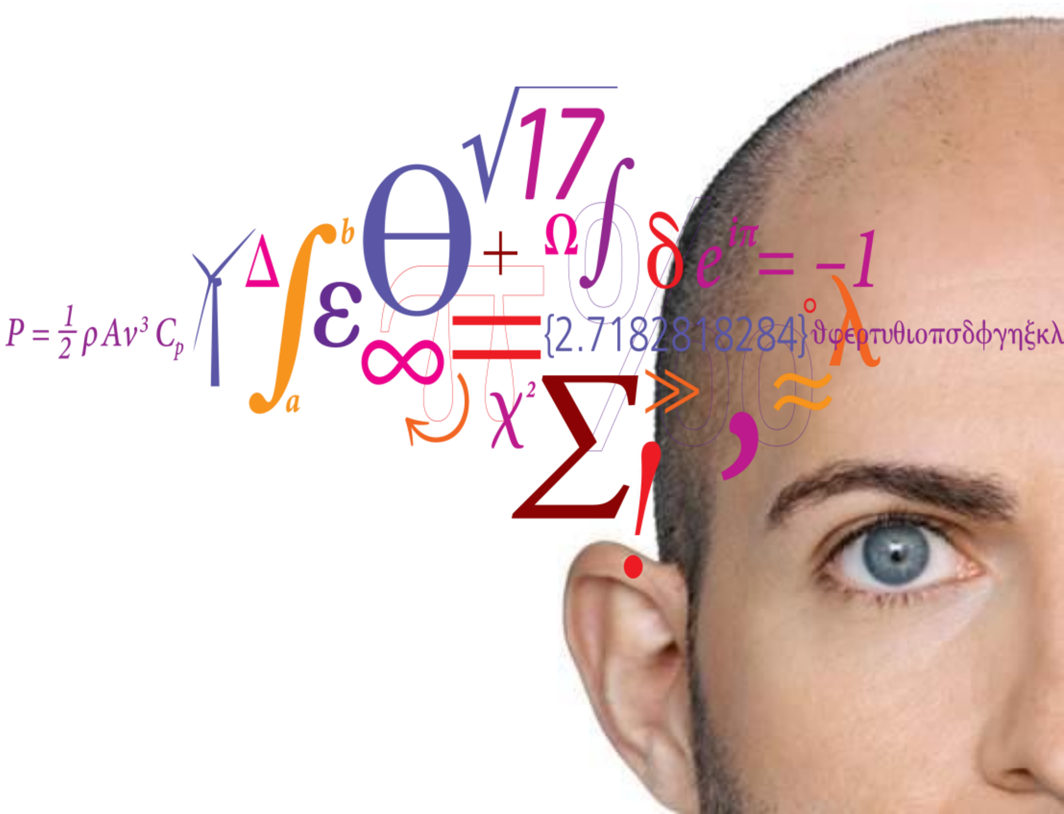
A Short History of (Wind Turbine) Aerodynamics

Jens Nørkær Sørensen and Valery Okulov
DTU Wind Energy

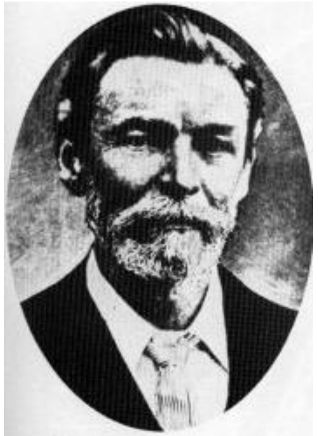
Presentation at the Wind Denmark Conference
Hedensted, October 30, 2018



DTU Vindenergi
Institut for Vindenergi

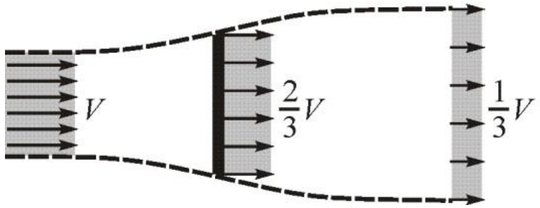
Momentum (or slipstream, or actuator disk) theory (1889)

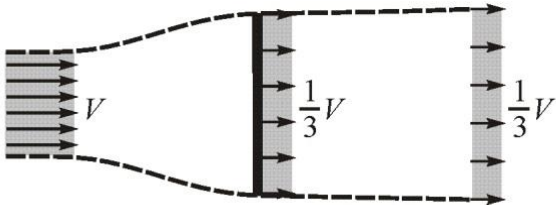
W. Rankine



R.E. Froude

Considerable discussions to understand the basics of the theory took place up to the first formulation of the vortex theory, but the English school kept a distrust to Froude’s theory for a long time.



