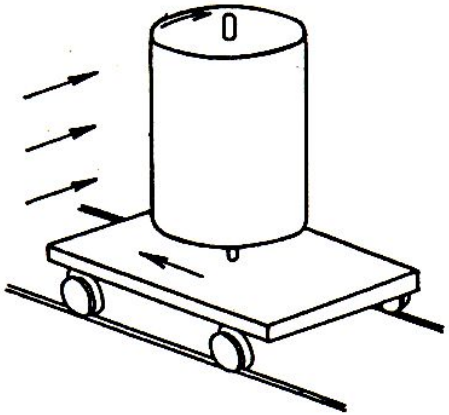




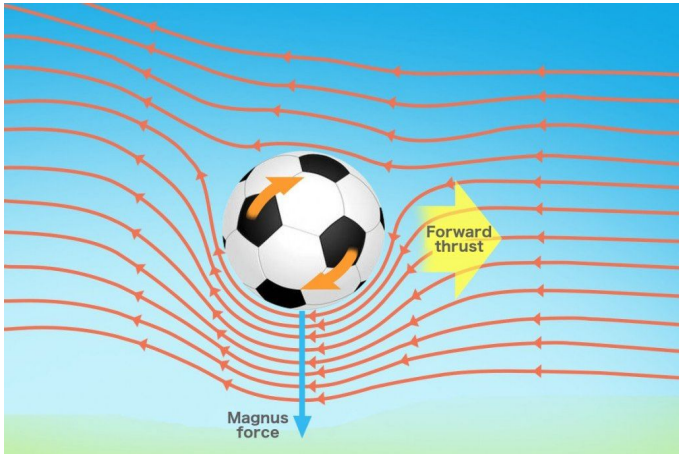


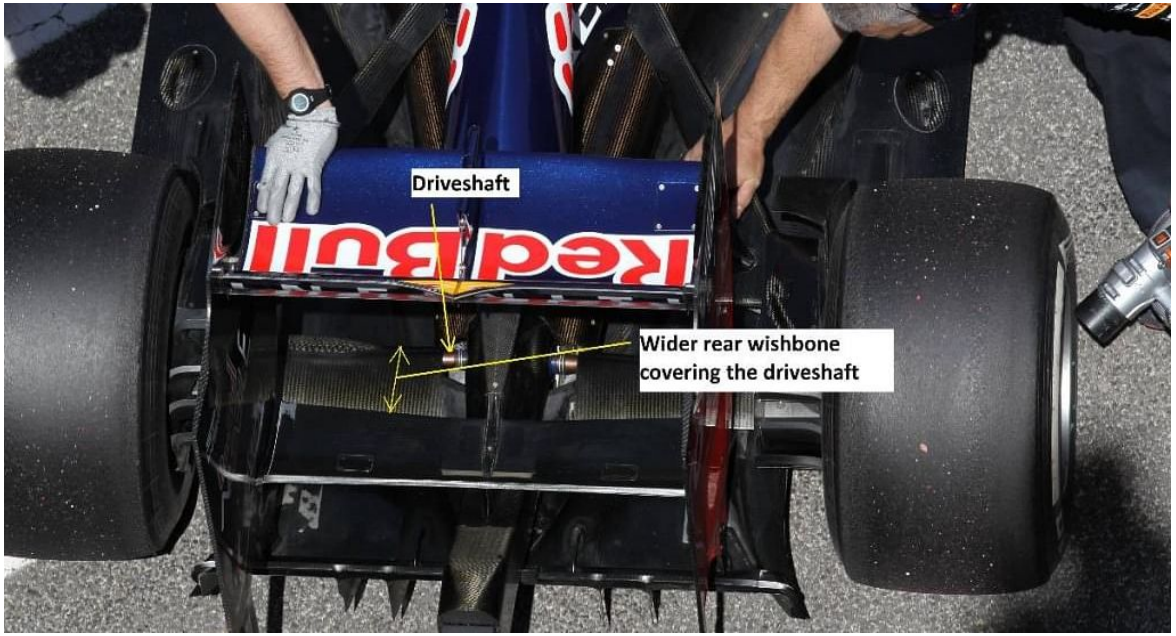


Magnus effect












ENERCON
ENERGY FOR THE WORLD
E-SHIP 1

Wind oscillator

