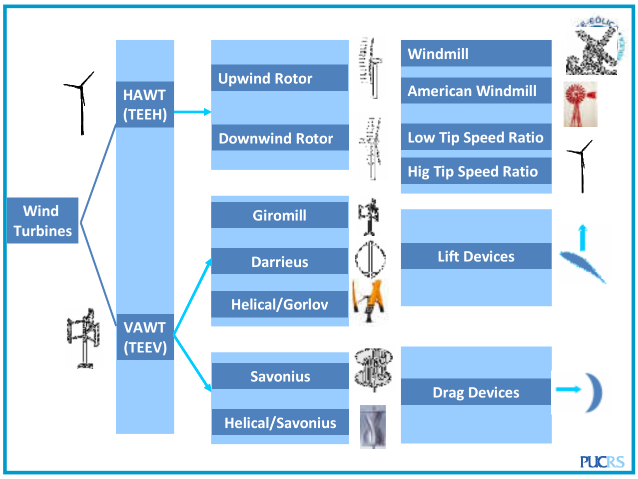
TURBINAS EÓLICAS DE EIXO VERTICAL


SMALL WIND TURBINES WORKSHOP
07 NOVEMBRO 2012
PUCRS | FACIN AUDITÓRIO 516
PORTO ALEGRE/RS | BRASIL

Prof. Jorge A. Villar Alé

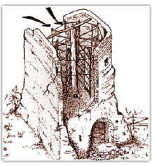
CONCEITOS BÁSICOS PRELIMINARES


Wind Turbines

HAWT (TEEH)
- Upwind Rotor
- Downwind Rotor
- Windmill
- American Windmill
- Low Tip Speed Ratio
- Hig Tip Speed Ratio

VAWT (TEEV)
- Giromill
- Darrieus
- Helical/Gorlov
- Lift Devices
- Savonius
- Helical/Savonius
- Drag Devices

(1000 A.C. - 1300 D.C.)



(1300 - 1875 D.C.)

USA (XIX)

USA
Inicio XX (1920)

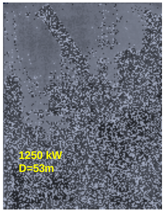
Estados Unidos
1888 - Charles Brush


Diâmetro:17m
Potencia: 12kW

Dinamarca
(1891) Poul la Cour.


D=23m
Pot=18 kW

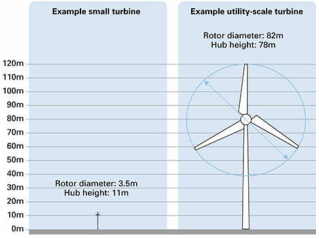
USA: (1941) Palmer Putman

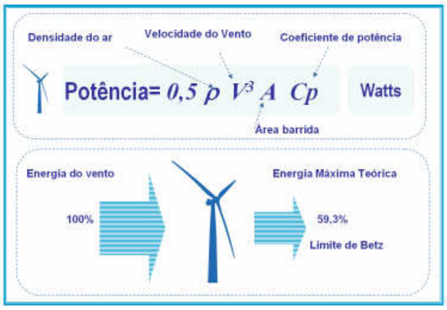

1250 kW
D=53m

Denominação	Tamanho
Micro-Turbinas	< 1,0 kW
Turbinas de pequeno porte	1 a 50 kW
Turbinas de médio porte	50 kW a 500 kW
Turbinas de grande porte	1MW a 4MW

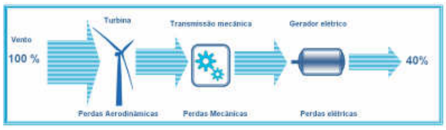
IEC-NORM 61400-2:2006
IEC < 200 m2 (Aprox. D=16m) < (50 a 60 kW)

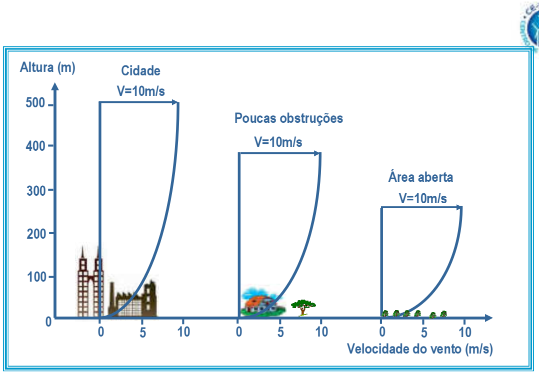
Aerogeradores	Potencia (kW)	Diâmetro (m)	Altura (m)
Micro-Turbinas	1	2,5	10
Pequeno	50	15	25
Médio	300	31	40
Grande	3000	100	100

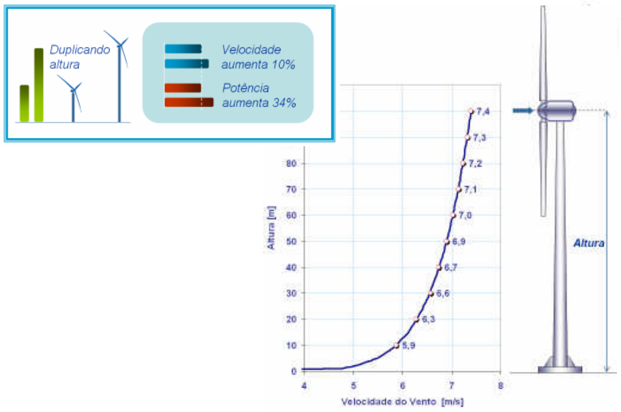




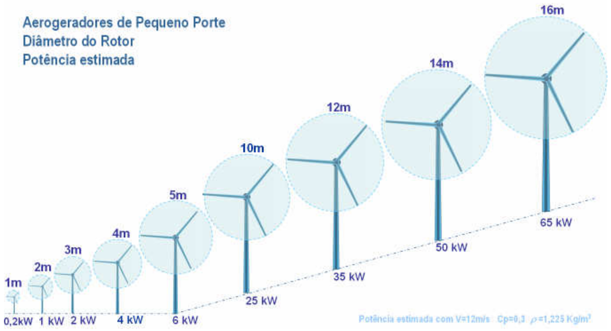
$$Potência = 0{,}5\ \rho\ V^3\ A\ C_p$$







Aerogeradores de Pequeno Porte
Diâmetro do Rotor
Potência estimada



Potência estimada com V=12m/s Cp=0,3 ρ=1,225 Kg/m³

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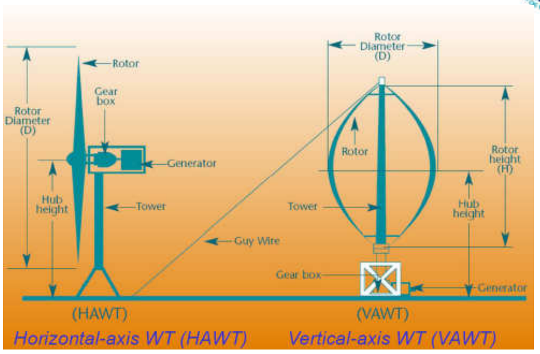
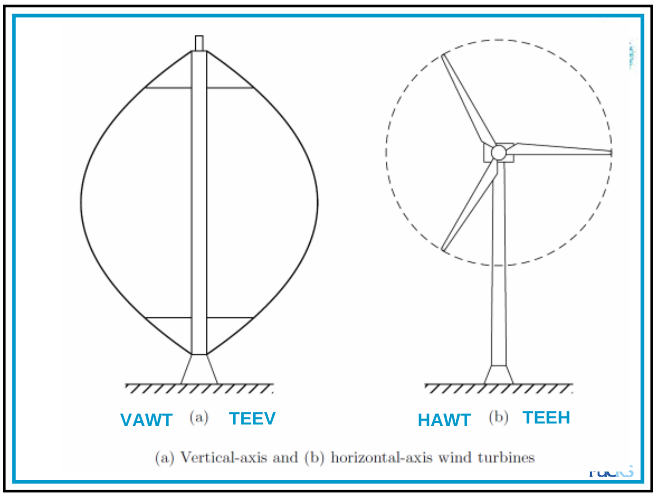
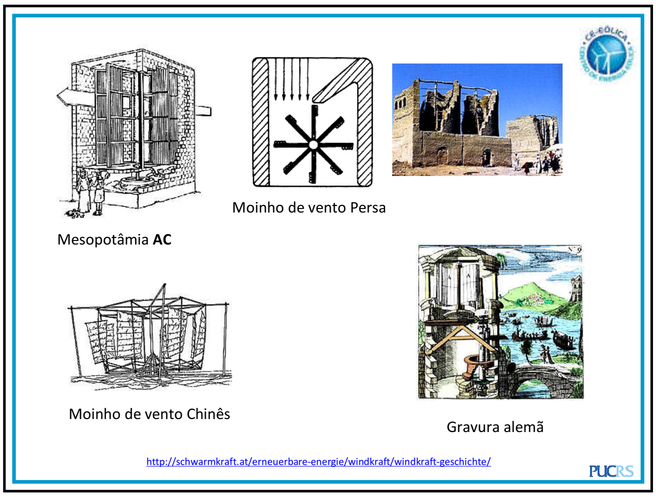




(a) Vertical-axis and (b) horizontal-axis wind turbines



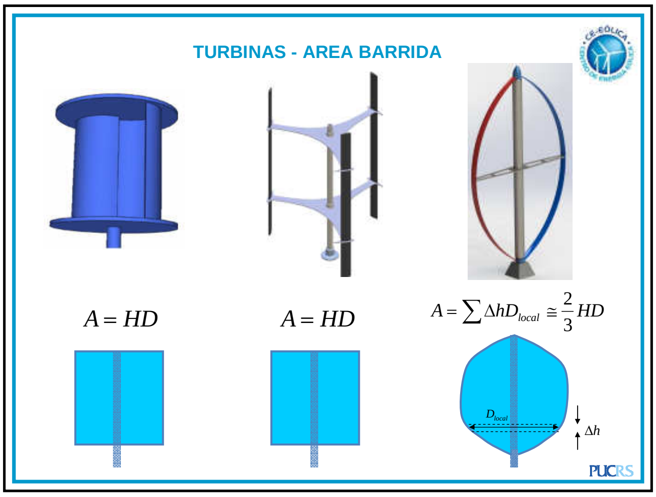
Mesopotâmia **AC**

Moinho de vento Persa

Moinho de vento Chinês

Gravura alemã

http://schwarmkraft.at/erneuerbare-energie/windkraft/windkraft-geschichte/

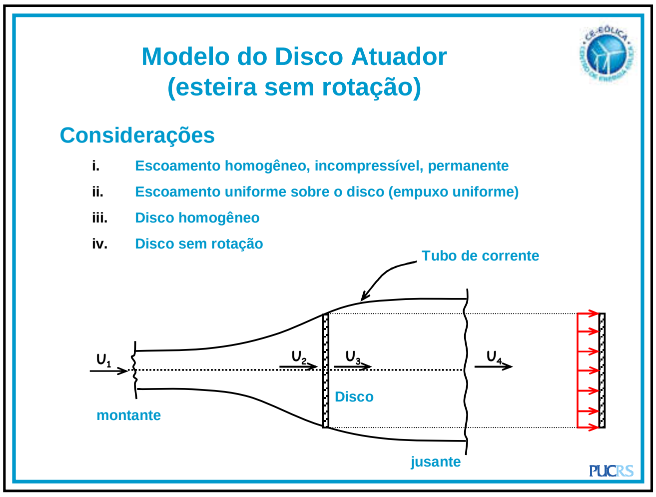


TURBINAS - AREA BARRIDA

$A = HD$

$A = HD$

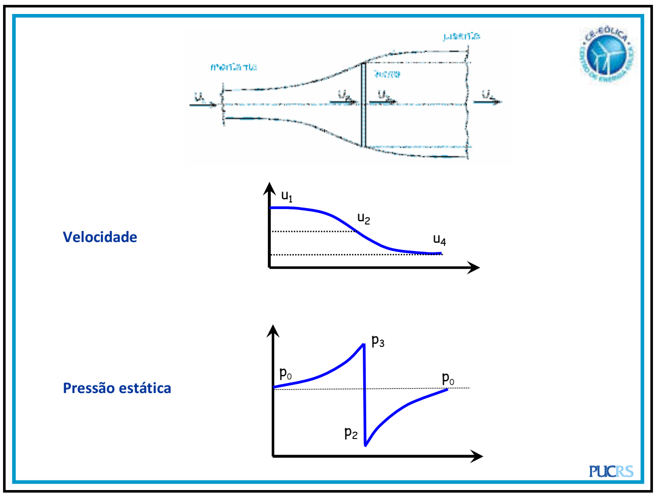
$A = \sum \Delta h D_{local} \cong \frac{2}{3} HD$



Modelo do Disco Atuador (esteira sem rotação)

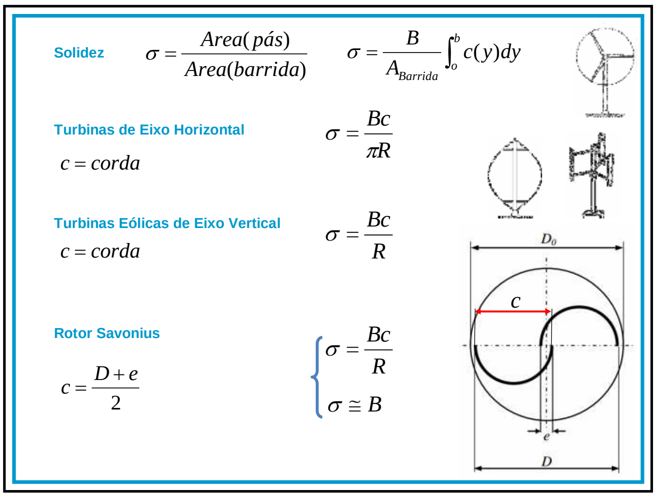
Considerações

- i. Escoamento homogêneo, incompressível, permanente
- ii. Escoamento uniforme sobre o disco (empuxo uniforme)
- iii. Disco homogêneo
- iv. Disco sem rotação



Velocidade

Pressão estática



Solidez $\sigma = \frac{Area(pás)}{Area(barrida)}$ $\sigma = \frac{B}{A_{Barrida}} \int_o^b c(y)dy$

Turbinas de Eixo Horizontal $\sigma = \frac{Bc}{\pi R}$

$c = corda$

Turbinas Eólicas de Eixo Vertical $\sigma = \frac{Bc}{R}$

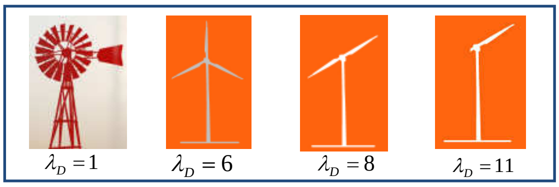
$c = corda$

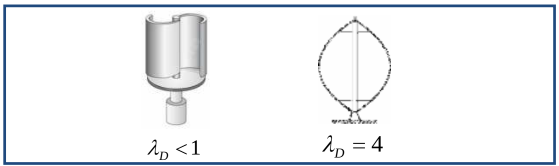
Rotor Savonius

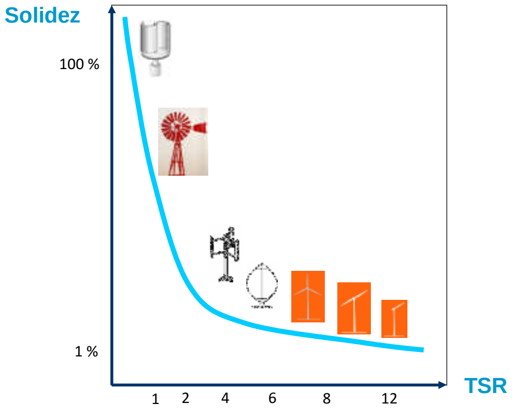
$c = \frac{D+e}{2}$

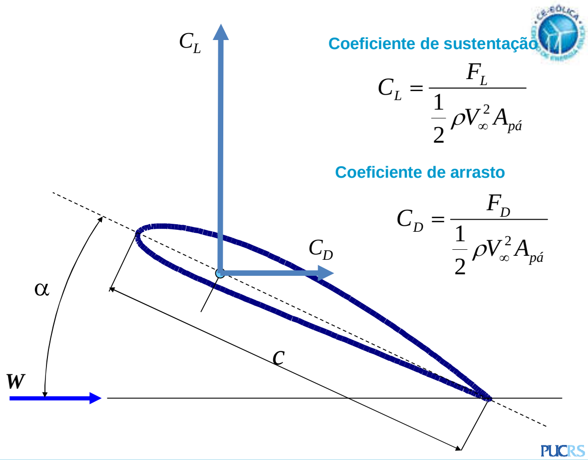
$$\begin{cases} \sigma = \frac{Bc}{R} \\ \sigma \cong B \end{cases}$$

Razão de velocidade de ponta –TSR $\lambda = \dfrac{\omega R}{V_\infty}$


$\lambda_D = 1$ $\lambda_D = 6$ $\lambda_D = 8$ $\lambda_D = 11$


$\lambda_D < 1$ $\lambda_D = 4$





Coeficiente de sustentação

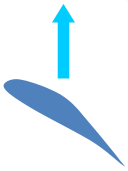
$$C_L = \frac{F_L}{\frac{1}{2}\rho V_\infty^2 A_{pá}}$$