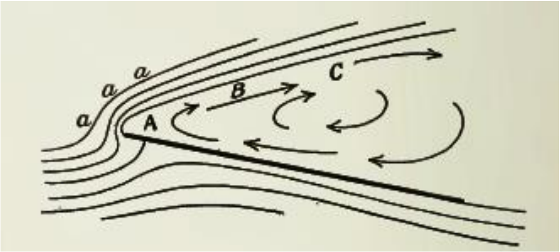


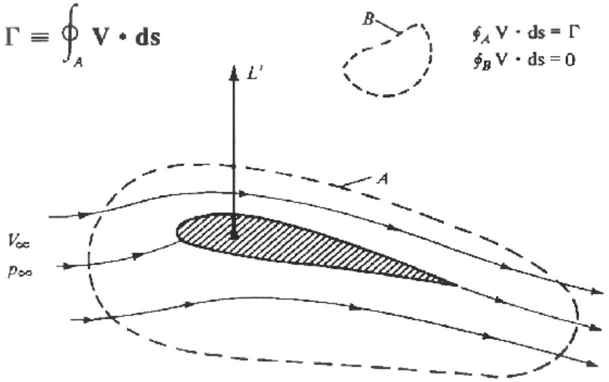
Aerodynamics of the aerofoil

Lord Rayleigh

M. Kutta

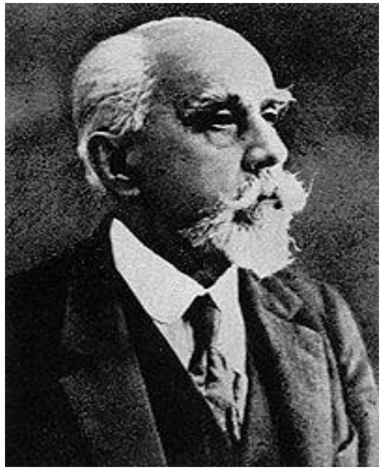
N. Joukowsky



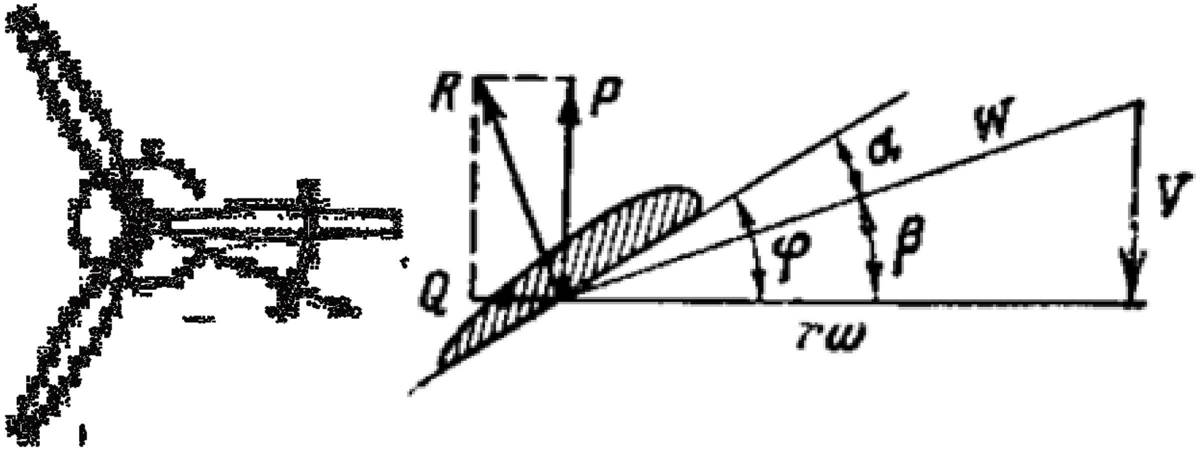


Considerable discussion about the aerodynamics of aerofoils resulted in the formulation of Kutta-Joukowsky theorem (1904).

Blade element theory (1892)



S. Drzewiecki

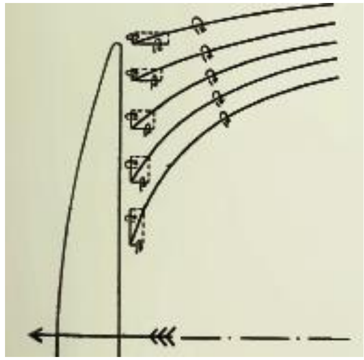


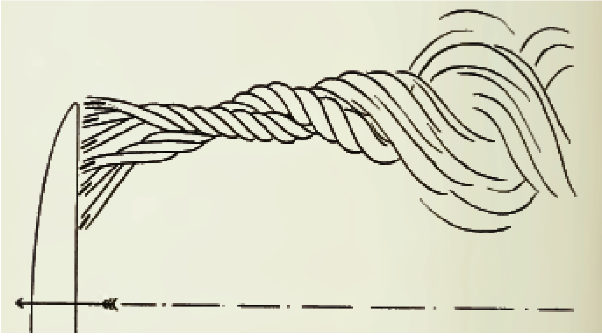
The original theory of Drzewecki was incomplete because it did not include the contribution from the induced velocity.

For this reason, propellers designed in accordance with his theory, in the beginning of the 20th century, were inferior to later design that included the induced velocity.