Coeficiente de arrasto

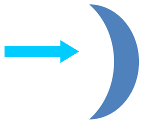
$$C_D = \frac{F_D}{\frac{1}{2}\rho V_\infty^2 A_{pá}}$$

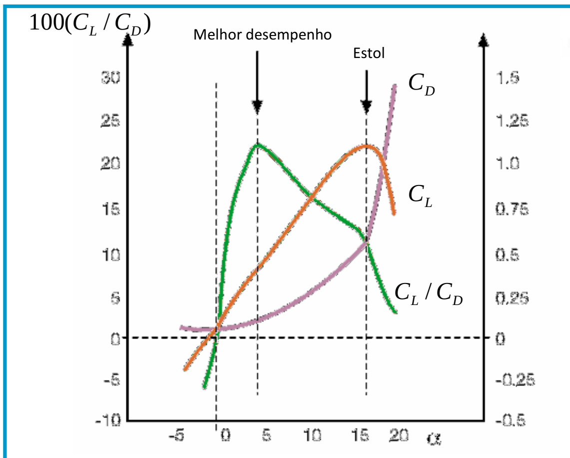
Coeficientes Aerodinâmicos

Sustentação $$C_L = \frac{F_L}{\frac{1}{2}\rho V_\infty^2 A_{pá}}$$

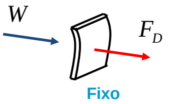


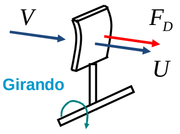
Arrasto $$C_D = \frac{F_D}{\frac{1}{2}\rho V_\infty^2 A_{pá}}$$





SISTEMAS QUE ATUAM POR ARRASTO





$$F_D = \frac{1}{2}\rho W^2 A C_D$$

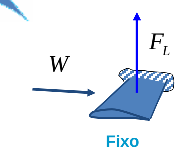
$$W = V - U$$

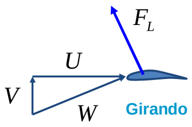
$$\lambda = \frac{U}{V}$$

$$W = V(1-\lambda)$$

$$\lambda < 1$$

SISTEMAS QUE ATUAM POR SUSTENTAÇÃO





$$W = \sqrt{V^2 + U^2}$$

$$F_L = \frac{1}{2}\rho W^2 A C_L$$

$$\lambda = \frac{U}{V}$$

$$W = V\sqrt{1+\lambda^2}$$

$$\lambda = 1 \ a \ 15$$

COEFICIENTES DE DESEMPENHO

Coeficiente de Potencia

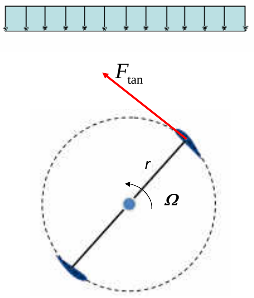
$$C_p = \frac{Potencia}{\frac{1}{2}\rho V_\infty^3 A}$$

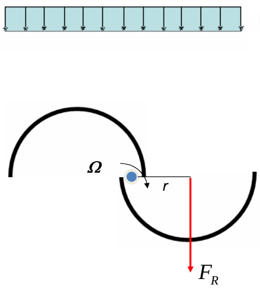
Coeficiente de Torque

$$C_Q = \frac{Torque}{\frac{1}{2}\rho V_\infty^2 A R}$$

Coeficiente de Empuxo

$$C_T = \frac{Empuxo}{\frac{1}{2}\rho V_\infty^2 A}$$





Força tangencial media

$$\overline{F}_{\tan} = \frac{1}{2\pi}\int_0^{2\pi} F_{\tan}\, d\theta$$

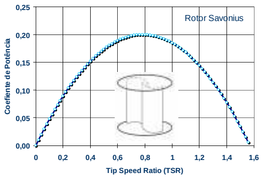
Torque

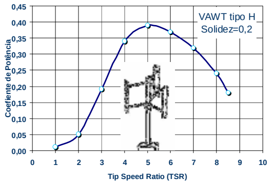
$$T = B\overline{F}_{\tan} r$$

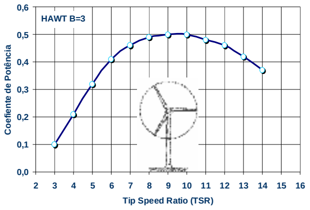
Potência

$$P = T\Omega$$

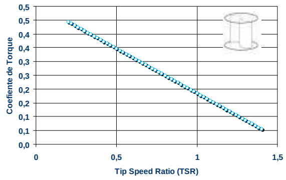
Coeficiente de Potência

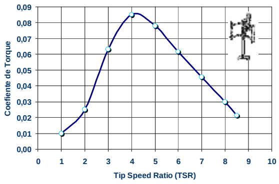


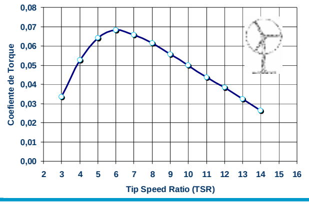




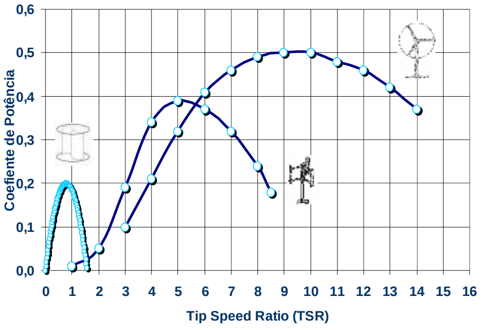
Coeficiente de Torque



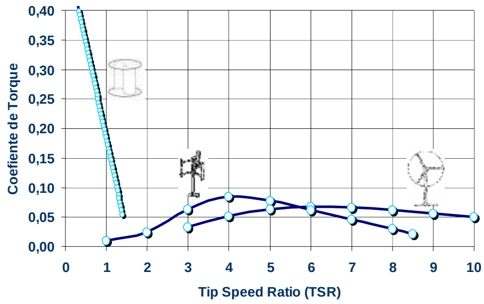


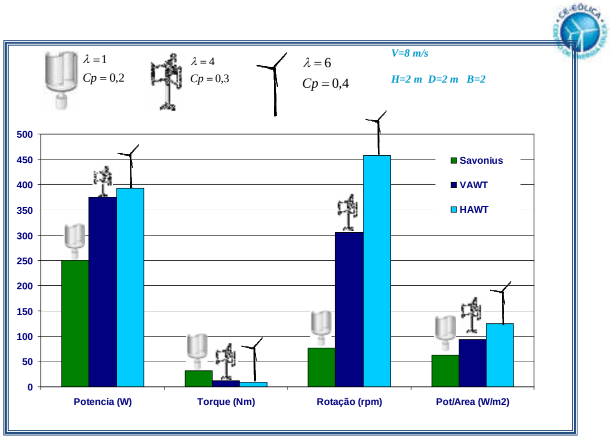


Coeficiente de Potência



Coeficiente de Torque





SAVONIUS

- Máquina que opera por arrasto
- Alto torque de partida
- Baixo TSR
- Baixo rendimento
- Acoplamento direto (sistemas bombeamento)

TIPO H ou DARRIEUS

- Máquina que opera por sustentação
- Baixo torque de partida
- Maior TSR
- Maior rendimento
- Acoplamento direto (gerador elétrico)

ROTOR SAVONIUS

Sigurd Savonius
(1884 - 1931)

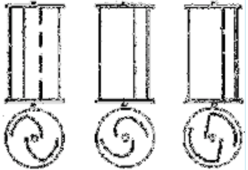
Patente
(1926)

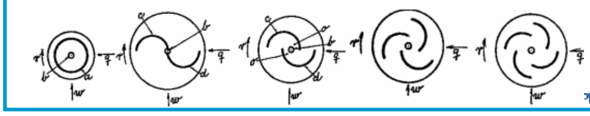
UNITED STATES PATENT OFFICE

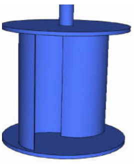
SIGURD J. SAVONIUS, OF HELSINGFORS, FINLAND

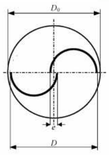
WIND ROTOR

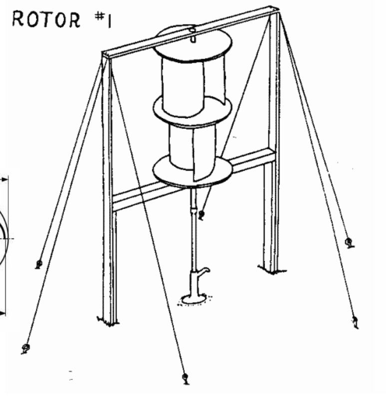
Application filed October 11, 1926, Serial No. [illegible] and in Great Britain December 16, [illegible]











SAVONIUS ROTOR PUMPING WATER

E&MP 100.002

Power from Wind

May 13, 1931

The new S-shaped rotor invented by S. J. Savonius of Helsingfors, Finland.

This is the most efficient means known of getting power from moving air and has been used as a ventilator.

A similar rotor can also be used as a tidal motor in which case it always turns in the same direction regardless of whether the tide is ebbing or flooding. Savonius rotor pumping water.

Original Caption by Science Service
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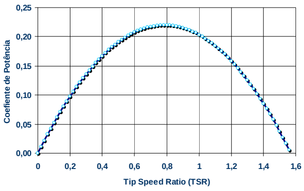
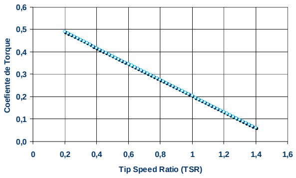
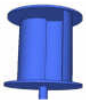
http://scienceservice.si.edu/pages/100002.htm



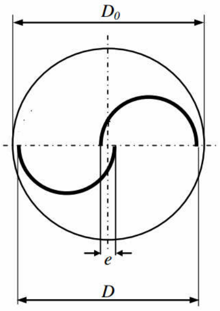


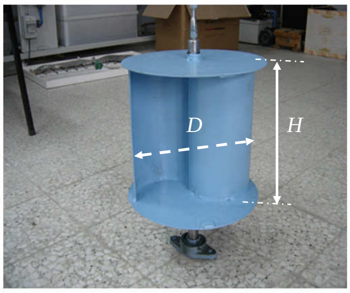
$$C_p = \frac{Potencia}{\frac{1}{2}\rho V_\infty^3 A}$$



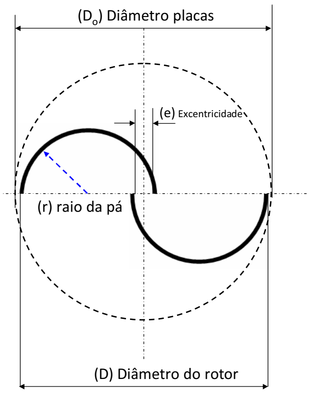
$$C_Q = \frac{Torque}{\frac{1}{2}\rho V_\infty^2 AR}$$

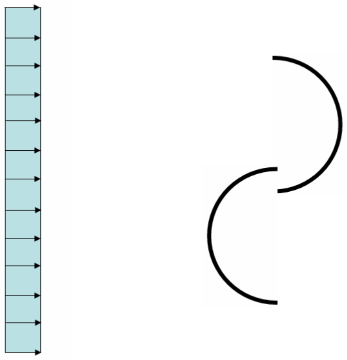
$$TSR = \frac{Velocidade - Tangencial}{Velocidade - do - Vento}$$

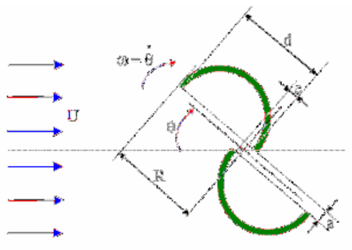




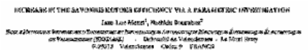
Razão de Excentricidade e / D **Razão de Aspecto** H / D

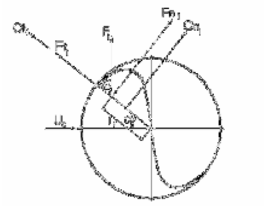


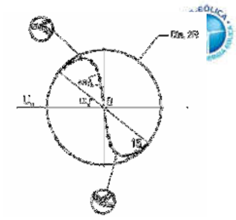




Numero Módulos	Numero de Pás (B)	Raio da placas Extremas	Altura Rotor (H)	Excentricidade Principal (e)	Excentricidade secundaria (a)
> 2, 3,4 ...	**> 2**	**1,1 R**	**4R**	**0,15d a 0,3d**	**0**







$$C_{ni} = \frac{F_{ni}}{\frac{1}{2}\rho U_0^2 R}, \quad C_{ti} = \frac{F_{ti}}{\frac{1}{2}\rho U_0^2 R}$$

The total drag coefficient and the torque coefficient for an **individual blade** at a particular rotor angle, α are evaluated by integrating the coefficients over the blade surfaces

$$F_{n_i} = \Delta P_i \Delta S_i \sin\phi_i, \qquad F_{t_i} = \Delta P_i \Delta S_i \cos\phi_i$$

$$T_i = F_{n_i} r_i \qquad C_{q_i} = \frac{T_i}{\frac{1}{2}\rho U_0^2 R \frac{R}{2}}$$

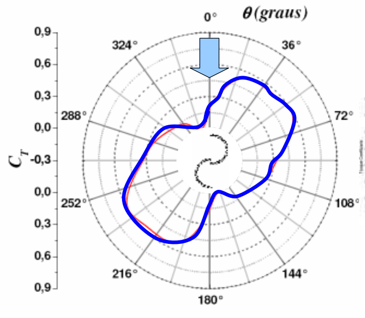
$$C_n(\alpha) = \sum_{i=1}^{8} C_{n_i}, \qquad C_t(\alpha) = \sum_{i=1}^{8} C_{t_i}, \qquad C_q(\alpha) = \sum_{i=1}^{8} C_{q_i}$$

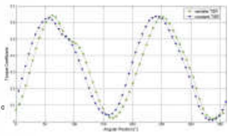
EXPERIMENTAL INVESTIGATION OF AERODYNAMIC CHARACTERISTICS OF TWO, THREE AND FOUR BLADED S-SHAPED STATIONARY SAVONIUS ROTORS.

Md. Quamrul Islam, Md. Nazim Hasan and Sumon Saha

Proceedings of the
International Conference on Mechanical Engineering 2005
(ICME2005) 28- 30 December 2005, Dhaka, Bangladesh

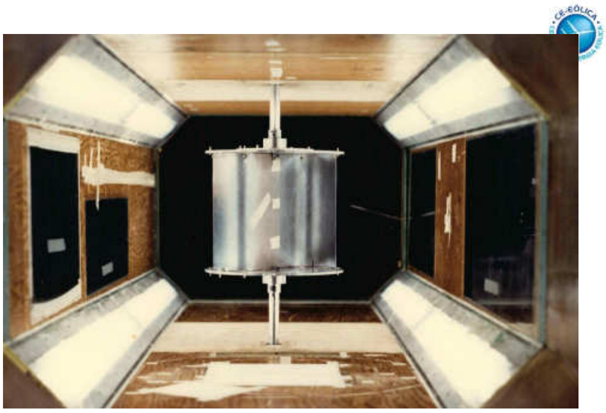
Coeficiente de Torque Estático

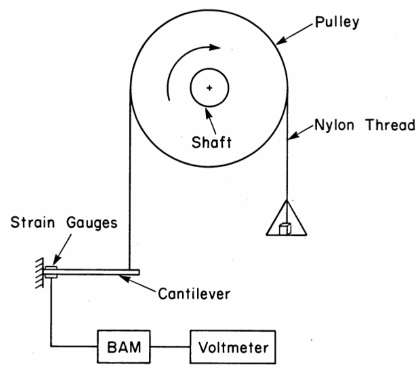




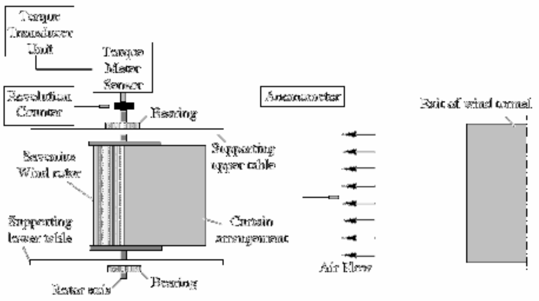
ROTOR SAVONIUS

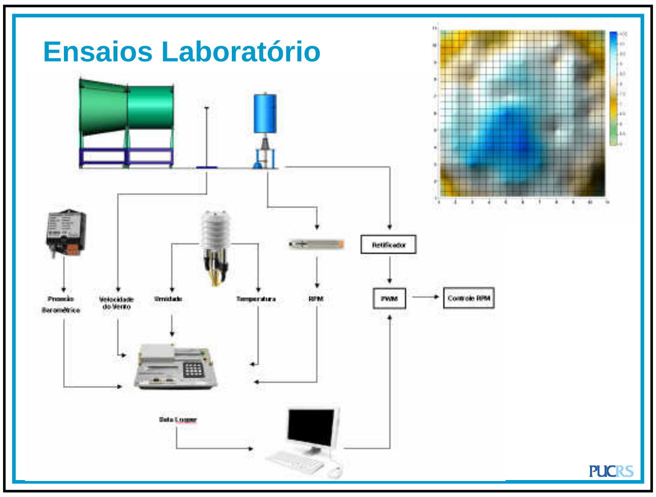
RESULTADOS EXPERIMENTAIS



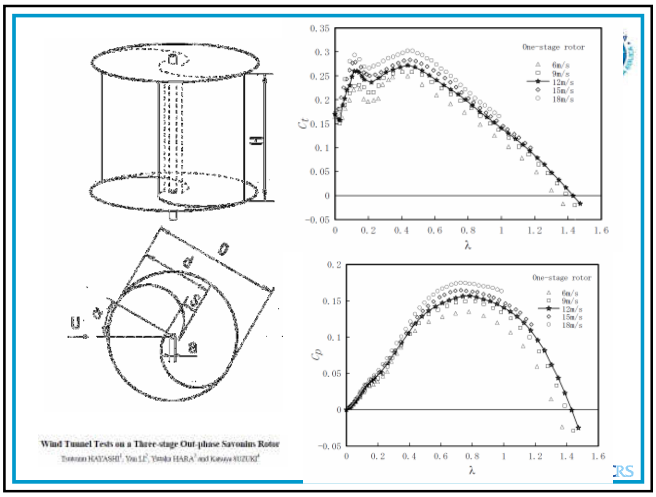


Prony brake arrangement for measurement of torque output.



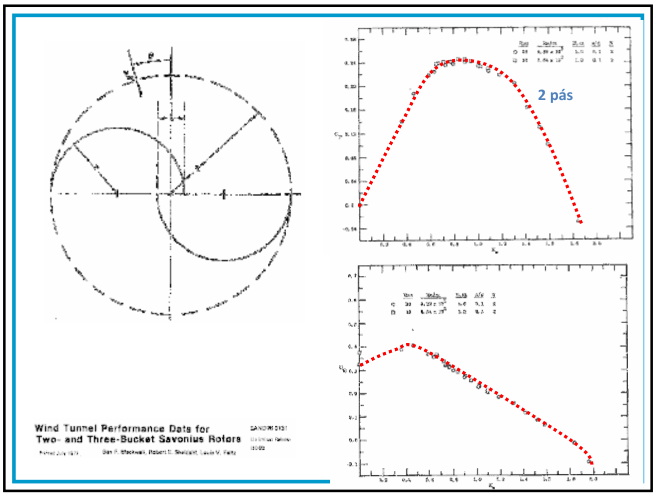


Ensaios Laboratório



Wind Tunnel Tests on a Three-stage Out-phase Savonius Rotor

Tsutomu HAYASHI[1], Yan LI[2], Yutaka HARA[3] and Katsuya SUZUKI[4]

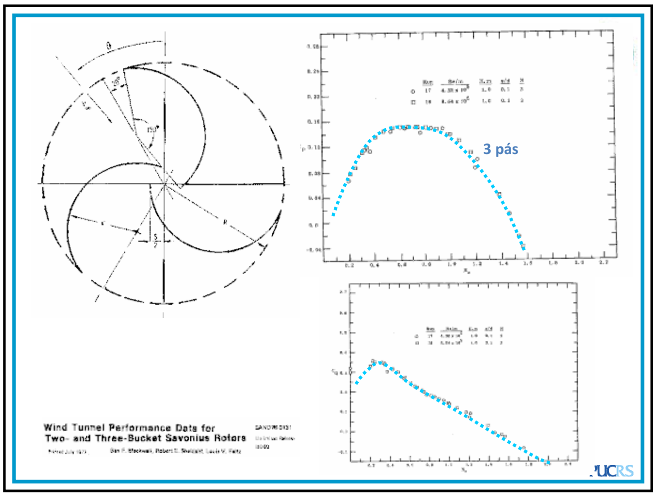


Wind Tunnel Performance Data for Two- and Three-Bucket Savonius Rotors

SAND76-0131 Unlimited Release UC-60

Printed July 1977

Ben F. Blackwell, Robert E. Sheldahl, Louis V. Feltz



Wind Tunnel Performance Data for Two- and Three-Bucket Savonius Rotors

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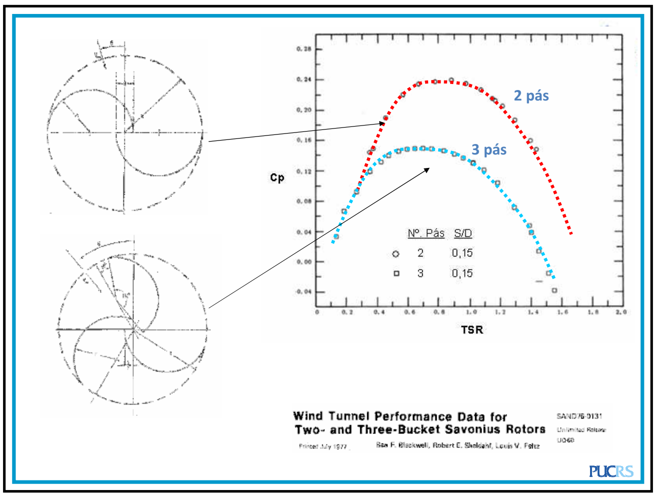

Wind Tunnel Performance Data for Two- and Three-Bucket Savonius Rotors

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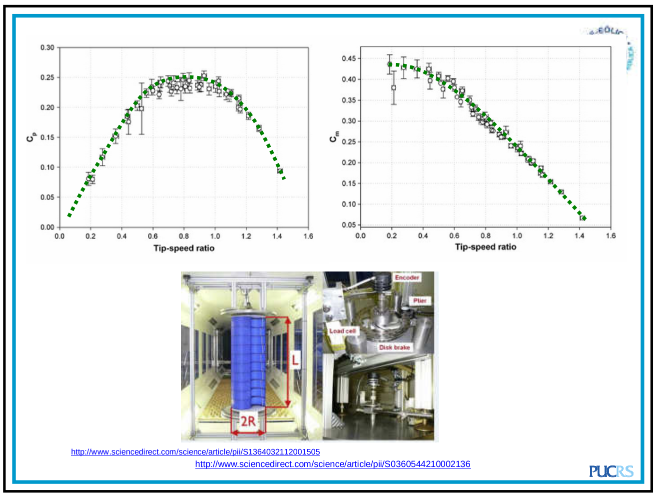

http://www.sciencedirect.com/science/article/pii/S1364032112001505

http://www.sciencedirect.com/science/article/pii/S0360544210002136

ROTOR SAVONIUS MODIFICADO

Experimental investigations on single stage modified Savonius rotor

M.A. Kamoji[a], S.B. Kedare[a], S.V. Prabhu[b,*]

[a] Energy Science and Engineering Department, Indian Institute of Technology, Bombay, Powai, Mumbai – 400076, India
[b] Department of Mechanical Engineering, Indian Institute of Technology, Bombay, Powai, Mumbai – 400 076, India

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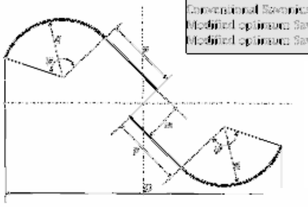
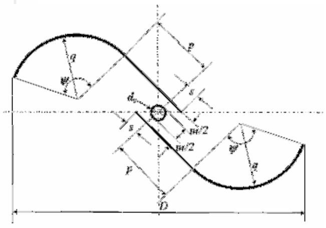
Rotor	Re = 100,000	
	$C_{p\max}$	TSR at $C_{p\max}$
Conventional Savonius	0.15	0.77
Modified optimum Savonius (with shaft)	0.12	0.58
Modified optimum Savonius (without shaft)	0.18	0.63



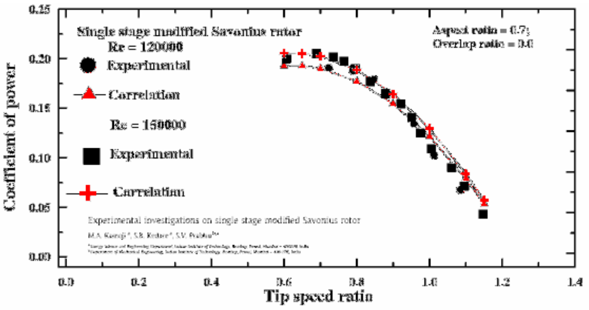
Experimental investigations on single stage modified Savonius rotor

M.A. Kamoji[a], S.B. Kedare[a], S.V. Prabhu[b,*]



$$\frac{C_Q}{\mathrm{Re}^{0,3}} = -0{,}0107\lambda + 0{,}0149$$

$77600 \geq Re \leq 155000$;
$TSR \geq 0.6$



Experimental investigations on single stage modified Savonius rotor

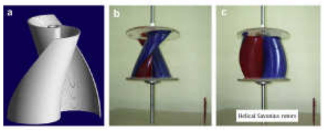
M.A. Kamoji[a], S.B. Kedare[a], S.V. Prabhu[b,*]

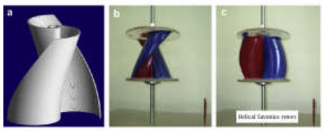
ROTOR SAVONIUS HELICOIDAL

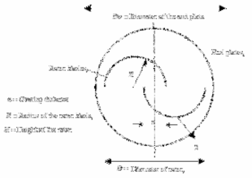
Renewable Energy 94 (2009) 521–529

Performance tests on helical Savonius rotors

M.A. Kamoji[a], S.B. Kedare[a], S.V. Prabhu[b,*]

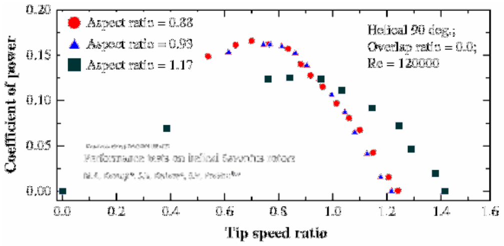






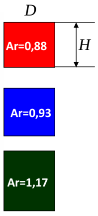
Aspect ratio (H/D)

Overlap ratio (a/D)



Performance tests on helical Savonius rotors

M.A. Kamoji[a], S.B. Kedare[a], S.V. Prabhu[b,*]



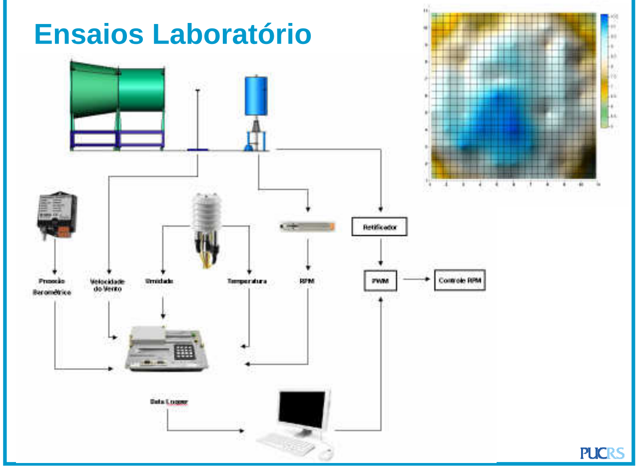
Reynolds number	Helical Savonius; overlap ratio = 0.0; aspect ratio = 0.88		Helical Savonius; overlap ratio = 0.1; aspect ratio = 0.96		Conventional Savonius; overlap ratio = 0.15; aspect ratio = 1.0	
	Cp$_{\max}$	TSR	Cp$_{\max}$	TSR	Cp$_{\max}$	TSR
Re = 120000	0.17	0.70	0.12	0.70	0.17	0.78
Re = 150000	0.17	0.65	0.13	0.77	0.18	0.76

Renewable Energy 94 (2009) 521–529

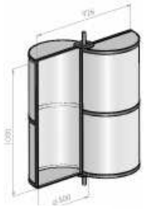
Performance tests on helical Savonius rotors

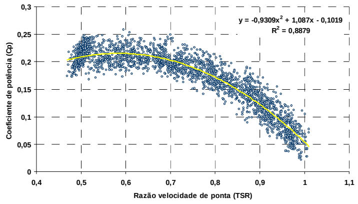
M.A. Kamoji[a], S.B. Kedare[a], S.V. Prabhu[b,*]

Ensaios Laboratório

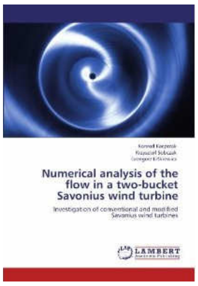


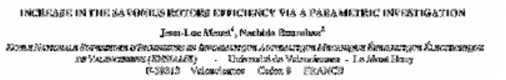
Resultados Laboratório





ROTOR SAVONIUS CFD



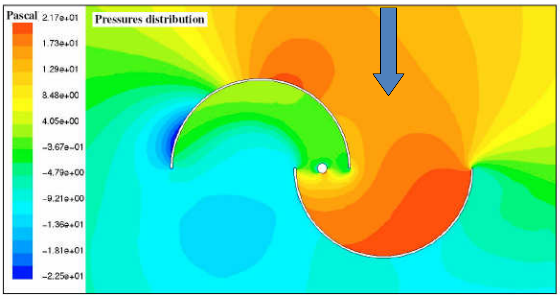


INCREASE IN THE SAVONIUS ROTORS EFFICIENCY VIA A PARAMETRIC INVESTIGATION

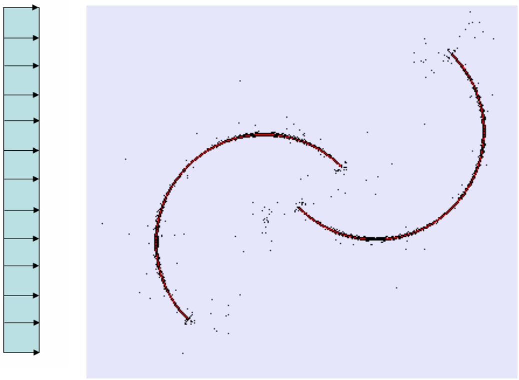
Jean-Luc Menet[1], Nachida Bourabaa[2]

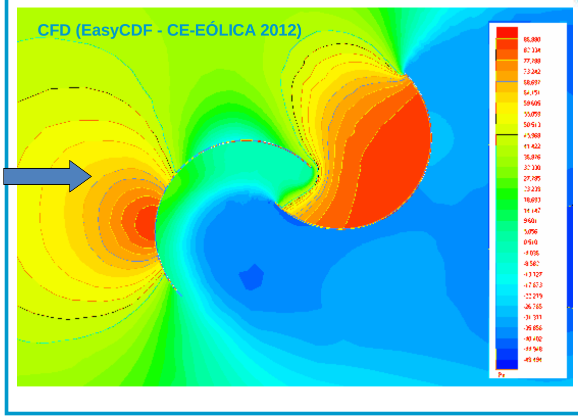
Ecole Nationale Supérieure d'Ingénieurs en Informatique Automatique Mécanique Energétique Electronique de Valenciennes (ENSIAME) - Université de Valenciennes - Le Mont Houy

F-59313 Valenciennes Cedex 9 FRANCE

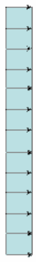


CFD (EasyCDF - CE-EÓLICA 2012)

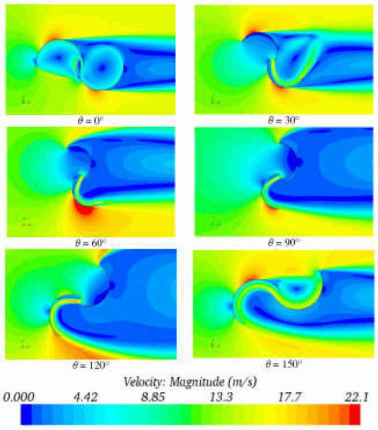


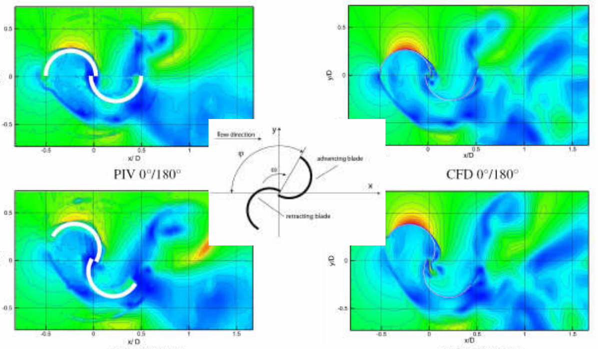


ANÁLISE AERODINÂMICA DE TURBINAS EÓLICAS SAVONIUS EMPREGANDO
DINÂMICA DOS FLUIDOS COMPUTACIONAL
[illegible]
Dissertação para obtenção do Título de
Mestre em Engenharia
UNIVERSIDADE FEDERAL DO RIO GRANDE DO SUL