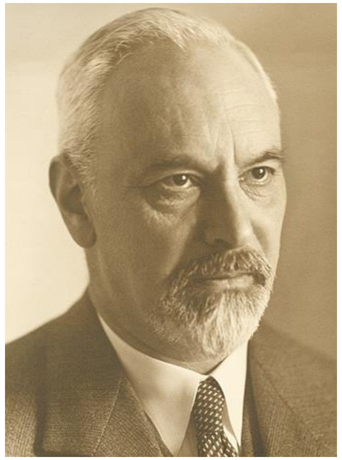
Wing Aerodynamics

F. Lanchester

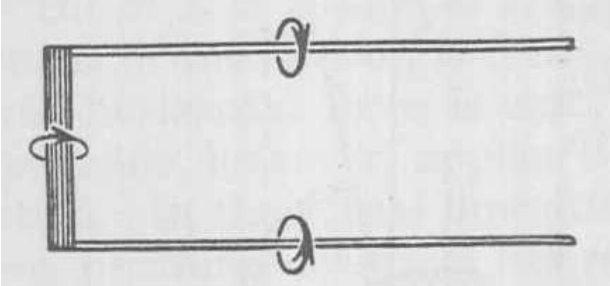




The first picture of the wing (tip) vortex by Lanchester (1907)

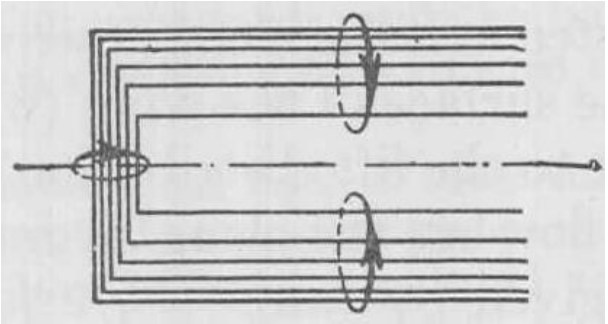


L. Prandtl



The first simplified vortex model of a wing (Prandtl 1913)

Used by Joukowsky in his rotor (vortex) theory

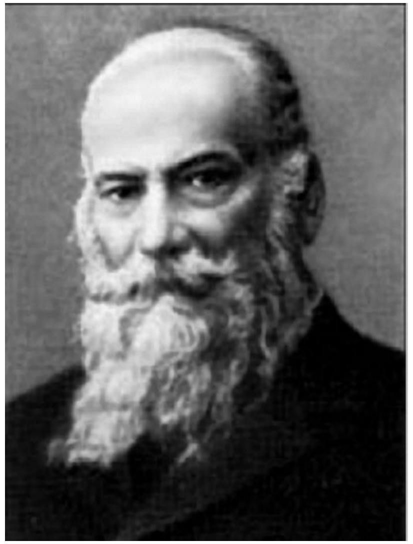


More accurate vortex model (Prandtl 1918)

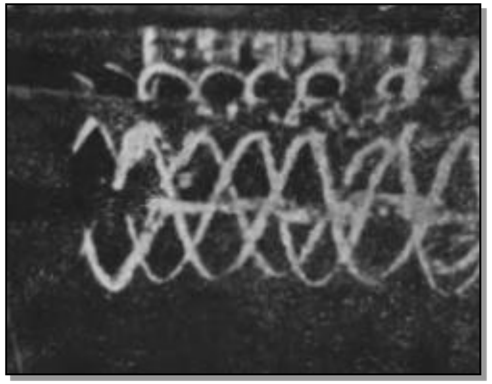
Used by Betz it in his rotor theory

Rotor (vortex) theory of Joukowsky (October 1912)

was formulated in the first article in a series of 4 articles "Vortex theory of screw propeller" (1912-1918)



N.E. Joukowsky



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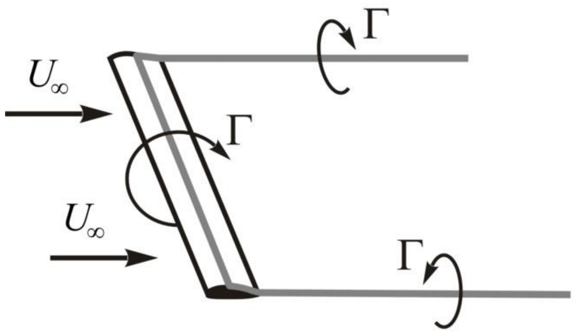