Campo de velocidades no escoamento com o rotor estático e Re = 867.000





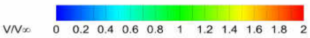
PIV 0°/180°

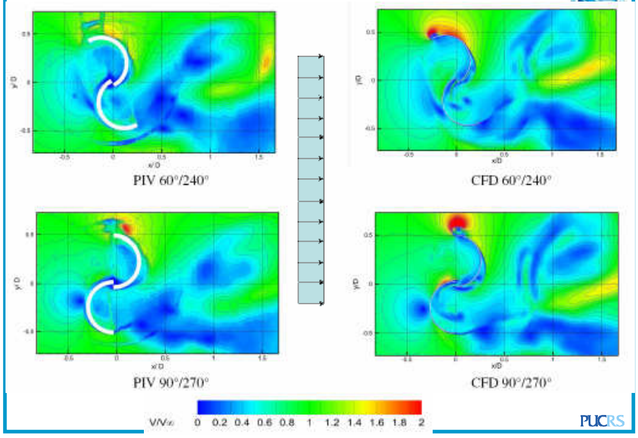
CFD 0°/180°

PIV 30°/210°

CFD 30°/210°

Exploring the Flow around a Savonius Wind Turbine
Ivan Dobrev , Fawaz Massouh
16th Int Symposium on Applications of Laser Techniques to Fluid Mechanics
Lisbon, Portugal, 09-12 July, 2012



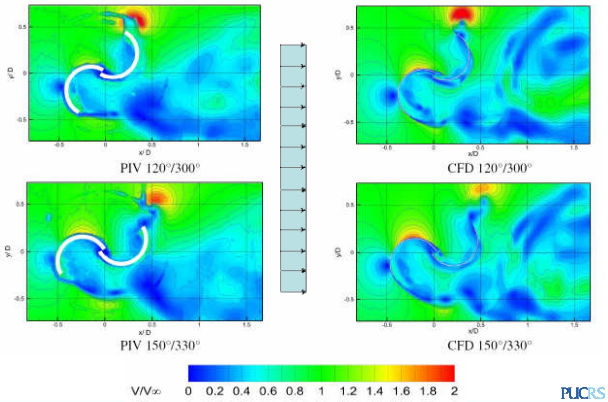


PIV 60°/240°

CFD 60°/240°

PIV 90°/270°

CFD 90°/270°



PIV 120°/300°

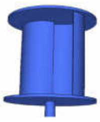
CFD 120°/300°

PIV 150°/330°

CFD 150°/330°

Savonius Rotor

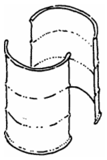
Vertical Axis Helical Savonius Rotor



http://savonius-balaton.hupont.hu/95/verticalwindch-swiss

Savonius Bombeamento de Água

http://www.lnux-host.org/energy/savonius_turbine.jpg



Geração de Eletricidade

D=1,21 m
H=2,65 m

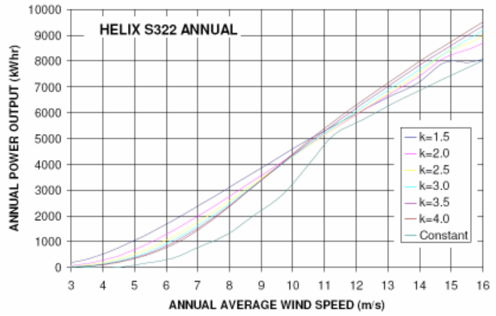
Helixwind 2 kW

www.helixwind.com

http://en.wikipedia.org/wiki/File:Savonius_wind_turbine.jpg

Generator - 2.0 kW (peak) Permanent Magnet Generator

Rotor Dimensions - D=1,21 m H=2,65 m Retail Price: **$10,500 USD** ??



http://www.helixwind.com/en/S322.php#s322pricing

- •TURBINA DARRIEUS
- •ROTOR DE PÁS RETAS
- •ROTOR HELICOIDAL

Georges Darrieus
(1888-1979)

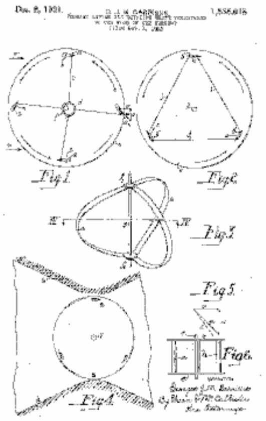
Darrieus, G.J.M.
Turbine having its rotating shaft transverse to the flow of the current. US Patent No. 1,835,018, 1931.

UNITED STATES PATENT OFFICE

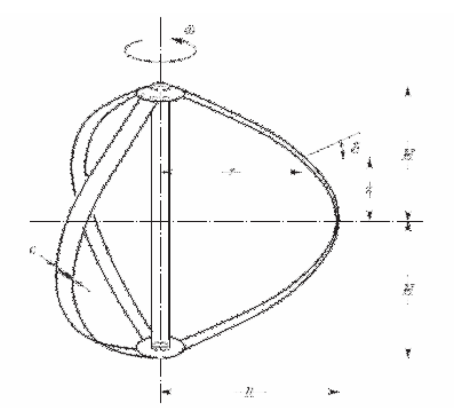
GEORGES JEAN MARIE DARRIEUS, OF PARIS, FRANCE, ASSIGNOR TO SOCIÉTÉ ANONYME POUR L'EXPLOITATION DES PROCÉDÉS MAURICE LEBLANC-VICKERS, OF PARIS, FRANCE

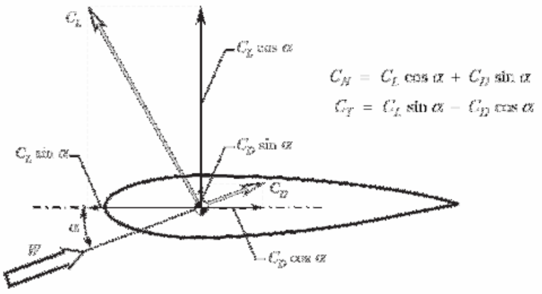
TURBINE HAVING ITS ROTATING SHAFT TRANSVERSE TO THE FLOW OF THE CURRENT

Application filed October 1, 1926, Serial No. [illegible], and in France October [illegible], 1925.



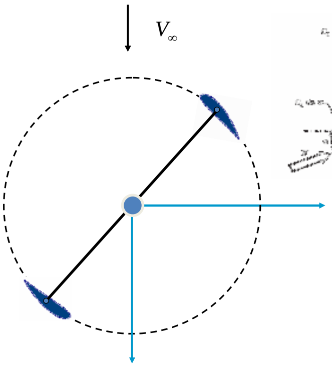
Darrieus
Inventor Frances
Georges Jean Marie Darrieus
Patentes
Francia (1925)
Estados Unidos (1931)

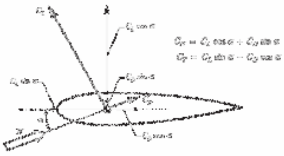


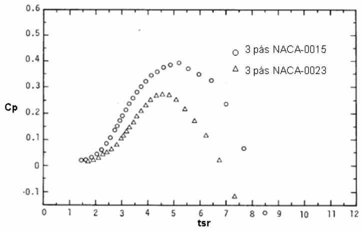


$$C_N = C_L \cos \alpha + C_D \sin \alpha$$

$$C_T = C_L \sin \alpha - C_D \cos \alpha$$

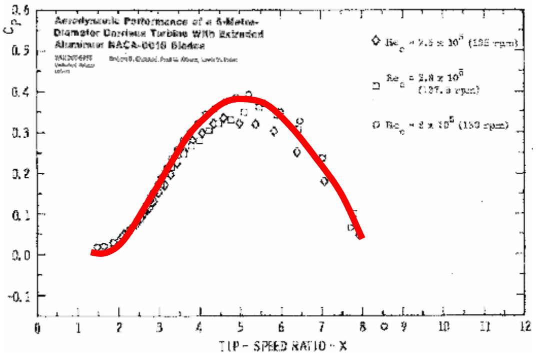


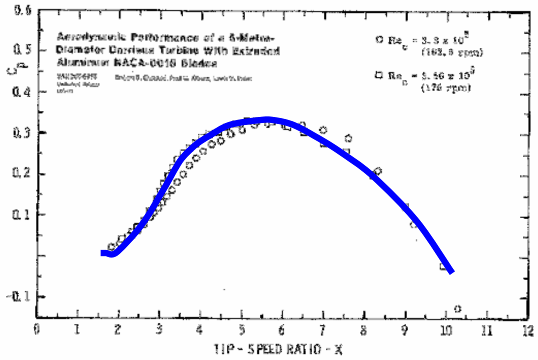




Coeficiente de potência de turbina Darrieus.

Sheldahl R. E., Klimas P. C., Feltz L. V., " "Aerodynamic Performance of a 5m diameter Darrieus Turbine with Extruded Aluminium NACA-0015 Blades", Sandia Laboratories, Journal of Energy, vol. 4. 1980, p. 227-232.



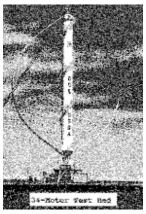


SANDIA TESTS: 2 m, 5 m, 17 m (100 kW), 34 m (625kW)

Sandia 2-m VAWT

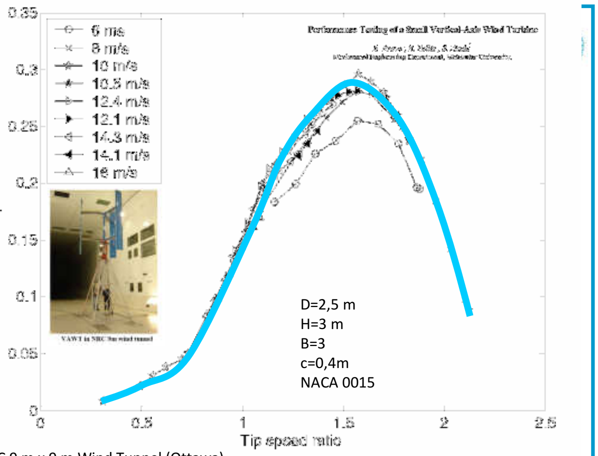
FLoWind 19m
250 kW (20 m/s)

17 m (100 kW),



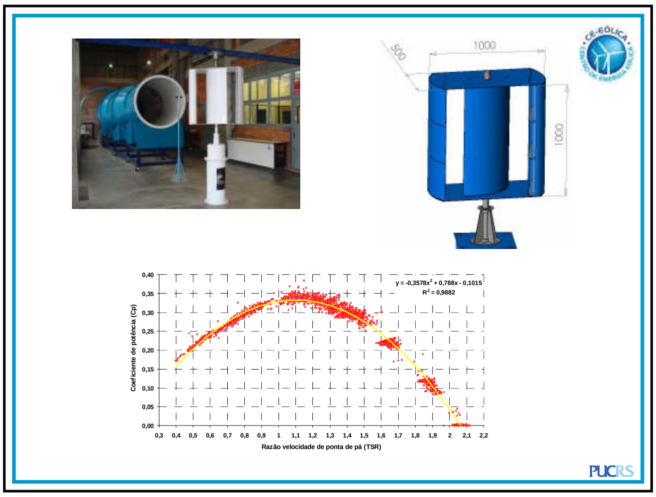
34 m (625kW)

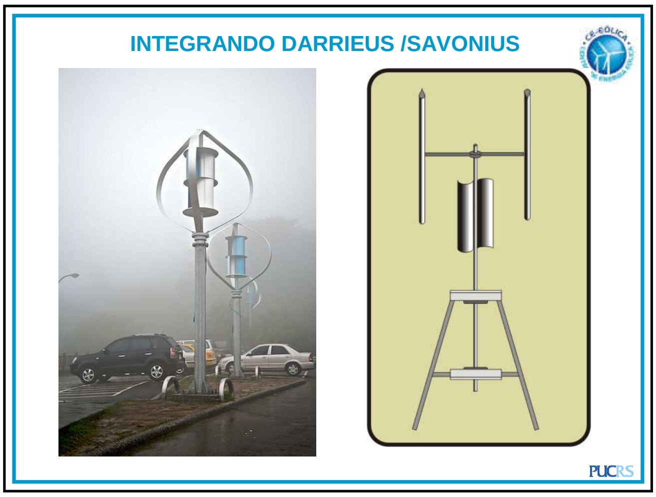
http://www.windsofchange.dk/WOC-usaturb.php



D=2,5 m
H=3 m
B=3
c=0,4m
NACA 0015

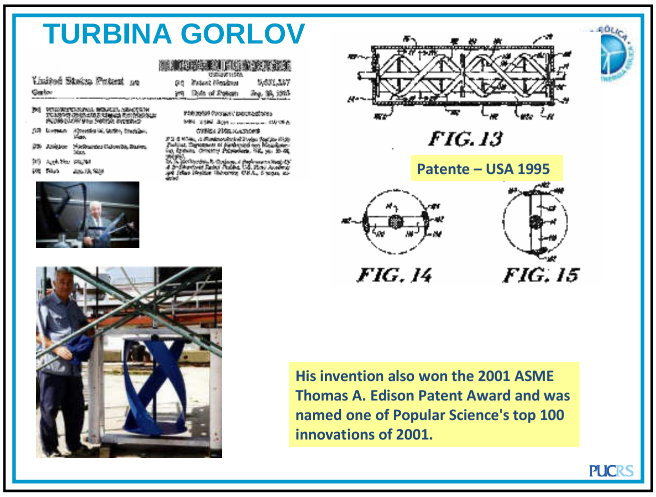
NRC 9 m x 9 m Wind Tunnel (Ottawa)





INTEGRANDO DARRIEUS /SAVONIUS

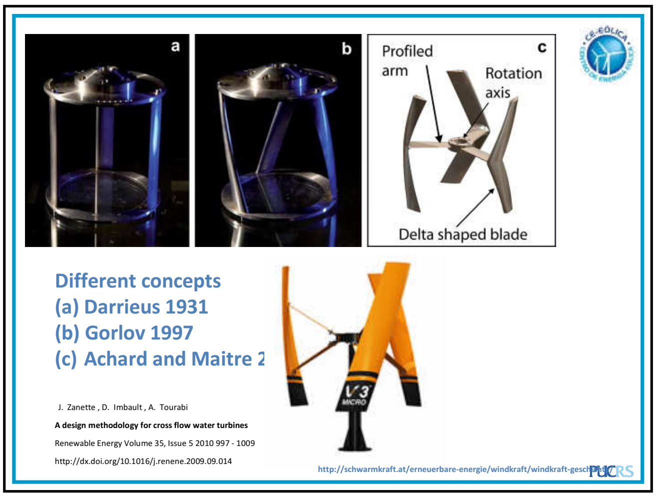
http://de.wikipedia.org/wiki/Darrieus-Rotor



TURBINA GORLOV

Patente – USA 1995

His invention also won the 2001 ASME Thomas A. Edison Patent Award and was named one of Popular Science's top 100 innovations of 2001.