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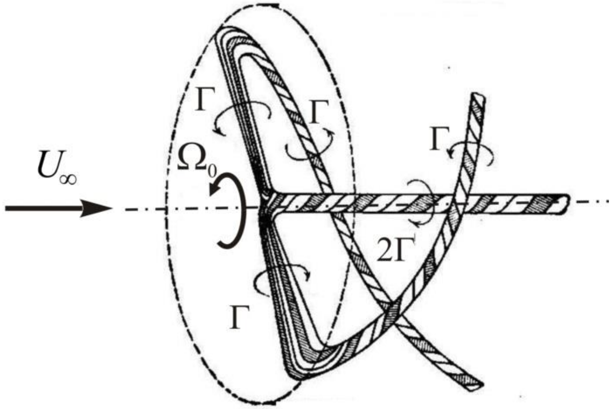
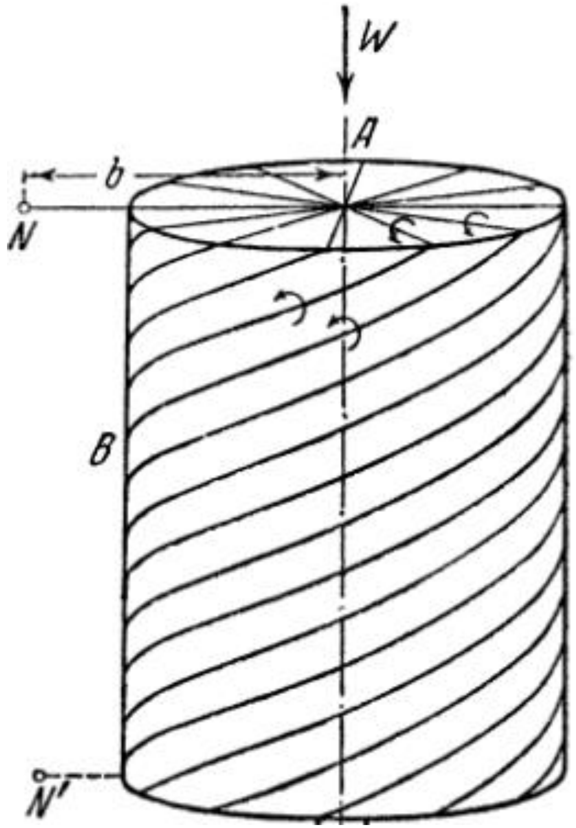
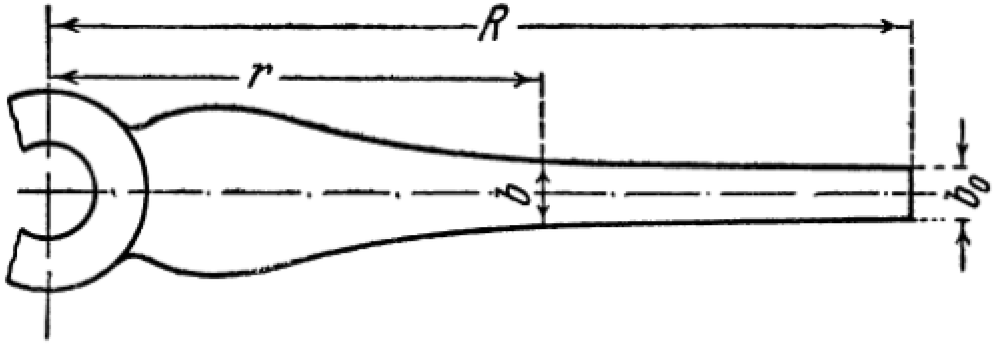


Flamm's visualization and the first wing vortex system are the basis of his theory

Rotor with infinite number of blades in his first article (1912)



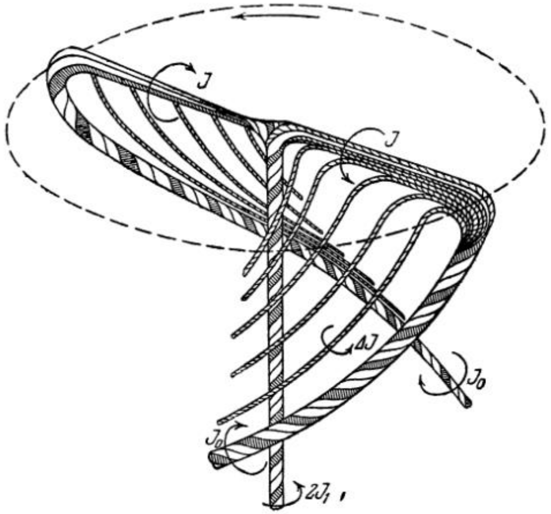


A complete solution with a definition of induced velocity and blade form was found by vortex theory for rotors with an infinite number of blades (Joukowsky 1912)

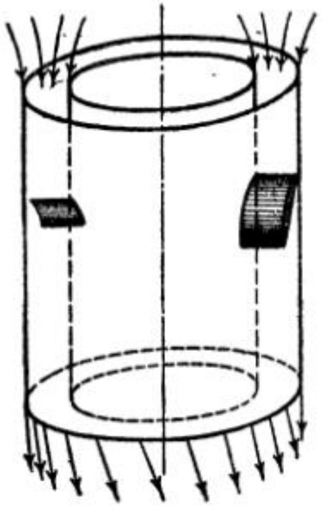
In the first article (1912) Joukowsky proposed the rotor vortex theory with a finite number of blades, but he could only solve the infinite-bladed case!

2nd article of “Vortex theory of screw propeller” (1914)

V. Vetchinkin
(pupil of Joukowsky)



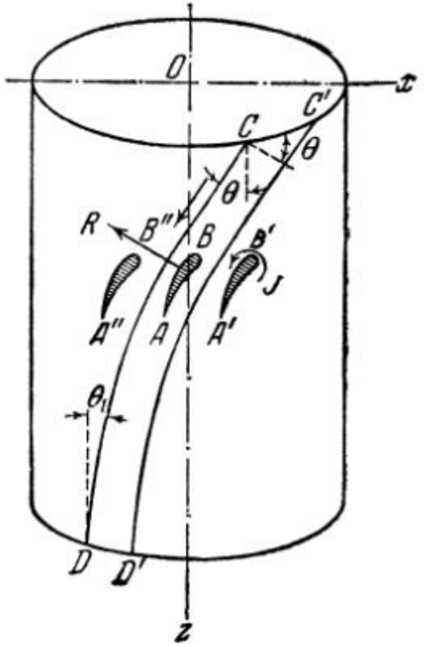
Vortex system for rotor with arbitrary circulation along blade (Vetchinkin, 1913)