Different concepts
(a) Darrieus 1931
(b) Gorlov 1997
(c) Achard and Maitre 2

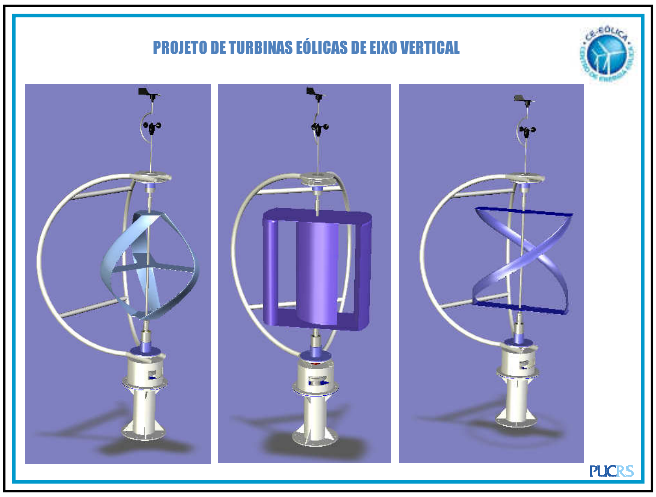
J. Zanette , D. Imbault , A. Tourabi

A design methodology for cross flow water turbines

Renewable Energy Volume 35, Issue 5 2010 997 - 1009

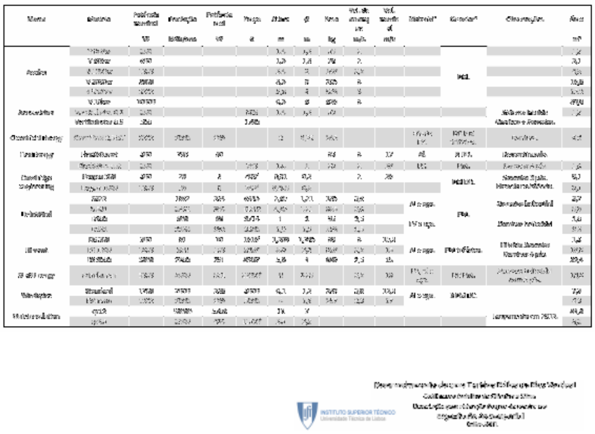
http://dx.doi.org/10.1016/j.renene.2009.09.014

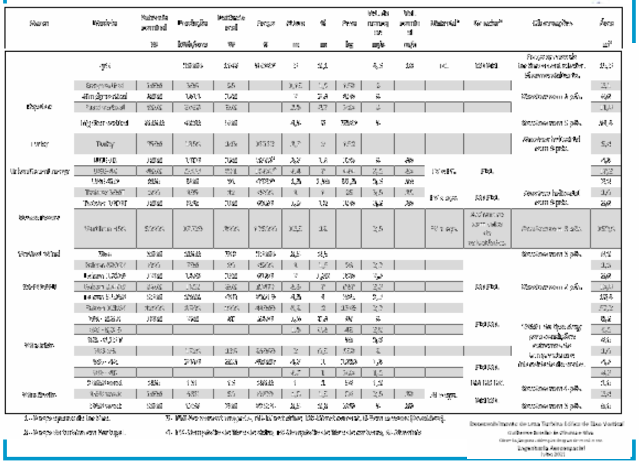
http://schwarmkraft.at/erneuerbare-energie/windkraft/windkraft-gesch

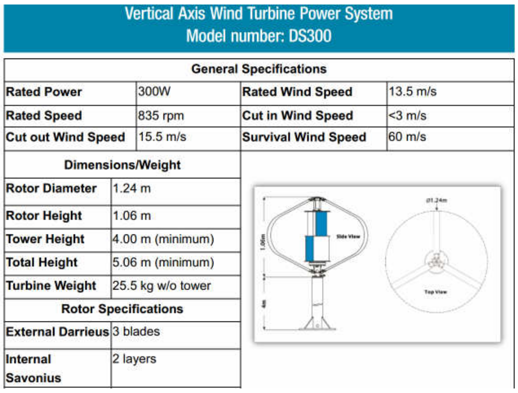


PROJETO DE TURBINAS EÓLICAS DE EIXO VERTICAL

VAWT - TURBINAS COMERCIAIS







Vertical Axis Wind Turbine Power System
Model number: DS300

General Specifications			
Rated Power	300W	**Rated Wind Speed**	13.5 m/s
Rated Speed	835 rpm	**Cut in Wind Speed**	<3 m/s
Cut out Wind Speed	15.5 m/s	**Survival Wind Speed**	60 m/s

Dimensions/Weight	
Rotor Diameter	1.24 m
Rotor Height	1.06 m
Tower Height	4.00 m (minimum)
Total Height	5.06 m (minimum)
Turbine Weight	25.5 kg w/o tower
Rotor Specifications	
External Darrieus	3 blades
Internal Savonius	2 layers

Generator Specifications

Generator Type	AC, 3phase, Synchronism PMG
Rated Output	300W

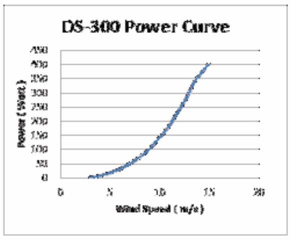
Braking System

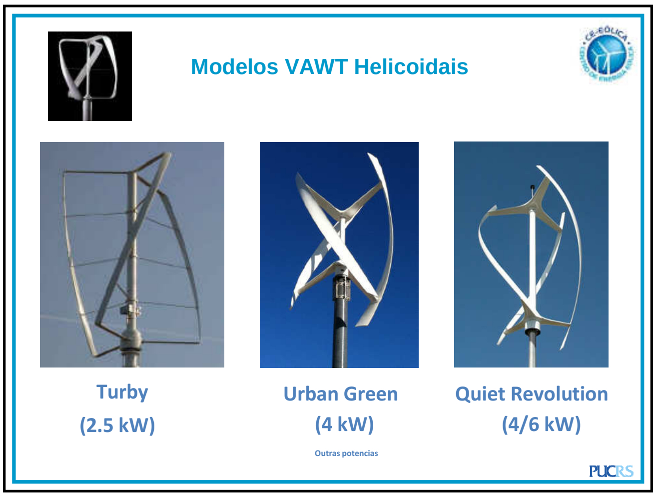
Automatic	3 phase short circuit braking system
Manual	Optional

Operation Conditions

Ambient Temperature	-10~40°C
Ambient Humidity	95% max.

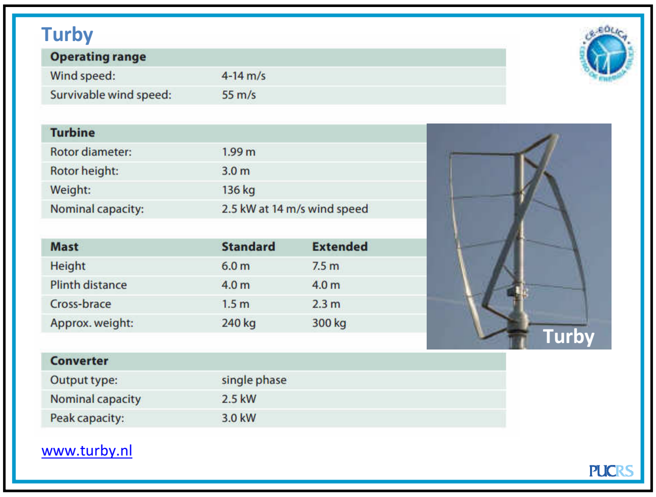
Power Curve





Modelos VAWT Helicoidais

Turbinas de Eixo Vertical		
Green Energy Solution	2,5 kW	USA
Ropatec HE	3 kW	Itália
Green Energy Solution	5 kW	USA
QuietRevolution qr5	6 kW	Inglaterra
Ropatec	6 kW	Itália
Green Energy Solution	10 kW	USA
Ropatec Mega Star	20 kW	Itália
Green Energy Solution	25 kW	USA
Green Energy Solution	50 kW	USA
Green Energy Solution	100 kW	USA
Green Energy Solution	150 kW	USA



Turby

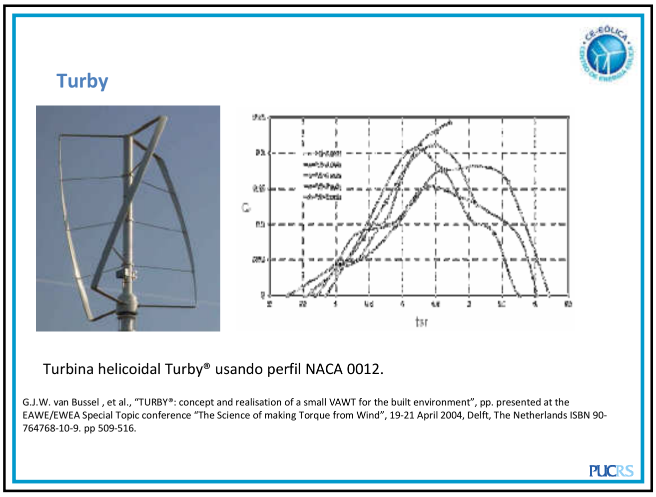
Operating range	
Wind speed:	4-14 m/s
Survivable wind speed:	55 m/s

Turbine	
Rotor diameter:	1.99 m
Rotor height:	3.0 m
Weight:	136 kg
Nominal capacity:	2.5 kW at 14 m/s wind speed

Mast	Standard	Extended
Height	6.0 m	7.5 m
Plinth distance	4.0 m	4.0 m
Cross-brace	1.5 m	2.3 m
Approx. weight:	240 kg	300 kg

Converter	
Output type:	single phase
Nominal capacity	2.5 kW
Peak capacity:	3.0 kW

www.turby.nl



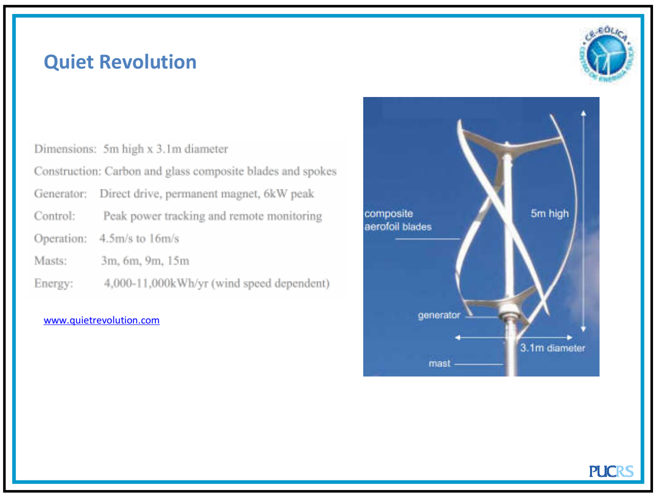
Turby

Turbina helicoidal Turby® usando perfil NACA 0012.

G.J.W. van Bussel , et al., "TURBY®: concept and realisation of a small VAWT for the built environment", pp. presented at the EAWE/EWEA Special Topic conference "The Science of making Torque from Wind", 19-21 April 2004, Delft, The Netherlands ISBN 90-764768-10-9. pp 509-516.

Quiet Revolution

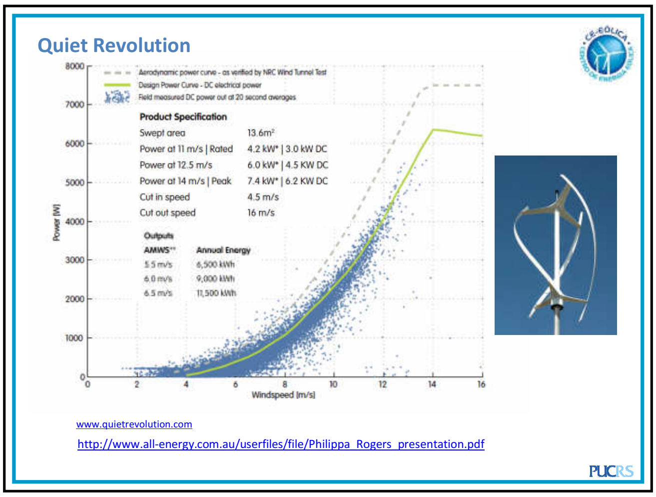
www.quietrevolution.com



Quiet Revolution

Dimensions: 5m high x 3.1m diameter
Construction: Carbon and glass composite blades and spokes
Generator: Direct drive, permanent magnet, 6kW peak
Control: Peak power tracking and remote monitoring
Operation: 4.5m/s to 16m/s
Masts: 3m, 6m, 9m, 15m
Energy: 4,000-11,000kWh/yr (wind speed dependent)

www.quietrevolution.com



Quiet Revolution

Product Specification

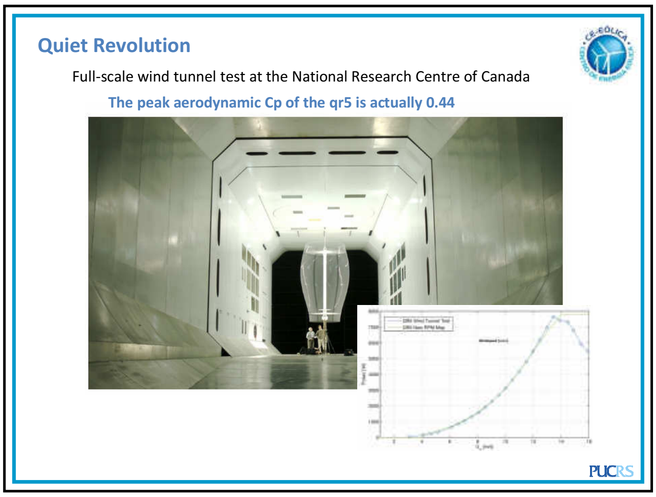
Swept area	13.6m²
Power at 11 m/s | Rated	4.2 kW* | 3.0 kW DC
Power at 12.5 m/s	6.0 kW* | 4.5 KW DC
Power at 14 m/s | Peak	7.4 kW* | 6.2 KW DC
Cut in speed	4.5 m/s
Cut out speed	16 m/s

Outputs

AMWS**	Annual Energy
5.5 m/s	6,500 kWh
6.0 m/s	9,000 kWh
6.5 m/s	11,500 kWh

www.quietrevolution.com

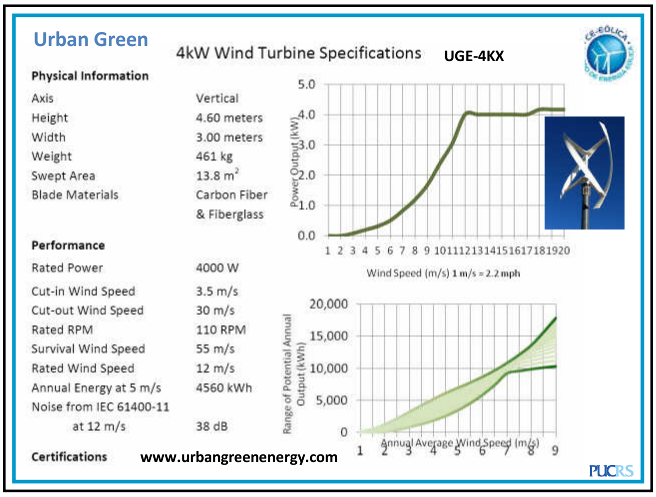
http://www.all-energy.com.au/userfiles/file/Philippa_Rogers_presentation.pdf



Quiet Revolution

Full-scale wind tunnel test at the National Research Centre of Canada

The peak aerodynamic Cp of the qr5 is actually 0.44



Urban Green

4kW Wind Turbine Specifications

UGE-4KX

Physical Information

Axis	Vertical
Height	4.60 meters
Width	3.00 meters
Weight	461 kg
Swept Area	13.8 m²
Blade Materials	Carbon Fiber & Fiberglass

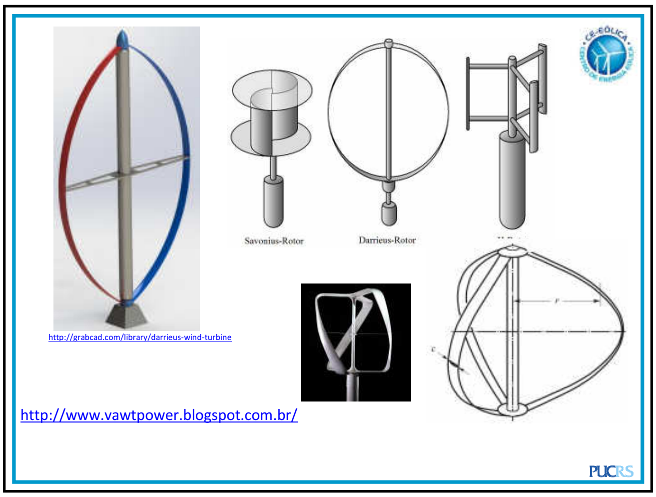
Performance

Rated Power	4000 W
Cut-in Wind Speed	3.5 m/s
Cut-out Wind Speed	30 m/s
Rated RPM	110 RPM
Survival Wind Speed	55 m/s
Rated Wind Speed	12 m/s
Annual Energy at 5 m/s	4560 kWh
Noise from IEC 61400-11 at 12 m/s	38 dB

Certifications

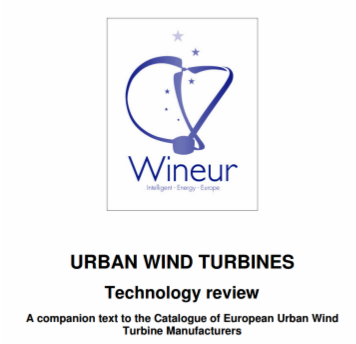
www.urbangreenenergy.com

http://www.sciencedirect.com/science/article/pii/S0360544211003616



http://grabcad.com/library/darrieus-wind-turbine

http://www.vawtpower.blogspot.com.br/



URBAN WIND TURBINES

Technology review

A companion text to the Catalogue of European Urban Wind Turbine Manufacturers

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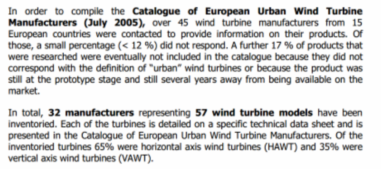
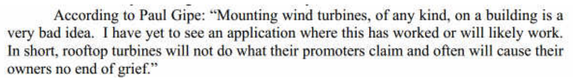


In order to compile the **Catalogue of European Urban Wind Turbine Manufacturers (July 2005),** over 45 wind turbine manufacturers from 15 European countries were contacted to provide information on their products. Of those, a small percentage (< 12 %) did not respond. A further 17 % of products that were researched were eventually not included in the catalogue because they did not correspond with the definition of "urban" wind turbines or because the product was still at the prototype stage and still several years away from being available on the market.

In total, **32 manufacturers** representing **57 wind turbine models** have been inventoried. Each of the turbines is detailed on a specific technical data sheet and is presented in the Catalogue of European Urban Wind Turbine Manufacturers. Of the inventoried turbines 65% were horizontal axis wind turbines (HAWT) and 35% were vertical axis wind turbines (VAWT).

32 Fabricantes

57 Modelos de SWTG
65% (HAWT)
35% (VAWT)



According to Paul Gipe: "Mounting wind turbines, of any kind, on a building is a very bad idea. I have yet to see an application where this has worked or will likely work. In short, rooftop turbines will not do what their promoters claim and often will cause their owners no end of grief."