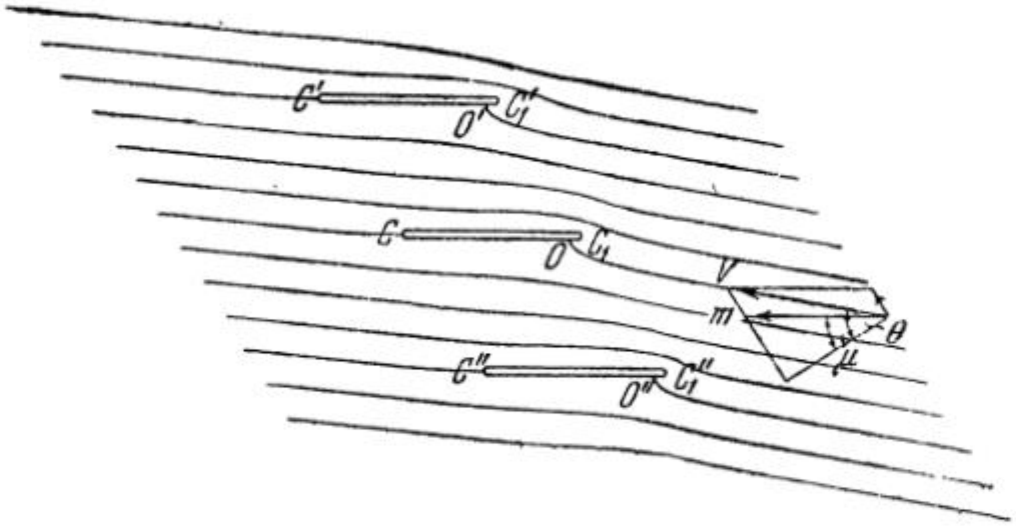


Blade element approach to the Vetchinkin’s rotor (Joukowsky 1914)

In the second article (1914), Joukowsky only described the method but he could not formulate a law for optimization

3rd article of “Vortex theory of screw propeller” (1915)

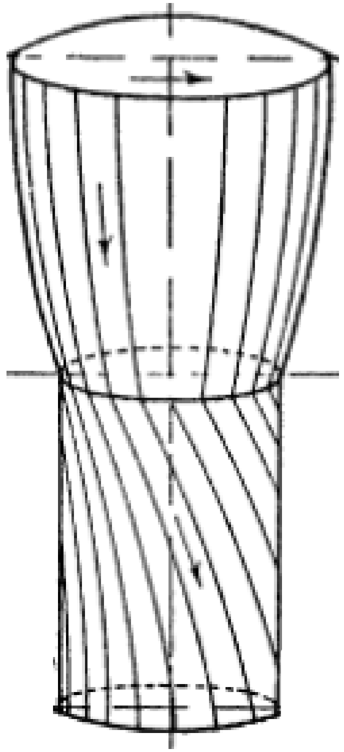




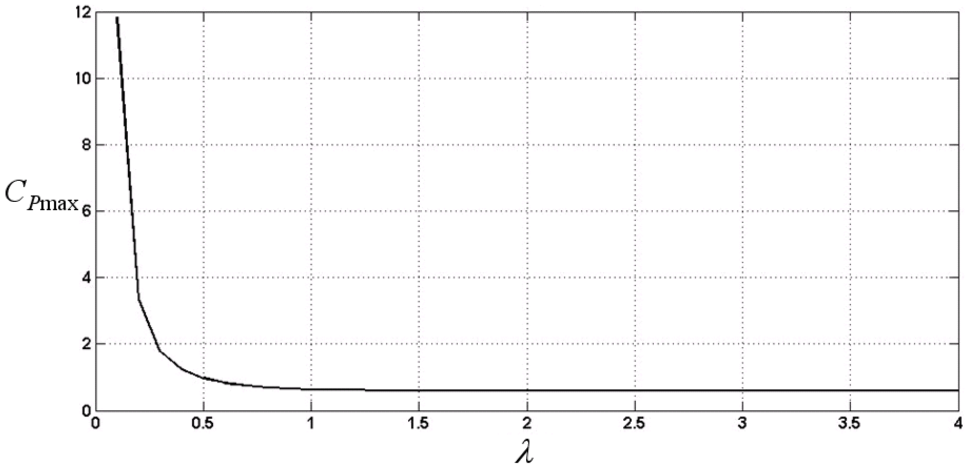
In the third article (1914), Joukowsky for the first time created the theory of hydrodynamical cascades using blade profiles

4th article of "Vortex theory of screw propeller" (1918)

The general momentum theory based on an understanding of the rotor flow from the vortex theory of the screw propeller has been formulated



Propeller case

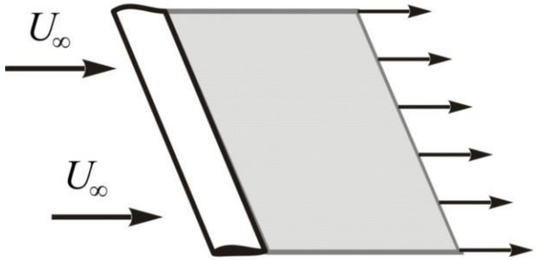


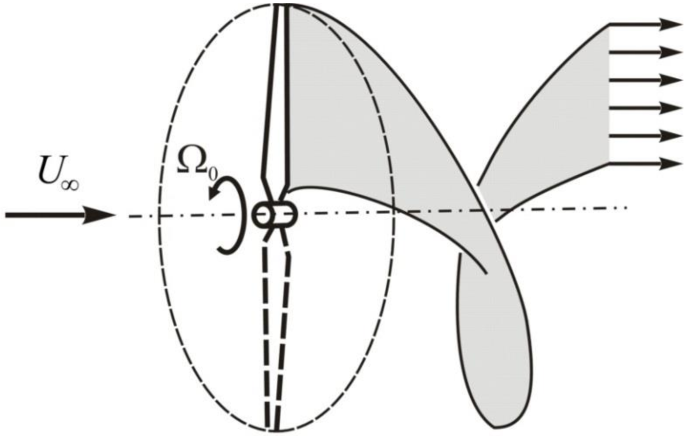
A partial case of the general theory for wind turbine rotor with constant circulation includes a paradox of infinite power for small tip speed ratio. This paradox has been discussed by Sørensen & van Kuik in (WE, 2011)

Rotor (vortex) theory of the German school (1919)

L. Prandtl

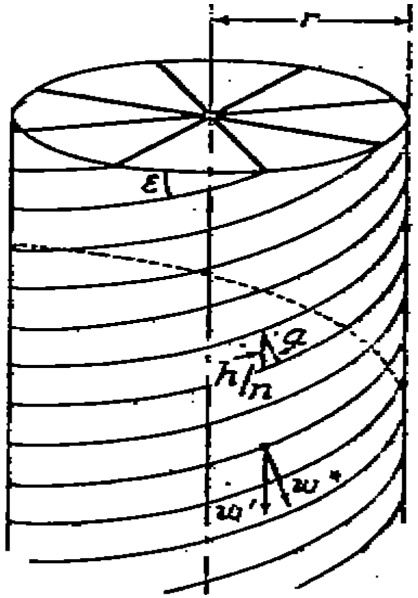
A. Betz
(pupil and successor of Prandtl)



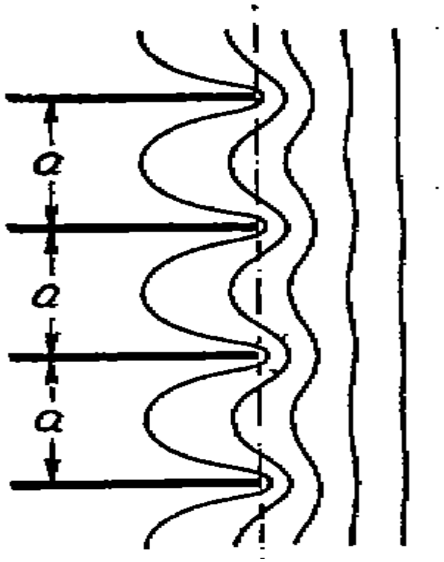


Betz rotor (vortex) theory was based on Prandtl's solution for a wing with an elliptical load distribution

Prandtl’s correction for finite number of blades (1919)



Idealized vortex system for screw propeller by Prandtl



Associative plane flow with the wake behind Betz rotor

In 1919, in an appendix of the dissertation of Betz, Prandtl introduced an approximate expression for the loading near the tip of a rotor with a finite number of blades. This was later used as tip correction in the BEM model.

Goldstein's solution for Betz rotor (1929)

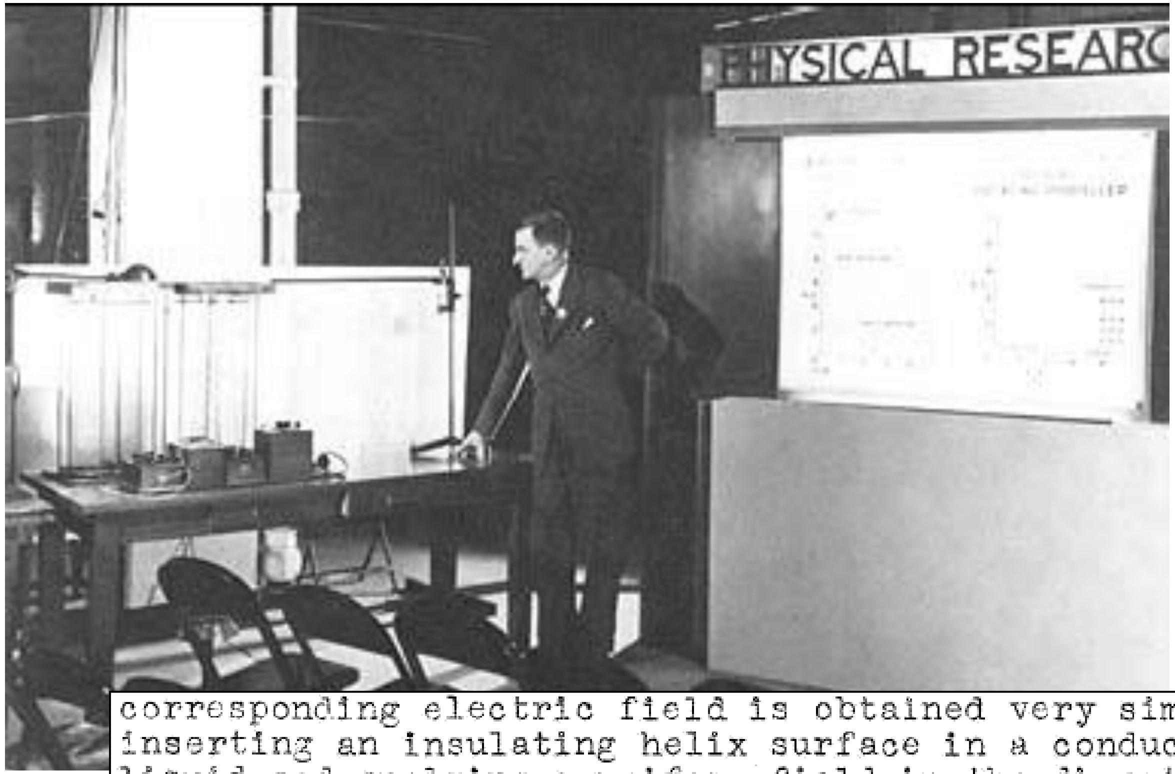
S. Goldstein

3.5. *The Determination of the Flow.*—The potential for the flow for $r \leqslant R$, $0 \leqslant \zeta \leqslant \pi$, is given by 3.1 (17), where the a_m have been determined to a sufficient approximation. Restoring the factor wv/ω, we may write, using 3.2 (8)