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Workshop - Small Wind Turbines

AERODINAMICA DE TURBINAS EÓLICAS DE EIXO VERTICAL

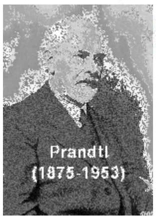

Rankine
(1820-1872)
William John Macquorn Rankine


Robert E. Froude
(1846–1924)

Disco Atuador Momentum Theory


Glaulert
(1892-1934)

Elemento de pá

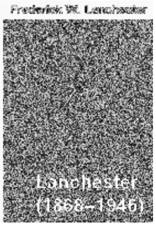

Prandtl
(1875-1953)

Camada limite

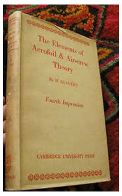

Albert Betz
(1885-1968)

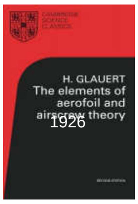

Joukowski
(1857-1941)
Nicolai Egorovich Joukowski

Limite de potencia


Frederick W. Lanchester
Lanchester
(1868–1946)

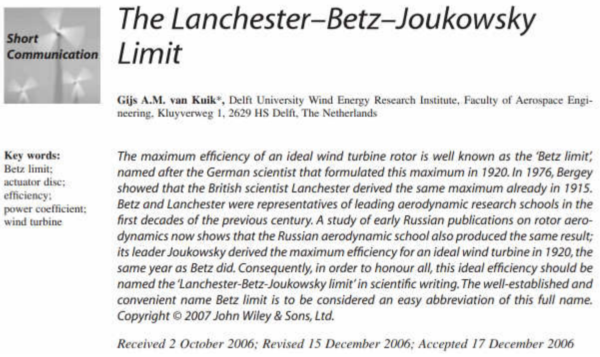
Toeria de Elemento de Pá – Blade Element Theory






Glaulert
(1892-1934)

H. Glauerts, "Windmills and Fans", Aerodynamic Theory (W.F. Durand, Ed.), Springer, Berlin, Germany, 1935


Short Communication

The Lanchester–Betz–Joukowsky Limit

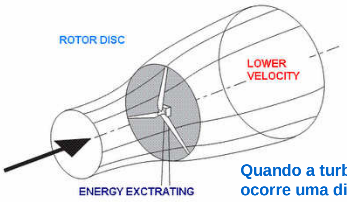
Gijs A.M. van Kuik*, Delft University Wind Energy Research Institute, Faculty of Aerospace Engineering, Kluyverweg 1, 2629 HS Delft, The Netherlands

Key words:
Betz limit;
actuator disc;
efficiency;
power coefficient;
wind turbine

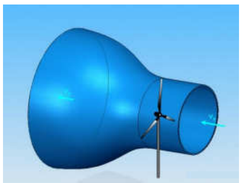
The maximum efficiency of an ideal wind turbine rotor is well known as the 'Betz limit', named after the German scientist that formulated this maximum in 1920. In 1976, Bergey showed that the British scientist Lanchester derived the same maximum already in 1915. Betz and Lanchester were representatives of leading aerodynamic research schools in the first decades of the previous century. A study of early Russian publications on rotor aerodynamics now shows that the Russian aerodynamic school also produced the same result; its leader Joukowsky derived the maximum efficiency for an ideal wind turbine in 1920, the same year as Betz did. Consequently, in order to honour all, this ideal efficiency should be named the 'Lanchester-Betz-Joukowsky limit' in scientific writing. The well-established and convenient name Betz limit is to be considered an easy abbreviation of this full name.

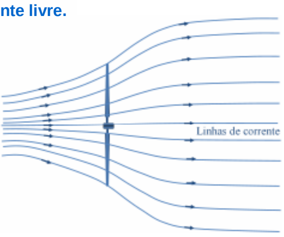
Received 2 October 2006; Revised 15 December 2006; Accepted 17 December 2006

Wind Energ. 2007; 10: 289–291



Quando a turbina absorve energia do vento ocorre uma diminuição da velocidade de corrente livre.





ESTUDO DE MODELOS AERODINAMICOS DE TEEV
MULTIPLE TUBOS DE CORRENTE
(MTC – Modelo de Strickland)

1. **Análise Aerodinâmica – Modelo MTC**
2. **Disco Atuador e Eq. da Quantidade de movimento**
3. **Teoria de elemento de pá**
4. **Força axial, força normal força tangencial**
5. **Velocidade Relativa e Ângulo de Ataque.**
6. **Coeficiente de Sustentação e Coeficiente de Arrasto**
7. **Modelo de Pontin para sustentação e arrasto**
8. **Torque, potência**
9. **Coeficiente de potência**
10. **Resultados do modelo**

Múltiplos Tubos de Corrente (MCT)

O modelo de Múltiplos Tubos de Corrente (MCT) foi desenvolvido por Strickland (1975).

Considera-se que uma serie de tubos de corrente atravessam o rotor.

São determinadas as forças aerodinâmicas igualando a equação da quantidade de movimento com as equações do elemento de pá.

Quando a turbina absorve energia do vento ocorre uma diminuição da velocidade de corrente livre.

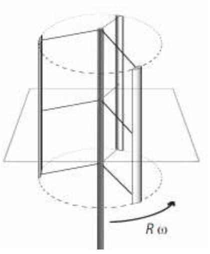
O ar escoa no entorno do elemento de pá afetando a velocidade relativa que atinge o elemento de pá (aerofólio) com um determinado ângulo de ataque gerando assim as forças aerodinâmicas que produzem torque no eixo e potência da máquina.

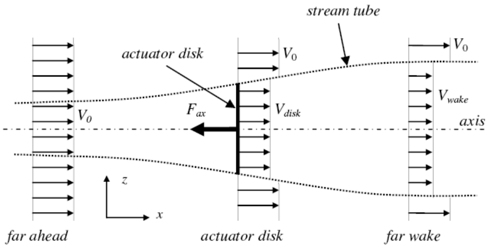
The Darrieus Turbine: A Performance Prediction Model Using Multiple Streamtubes [Report]. - Albuquerque, NM : Sandia Laboratories, 1975. - SAND75-0431.

Razão de velocidade de ponta –TSR $\lambda = \frac{\omega R}{V_\infty}$

Solidez $\sigma = \frac{Area(pás)}{Area(barrida)}$

TEEV **(a)** $\sigma = \frac{Bc}{R}$ **(b)** $\sigma = \frac{Bc}{2R}$



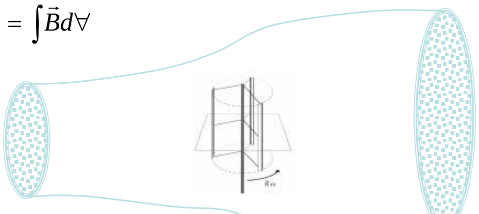


Actuator disk with stream tube

$$\vec{F} = \vec{F}_s + \vec{F}_B = \frac{\partial}{\partial t}\int_{VC} \vec{V}\rho d\forall + \int_{SC} \vec{V}\rho\vec{V}d\vec{A}$$

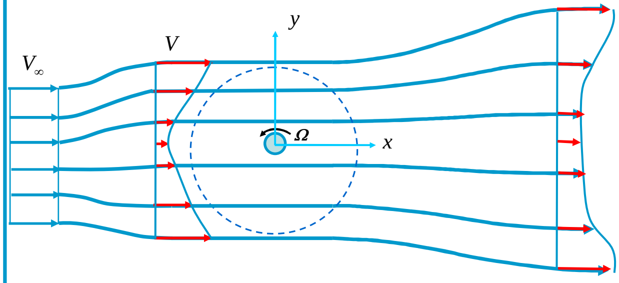
$$\vec{F}_s = \vec{F}_{sp} + \vec{F}_{s\tau} = \int pdA + \int \tau dA$$

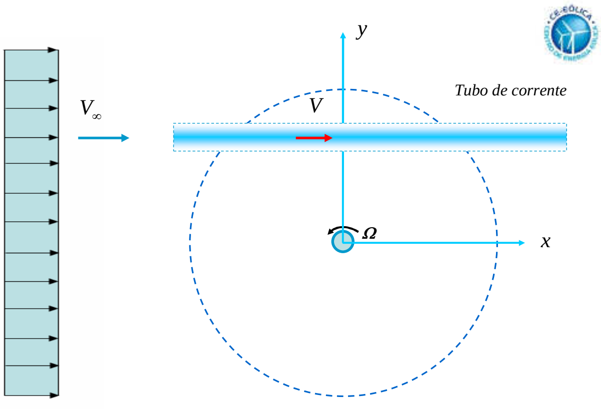
$$\vec{F}_B = \int \vec{B}d\forall$$

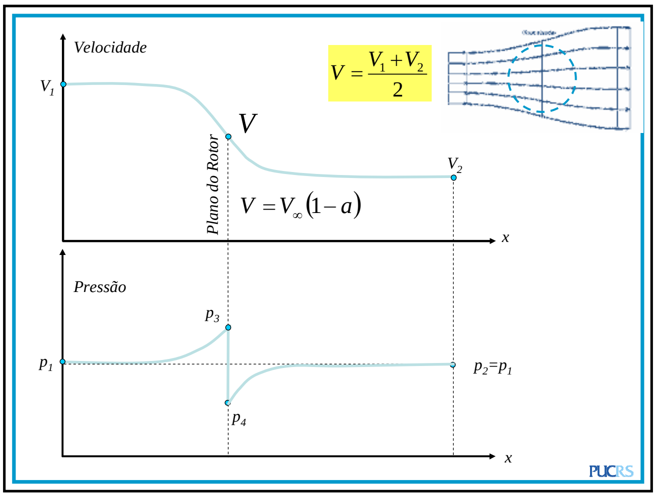


Disco atuador

Múltiplos Tubos de corrente

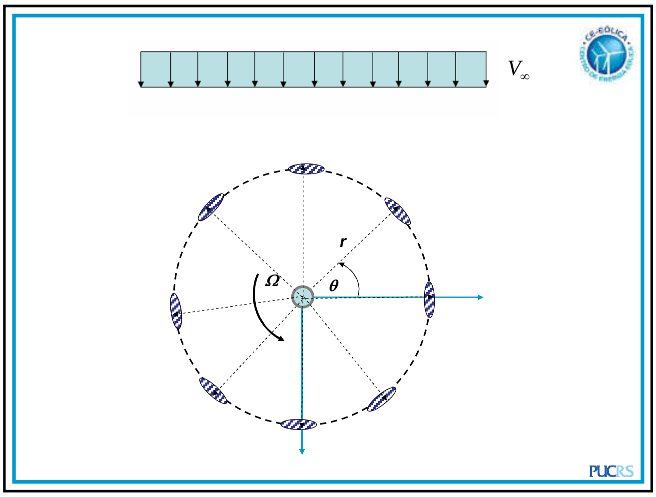


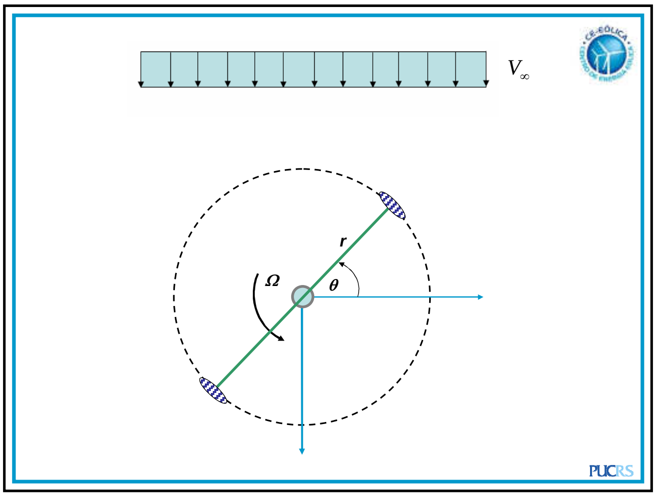


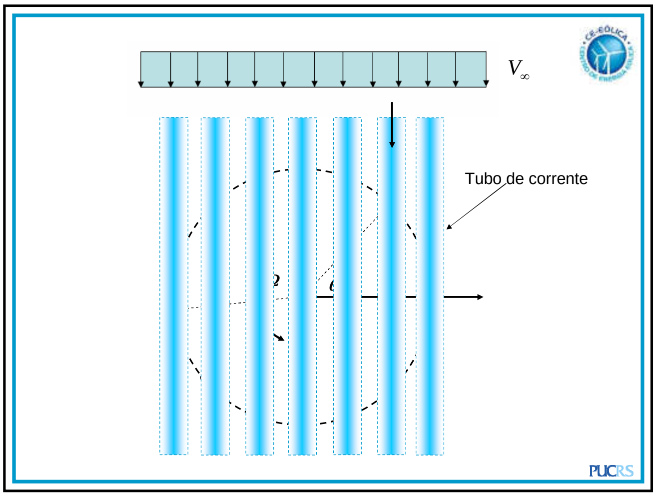


$$V = \frac{V_1 + V_2}{2}$$

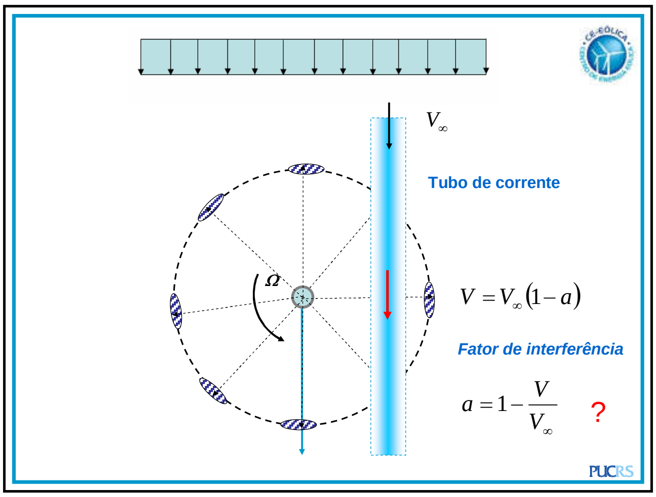
$$V = V_\infty (1 - a)$$







Tubo de corrente

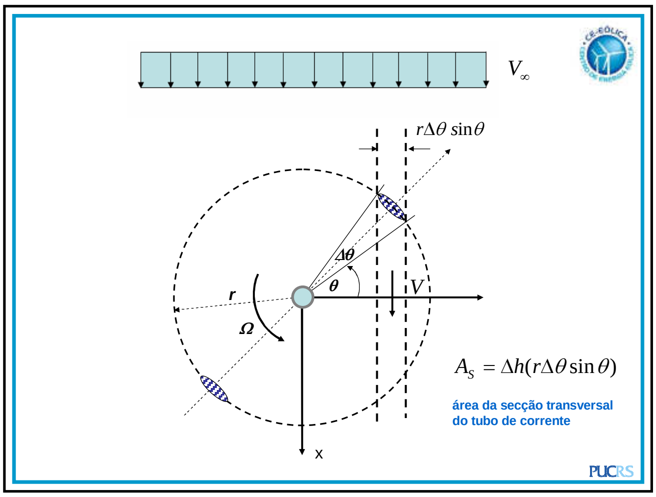


Tubo de corrente

$$V = V_\infty (1 - a)$$

Fator de interferência

$$a = 1 - \frac{V}{V_\infty} \quad ?$$

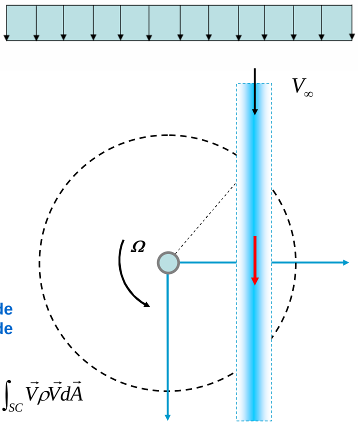


$$A_S = \Delta h (r \Delta\theta \sin\theta)$$

área da secção transversal do tubo de corrente

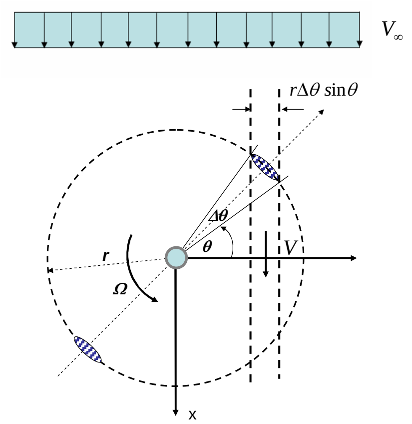
Força media na direção do escoamento exercida pelos elementos de pá que atravessam o tubo de corrente :

$\overline{F}_x$ **?**



Solução:
Aplicar Eq. da Quantidade de movimento num tubo de corrente.

$$\vec{F} = \vec{F}_s + \vec{F}_B = \frac{\partial}{\partial t}\int_{VC} \vec{V}\rho d\forall + \int_{SC} \vec{V}\rho \vec{V} d\vec{A}$$