$$\begin{aligned}
\frac{\omega\phi}{wv} &= \frac{4}{\pi}\frac{\mu^2}{1+\mu^2}\sum_{m=0}^{\infty}\frac{\cos(2m+1)\zeta}{(2m+1)^2} - \frac{4}{\pi}\sum_{m=0}^{\infty}\frac{F_{2m+1}(\mu)}{(2m+1)^2}\cos(2m+1)\zeta \\
&\quad - \sum_{m=0}^{\infty}\left(\frac{\mu_0^2}{1+\mu_0^2}A_m - \varepsilon_m\right)\frac{I_{2m+1}(\overline{2m+1}\,\mu)}{I_{2m+1}(\overline{2m+1}\,\mu_0)}\cos(2m+1)\zeta \\
&= \frac{\mu^2}{1+\mu^2}\left(\tfrac{1}{2}\pi - \zeta\right) - \frac{4}{\pi}\sum_{m=0}^{\infty}\frac{F_{2m+1}(\mu)}{(2m+1)^2}\cos(2m+1)\zeta \\
&\quad - \sum_{m=0}^{\infty}\left(\frac{\mu_0^2}{1+\mu_0^2}A_m - \varepsilon_m\right)\frac{I_{2m+1}(\overline{2m+1}\,\mu)}{I_{2m+1}(\overline{2m+1}\,\mu_0)}\cos(2m+1)\zeta. \qquad (1)
\end{aligned}$$

Unfortunately his solution was very complex to simulate, and Theodorsen later used the electromagnetic analogy to design blades for the screw propeller

Theodorsen’s measurements for Betz rotor (1945)



corresponding electric field is obtained very simply by
inserting an insulating helix surface in a conducting
liquid and applying a uniform field in the direction of

Theodore Theodorsen prepares an electromagnetic equipment to give a talk on the physics of a four-blade propeller in 1945.

The Betz-(Joukowsky) limit (1920)

Contributions	Year and Scientist		
	British school	German school	Russian school
Actuator disc theory	1865 W. Rankine 1889 R.E. Froude		
		1904 Finsterwalder 1910 Bendemann	
			1912 Sabinin 1913 Vetchinkin 1917 Bothezat 1918 Joukowsky
		1919 Prandtl	
Development of the actuator disc theory based on wrong approaches by Parsons, etc.[a]	*1911 Parsons*[b] *1915 Lanchester*[b]		
			1927 Sabinin
Corroboration of the actuator disc theory by the vortex theory			1913 Joukowsky
		1919 Betz	
Expansion of the actuator disc theory to wind turbines and formulation of the limit for the power coefficient			February 1920 Joukowsky
		August 1920 Munk September 1920 Betz July 1921 Hoff	

[a]The erroneous theories are indicated in italic.
[b]Corrections made here after initial publication.

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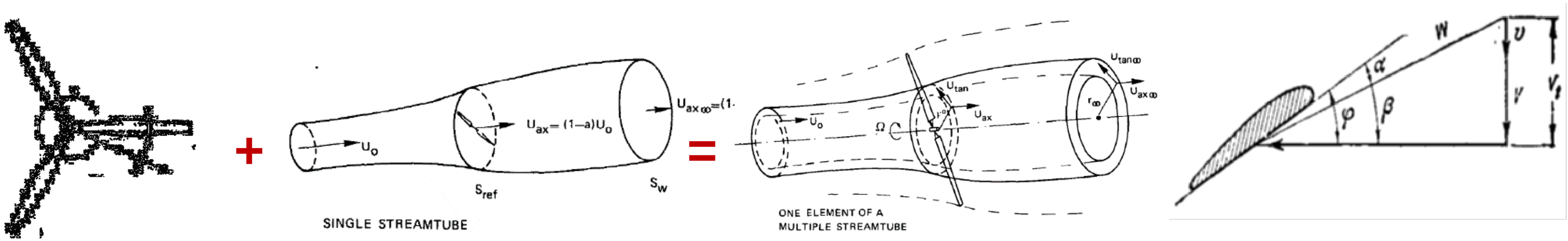
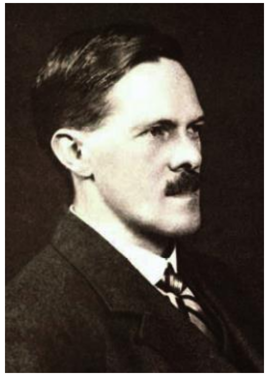
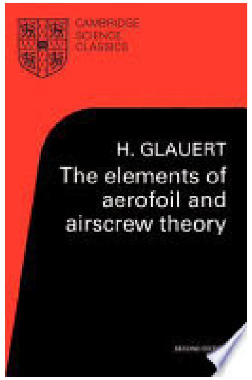
Blade-element/momentum (BEM) theory



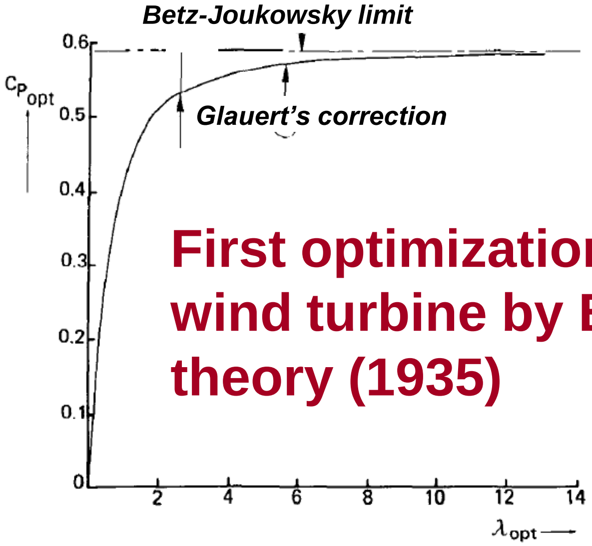
The first combination was made in Russia (Sabinin & Yuriev, 1912), then in Germany (Betz, 1915) and later in U.K (Fage & Collins, 1919). Finally, Glauert wrote a complete description of the BEM theory, including tip and yaw corrections.



H. Glauert (1892-1934)



Glauert (1926)



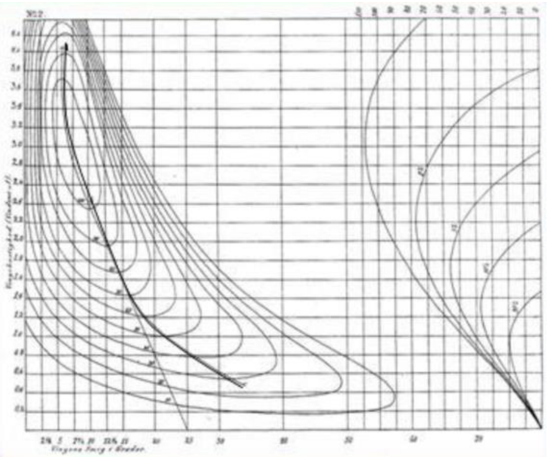
First optimization of wind turbine by BEM theory (1935)

Glauert, H. (1935) Airplane Propellers. In: Durand, W.F., Ed., Aerodynamic Theory, Springer Verlag, Berlin.

Poul La Cour (1846-1908):
A Danish physicist and wind power pioneer

- La Cours main contribution to wind turbine aerodynamics was his experimental investigations, using wind tunnels, full scale measurements, control (the ‘Krotostat’), and storage (hydrogen)
- La Cour’s work was ackowledged by Betz in the foreword to his text book ‘Wind-Energie’
- La Cour was aware of the aerofoil aerodynamics (the suction force), but could not explain it theoretically
- He based his optimum design on blade-element theory, but did not include the induced velocity

The ‘Research Center’, Askov, 1897



Design of the ideal rotor blade

Group photo (1904) from Landelektrikeruddannelsen

The modern development of wind turbine aerodynamics

Assumptions in BEM, as described at the end of the '70's:	Reality
Steady flow	Unsteady flow: Turbulent wind, Control actions, system vibrations
Axially symmetric conditions	Always yawed flow, giving rise to unsteadiness and non uniform induction
Approximately 2D sectional flow because of slender blades, comparable to slender wings	Rotating blades cause large 3D effects especially in stall
No radial interdependence	Especially in yawed flow ridiculous

H. Snel: 'From Betz to Better', Torque conference, Lyngby, 2007

Major breakthroughs since the 1970's

- 1973: State-of-the-art publications by Wilson & Lissamann (1974) and O. de Vries (1979)
- 1980: Development of aero-elastic design tools
- 1980: Extended BEM engineering models (3D effects, yaw, dynamical stall, unsteady inflow)
- 1985: Free wake vortex models
- 1990: Design of tailormade wind turbine aerofoils
- 2000: First CFD computations of wind turbine rotor
- 2000: NREL/NASA AMES 'full-scale' wind tunnel experiment
- 2006: Opening of LM Global R&D Wind Tunnel
- 2007: Modeling of floating wind turbines
- 2010: Aeroelastic tailoring (flap/twist coupling)
- 2010: Detailed modeling of aerodynamic devices (flaps, VG's, etc)
- 2014: Modeling of airborne wind turbines
- Future challenges: Laminar/turbulent transition, 3D stall, compressibility,
  high Reynolds number aerodynamics, vortex-induced vibrations

Stamps as evidence of the history of wind power

Denmark

U.S.A.

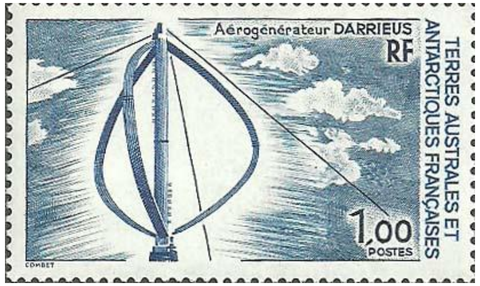
China

Tuvala

Sweden

Argentina

Canada



France

The Netherlands