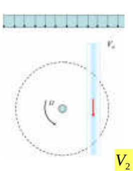


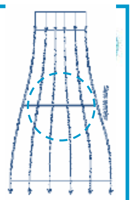
$$F_x = \frac{\partial}{\partial t}\int_{VC} u\rho d\forall + \int_{SC} u\rho \vec{V} d\vec{A}$$

$$F_x = \int_{A_1} V_1\rho V_1 dA_1 + \int_{A_2} V_2\rho V_2 dA_2$$

$$F_x = -V_1\dot{m} + V_2\dot{m}$$

$$F_x = (V_2 - V_1)\dot{m}$$





V_2

$$F_x = ([2V - V_1] - V_1)\dot{m} \leftarrow V_2 = [2V - V_1] \leftarrow V = \frac{V_1 + V_2}{2}$$

$$F_x = (2V - 2V_1)\dot{m}$$

$$F_x = 2(V - V_1)\dot{m} \longleftarrow \dot{m} = \rho V A_S$$

$$F_x = 2(V - V_\infty)\rho V A_S \qquad V_1 = V_\infty$$

$$\overline{F}_x = 2\rho\, A_S\; V\left(V_\infty - V\right)$$

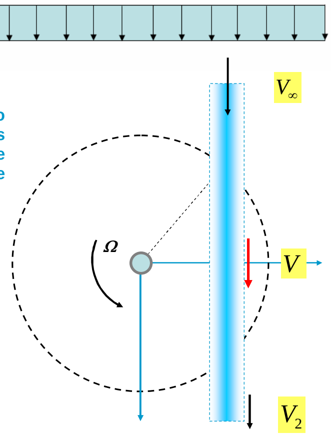
$$\vec{F} = \vec{F}_s + \vec{F}_B = \frac{\partial}{\partial t}\int_{VC} \vec{V}\rho d\forall + \int_{SC} \vec{V}\rho \vec{V} d\vec{A}$$

Força media na direção do escoamento exercida pelos elementos de pá que atravessam o tubo de corrente :

$\overline{F}_x$

$$\overline{F}_x = 2\rho\, A_S\; V\left(V_\infty - V\right)$$

Depende de V que
Depende do
Fator de interferência



O rotor possui *B* pás

Cada pá permanece um % de tempo: $\Delta\theta / \pi$ **no tubo de corrente**

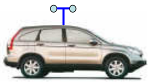
A força axial $\overline{F}_x$ **no tubo de corrente pode ser relacionada com a força axial exercida pelo elemento de pá.**

$$\overline{F}_x = B F_x \frac{\Delta\theta}{\pi}$$

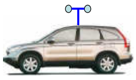
$U = 0$ **Parado**

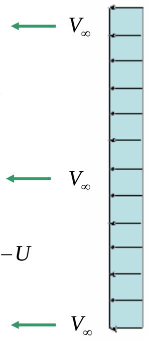
$W = V_\infty + U = V_\infty$ **Vento**

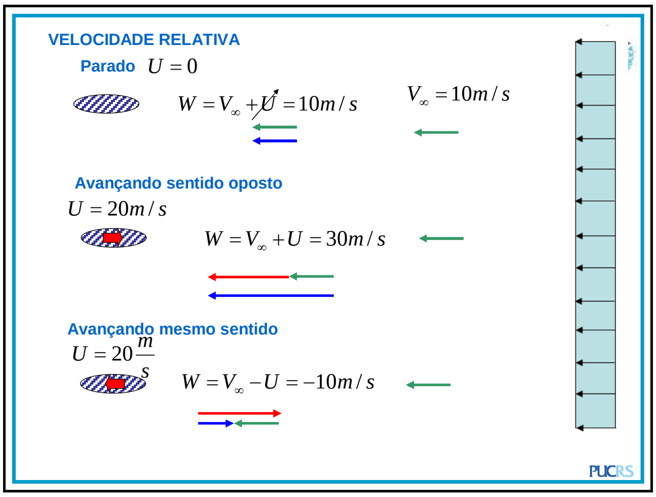
Avançando sentido oposto ao vento $W = V_\infty + U$



Avançando mesmo sentido que o vento $W = V_\infty - U$







VELOCIDADE RELATIVA

Parado $U = 0$

$W = V_\infty + \cancel{U} = 10m/s$

$V_\infty = 10m/s$

Avançando sentido oposto

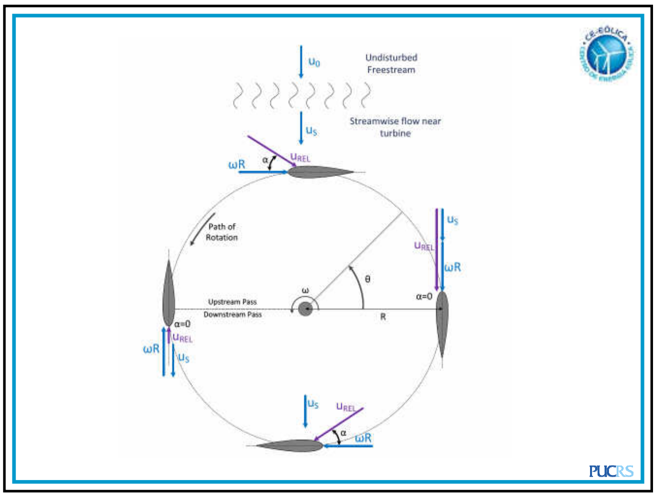
$U = 20m/s$

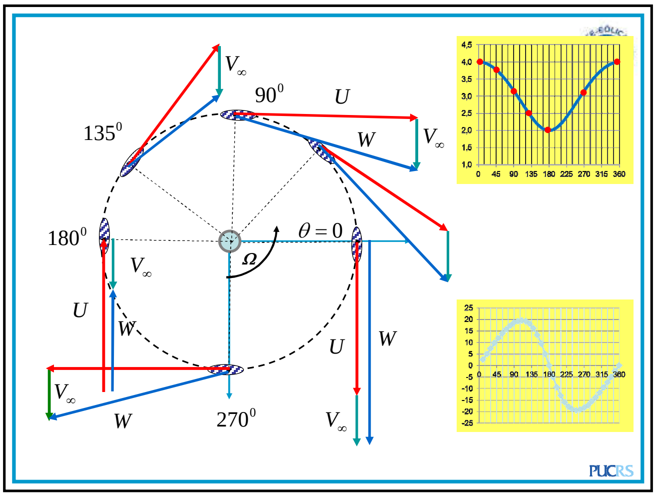
$W = V_\infty + U = 30m/s$

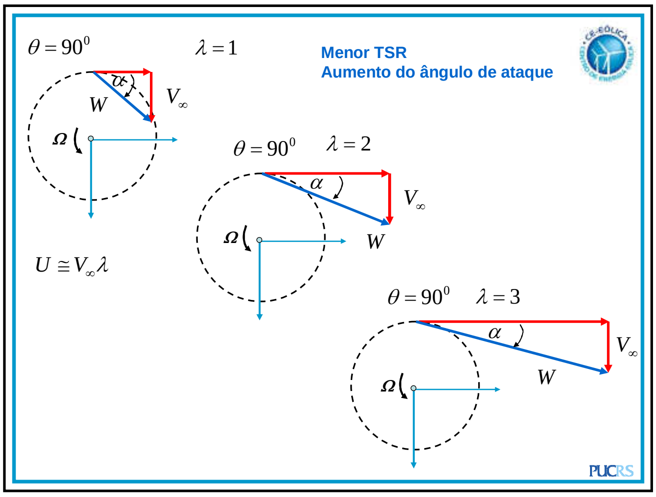
Avançando mesmo sentido

$U = 20\frac{m}{s}$

$W = V_\infty - U = -10m/s$







$\theta = 90^0$ $\lambda = 1$

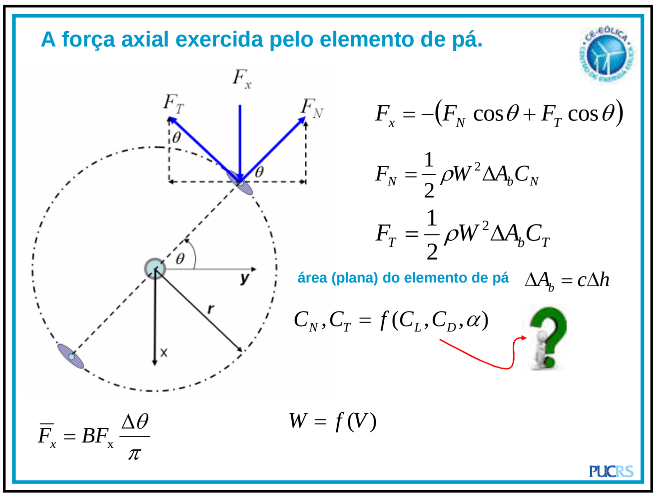
Menor TSR

Aumento do ângulo de ataque

$U \cong V_\infty \lambda$

$\theta = 90^0$ $\lambda = 2$

$\theta = 90^0$ $\lambda = 3$



A força axial exercida pelo elemento de pá.

$$F_x = -(F_N \cos\theta + F_T \cos\theta)$$

$$F_N = \frac{1}{2}\rho W^2 \Delta A_b C_N$$

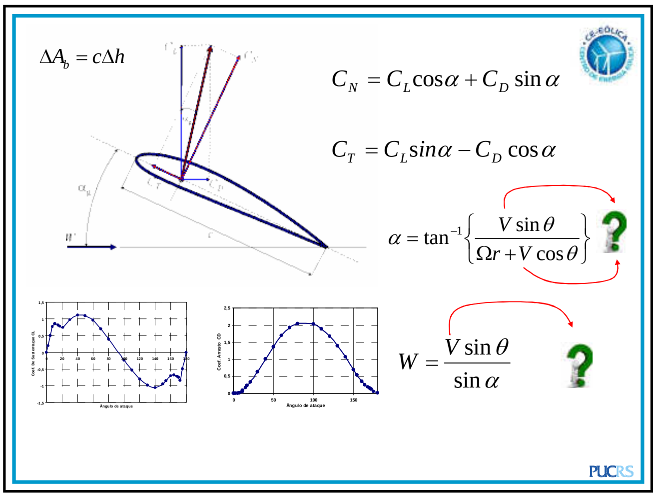
$$F_T = \frac{1}{2}\rho W^2 \Delta A_b C_T$$

área (plana) do elemento de pá $\Delta A_b = c\Delta h$

$$C_N, C_T = f(C_L, C_D, \alpha)$$

$$\overline{F}_x = BF_x \frac{\Delta\theta}{\pi}$$

$$W = f(V)$$



$$\Delta A_b = c\Delta h$$

$$C_N = C_L \cos\alpha + C_D \sin\alpha$$

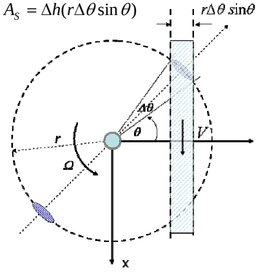
$$C_T = C_L \sin\alpha - C_D \cos\alpha$$

$$\alpha = \tan^{-1}\left\{\frac{V\sin\theta}{\Omega r + V\cos\theta}\right\}$$

$$W = \frac{V\sin\theta}{\sin\alpha}$$

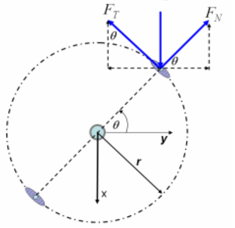
área da secção transversal do tubo de corrente

$A_S = \Delta h(r\Delta\theta \sin\theta)$



área (plana) do elemento de pá

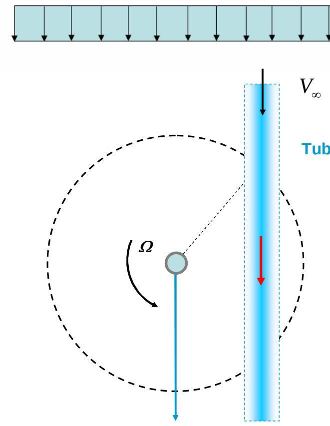
$\Delta A_b = c\Delta h$



$$\overline{F}_x = 2\rho\, A_S\ V\left(V_\infty - V\right)$$

$$F_x = -\left(F_N \cos\theta + F_T \cos\theta\right)$$

$$\overline{F}_x = NF_x \frac{\Delta\theta}{\pi}$$



Tubo de corrente

$$V = V_\infty(1-a)$$

Fator de interferência

$$a = 1 - \frac{V}{V_\infty}$$?

$$\overline{F}_x = 2\rho\, A_S\ V\left(V_\infty - V\right) \qquad \overline{F}_x = NF_x \frac{\Delta\theta}{\pi}$$

$$NF_x \frac{\Delta\theta}{\pi} = 2\rho\, A_S\ V\left(V_\infty - V\right)$$

$$\frac{NF_x}{2\rho\, A_S}\frac{\Delta\theta}{\pi} = V\left(V_\infty - V\right)$$

$$\frac{NF_x}{2\rho\, A_S}\frac{\Delta\theta}{\pi} = V\frac{V_\infty}{V_\infty}\left(V_\infty - V\right)$$

$$\frac{NF_x}{2\rho\, A_S}\frac{\Delta\theta}{\pi} = VV_\infty\left(1 - \frac{V}{V_\infty}\right)$$

$$\frac{NF_x}{2\rho\, A_S}\frac{\Delta\theta}{\pi} = VV_\infty\frac{V_\infty}{V_\infty}\left(1 - \frac{V}{V_\infty}\right)$$

$$\frac{NF_x}{2\rho\, A_S}\frac{\Delta\theta}{\pi} = V_\infty^2\frac{V}{V_\infty}\left(1 - \frac{V}{V_\infty}\right)$$

$$\frac{NF_x}{2\rho\, A_S}\frac{\Delta\theta}{\pi}\frac{1}{V_\infty^2} = \frac{V}{V_\infty}\left(1 - \frac{V}{V_\infty}\right)$$

$$a = 1 - \frac{V}{V_\infty} \qquad 1 - a = \frac{V}{V_\infty}$$

$$\frac{NF_x}{2\rho\, A_S}\frac{\Delta\theta}{\pi}\frac{1}{V_\infty^2} = \frac{V}{V_\infty}\left(1 - \frac{V}{V_\infty}\right)$$

$$\frac{NF_x}{2\rho\, A_S}\frac{\Delta\theta}{\pi}\frac{1}{V_\infty^2} = (1-a)a$$

$$F_x^* = \frac{NF_x}{2\rho\, A_S}\frac{\Delta\theta}{\pi}\frac{1}{V_\infty^2}$$

$$F_x^* = (1-a)a$$

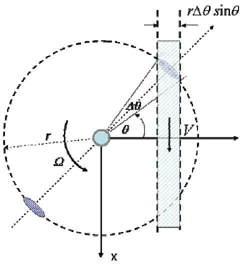
$$a = F_x^* + a^2$$?

$$\overline{F}_x = 2\rho\, A_S\ V\left(V_\infty - V\right) \qquad A_S = \Delta h(r\Delta\theta \sin\theta)$$

$$\overline{F}_x = NF_x \frac{\Delta\theta}{\pi}$$

$$\frac{NF_x}{2\pi\rho r\Delta h \sin\theta V_\infty^2} = \frac{V}{V_\infty}\left(1 - \frac{V}{V_\infty}\right)$$

$$F_x^* = \frac{NF_x}{2\pi\rho r\Delta h \sin\theta V_\infty^2}$$



Fator de interferência $a = 1 - \dfrac{V}{V_\infty}$

$$a = F_x^* + a^2$$

Eq. básica para solução iterativa da Eq. da Quantidade de Movimento dos tubos de corrente

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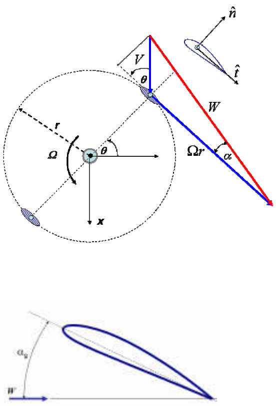
Velocidade Relativa e Ângulo de Ataque



$$\vec{W} = W_{\hat{n}} + W_{\hat{t}}$$

$$W_{\hat{t}} = \Omega r + V\cos\theta$$

$$W_{\hat{n}} = -Vsen\theta$$

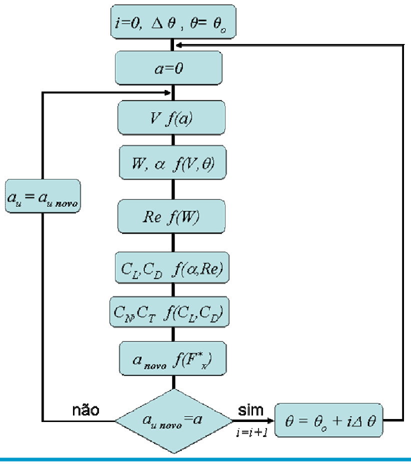
$$W = \sqrt{(\Omega r + V\cos\theta)^2 + (-Vsen\theta)^2}$$

$$\alpha_g = \tan^{-1}\left\{\frac{Vsen\theta}{\Omega r + V\cos\theta}\right\}$$

Também

$$Wsen\alpha = Vsen\theta$$

$$W = \frac{Vsen\theta}{sen\alpha}$$



i=0, $\Delta\theta$, θ= θ_o

a=0

$V\ f(a)$

$W,\ \alpha\ \ f(V,\theta)$

$Re\ \ f(W)$

$C_L, C_D\ \ f(\alpha, Re)$

$C_N, C_T\ \ f(C_L, C_D)$

$a_{novo}\ \ f(F^*_x)$

$a_{u\,novo} = a$

não

$a_u = a_{u\,novo}$

sim

$i = i+1$

$\theta = \theta_o + i\Delta\theta$

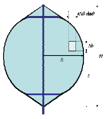
$$F_T(\theta)=\frac{1}{2}\rho C_T \Delta A_b W^2 \qquad \Delta A_b = c\Delta h$$

O torque do elemento de pá que passa pelo tubo de corrente é dada por

$$T_{el}(\theta)=F_T(\theta)r \qquad T_{el}(\theta)=\left(\frac{1}{2}\rho C_T c\Delta h W^2\right)r$$

O torque total de uma pá se obtém pelo somatório do torque de cada elemento desta pá.

Considerando que a pá foi segmentada em *NBe* elementos



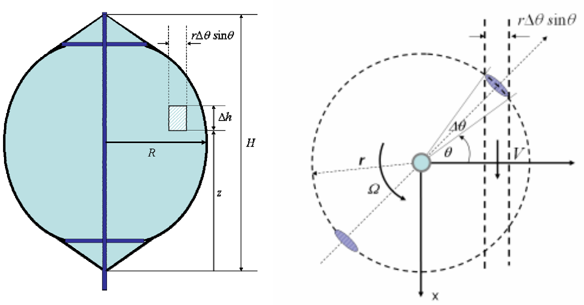
$$T=\sum_{1}^{N_{Be}} T_{el}(\theta)$$

O torque médio produzido pelo rotor com *B* pás é determinado fazendo a media temporal do torque total das *B* pás que formam parte do rotor.

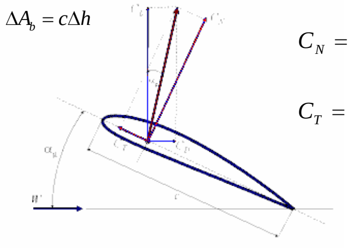
$$\overline{T}_B=\frac{B}{N_\theta}\sum_{1}^{N_\theta} T=\frac{B}{N_\theta}\sum_{1}^{N_\theta}\sum_{1}^{N_{Be}} T_{el}(\theta) \qquad C_p=\frac{\overline{T}_B\Omega}{\frac{1}{2}\rho A_t V_\infty^3}$$

N_θ	Número de segmentos angulares numa revolução.

Geometria e tubo de corrente numa turbina de eixo vertical



$$\Delta A_b = c\Delta h$$



$$C_N = C_L\cos\alpha + C_D\sin\alpha$$

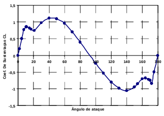
$$C_T = C_L sin\alpha - C_D\cos\alpha$$

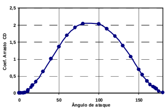
$$\alpha=\tan^{-1}\left\{\frac{V\sin\theta}{\Omega r+V\cos\theta}\right\}$$

?

$$W=\frac{V\sin\theta}{\sin\alpha}$$

?





Sustentação e Arrasto Aerodinâmico

MODELO DE PONTIN

A first order Mathematical Model of the Lift/Drag Characteristics of Aerofoil Sections
G.W Pontin – Wind Engineering Vol.5 Nº3 (1981)

Equacionamento da Sustentação e Arrasto Aerodinâmico

MODELO DE PONTIN A first order Mathematical Model of the Lift/Drag Characteristics of Aerofoil Sections
G.W Pontin – Wind Engineering Vol.5 Nº3 (1981)

Sustentação

(1) Para $\alpha < \alpha_{max}$

$$C_L = AR_1^4R_3^4\alpha^{o5}+B\alpha^o+C$$

(2) Para $\alpha_{max} < \alpha < 30^0$

$$C_L=\frac{C_D}{\tan\alpha}+R_2\left(30^0-\alpha\right)$$

(3) Para $30^0 < \alpha < 90^0$

$$C_L=\frac{C_D}{\tan\alpha}$$

***A,B,C,D,E,F, R_1,R_2,R_3*: parâmetros do aerofólio**

Arrasto

(1) Para $\alpha < \alpha_{max}$

$$C_D = R_1R_3\left[D+E\left(C_L-F\right)^2\right]$$

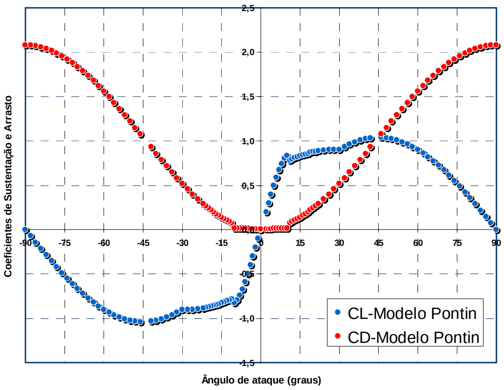
(2) Para $\alpha > \alpha_{max}$

$$C_D = 1{,}04\left[1-\cos(2\alpha)\right]$$

Onde:
A: Fator dependente do estol
B: Inclinação da curva de sustentação (slope)
C: Sustentação: C_L para $\alpha=0^0$
D: Arrasto mínimo CD(min)
E: Controle da variação de C_D em função C_L
F: Sustentação: C_L para CD(min)
R1: Correção de Re antes do estol
R2: Correção de Re após estol
R3: Correção por rugosidade

Equacionamento da Sustentação e Arrasto Aerodinâmico

MODELO DE PONTIN

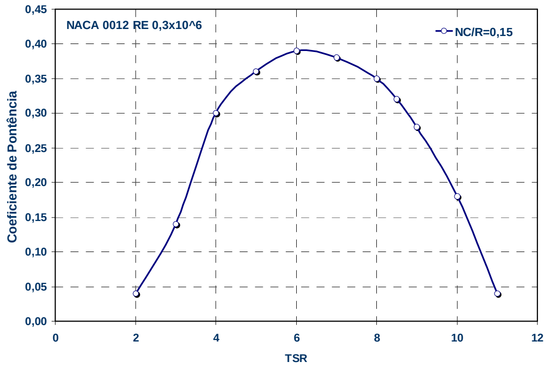


Workshop - Small Wind Turbines

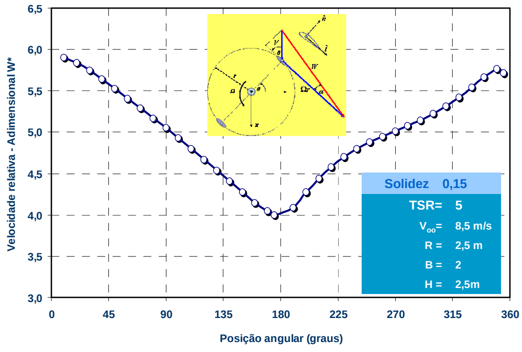
Múltiplos Tubos de Corrente (MCT)

RESULTADOS DO MODELO

Resultados Múltiplos Tubos de Corrente (MCT)



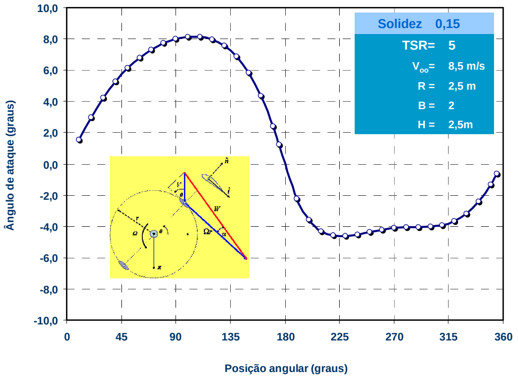
VELOCIDADE RELATIVA – ADIMENSIONAL W*



Solidez 0,15

TSR= 5
V_{oo}= 8,5 m/s
R = 2,5 m
B = 2
H = 2,5m

ÂNGULO DE ATAQUE

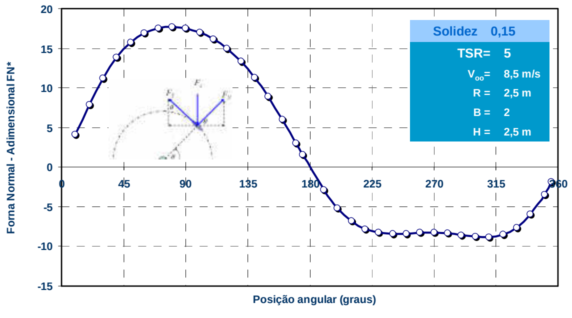


Solidez 0,15

TSR= 5
V_{oo}= 8,5 m/s
R = 2,5 m
B = 2
H = 2,5m

FORÇA NORMAL – ADIMENSIONAL FN*

$$F_N^* = C_N \left(\frac{W}{V_\infty}\right)^2$$

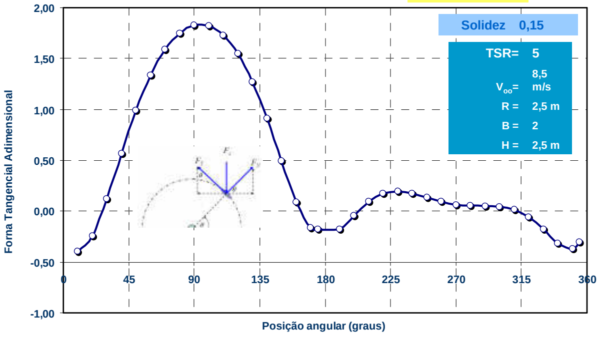


Solidez 0,15

TSR= 5
V_{oo}= 8,5 m/s
R = 2,5 m
B = 2
H = 2,5 m

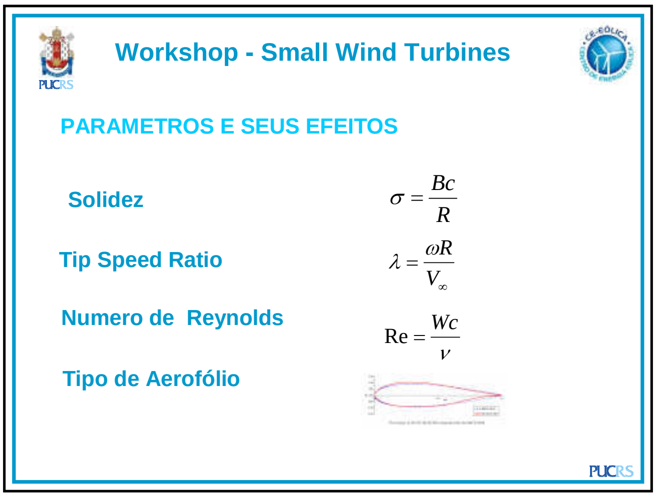
FORÇA TANGENCIAL – ADIMENSIONAL FT*

$$F_T^* = C_T \left(\frac{W}{V_\infty}\right)^2$$



Solidez 0,15

TSR= 5
V_{oo}= 8,5 m/s
R = 2,5 m
B = 2
H = 2,5 m



Workshop - Small Wind Turbines

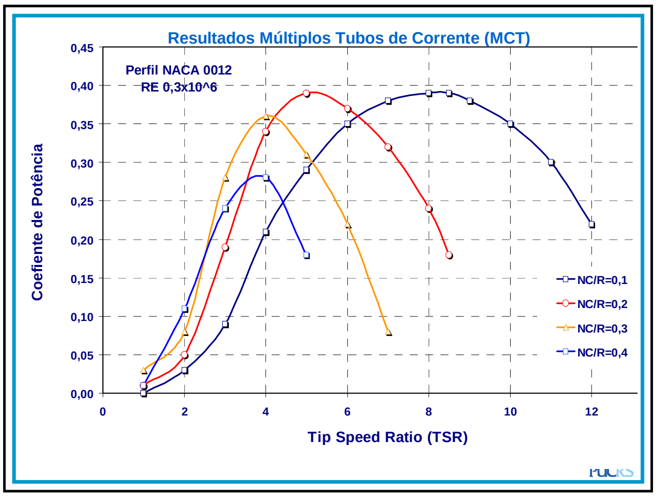
PARAMETROS E SEUS EFEITOS

Solidez $\sigma = \frac{Bc}{R}$

Tip Speed Ratio $\lambda = \frac{\omega R}{V_\infty}$

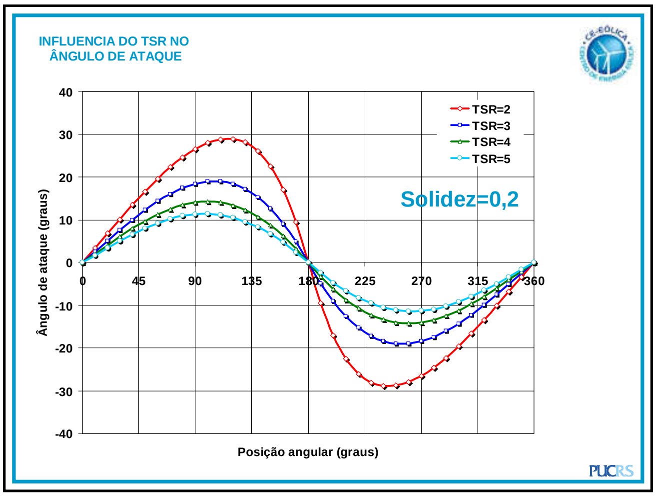
Numero de Reynolds $\mathrm{Re} = \frac{Wc}{\nu}$

Tipo de Aerofólio



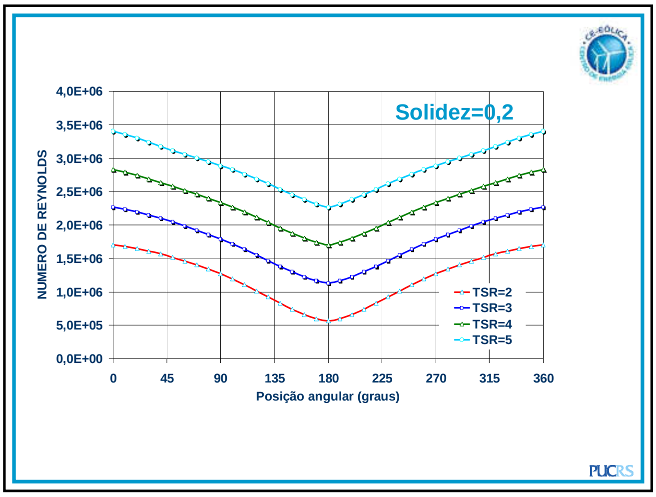
Resultados Múltiplos Tubos de Corrente (MCT)

Perfil NACA 0012
RE 0,3x10^6

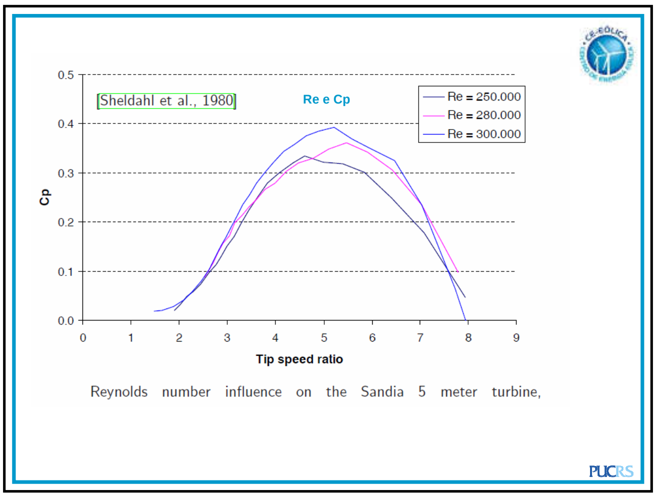


INFLUENCIA DO TSR NO ÂNGULO DE ATAQUE

Solidez=0,2



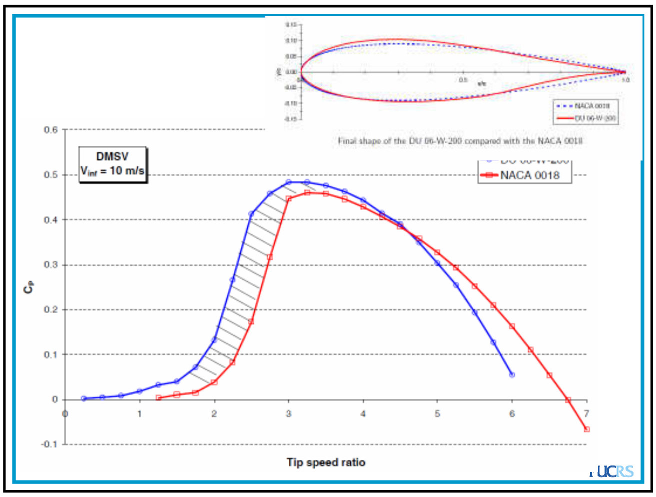
Solidez=0,2



[Sheldahl et al., 1980]

Re e Cp

Reynolds number influence on the Sandia 5 meter turbine,



Final shape of the DU 06-W-200 compared with the NACA 0018

PUCRS

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