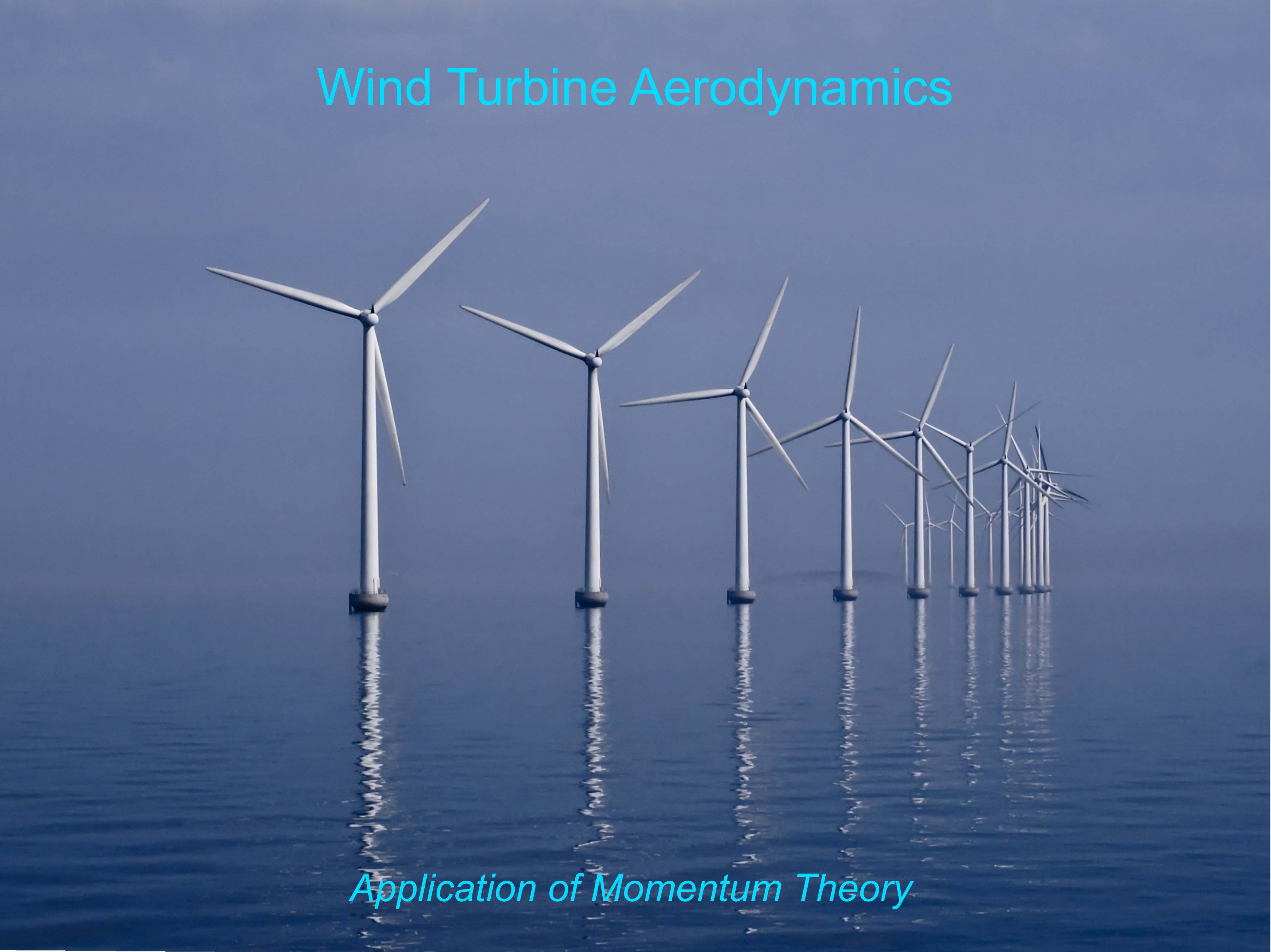
Wind Turbine Aerodynamics



Application of Momentum Theory

Recommended Reading

Hansen, Martin O.L. (2008). Aerodynamics of Wind Turbines (2nd Edition). Earthscan.

1. GeneGeneral Introduction to Wind Turbines
4. 1-D Momentum Theory for an Ideal Wind Turbine

Online version available at:
http://app.knovel.com/hotlink/toc/id:kpAWTE0001/aerodynamics-wind-turbines

Burton, Tony Sharpe, David Jenkins, Nick Bossanyi, Ervin (2001). Wind Energy Handbook. John Wiley & Sons.

1. Introduction
2. The Wind Resource
3. Aerodynamics of Horizontal-AxisWind Turbines
    - 3.1 Introduction
    - 3.2 The Actuator Disc Concept
    - 3.6 Breakdown of the Momentum Theory
4. Wind-turbine Performance
    - 4.1 The Performance Curves
    - 4.2 Constant Rotational Speed Operation
    - 4.3 Comparison of Measured with TheoreticalPerformance

Online version available at:
http://app.knovel.com/hotlink/toc/id:kpWEH00005/wind-energy-handbook

Recommended Reading

Sorensen, John D. Sorensen, Jens N. (2011). Wind Energy Systems - Optimising Design and Construction for Safe and Reliable Operation. Woodhead Publishing.

4. Wind turbine wakes and wind farm aerodynamics
    - 4.1 Introduction
    - 4.2 One-dimensional momentum theory
    - 4.4 Computational fuid dynamics modelingof wind turbine rotors
    - 4.5 Wind farm aerodynamics
    - 4.6 Simulation of fow and turbulence in wind farms
    - 4.7 Future trends

Online version available at:
http://app.knovel.com/hotlink/toc/id:kpWESODCS2/wind-energy-systems-optimising

Codes

https://bsol.bsigroup.com/en/BsolHomePage/

BS EN 61400-1:2005 "Wind turbines — Part 1: Design requirements"
BS EN 61400-2:2006 "Wind turbines — Part 2: Design requirements for small wind turbines"
BS EN 61400-3:2009 "Wind turbines — Part 3: Design requirements for offshore wind turbines"

All sorts of stuff

http://www.homepages.ucl.ac.uk/~uceseug/Fluids2/Wind_Turbines/

e.g

Report based on real data from Blyth Wind Farm:

.../Codes_and_Manuals/DesignMethodsReport.pdf

Norwegian Design Code:

.../Codes_and_Manuals/os-j101.pdf

Review on Wake Aerodynamics:

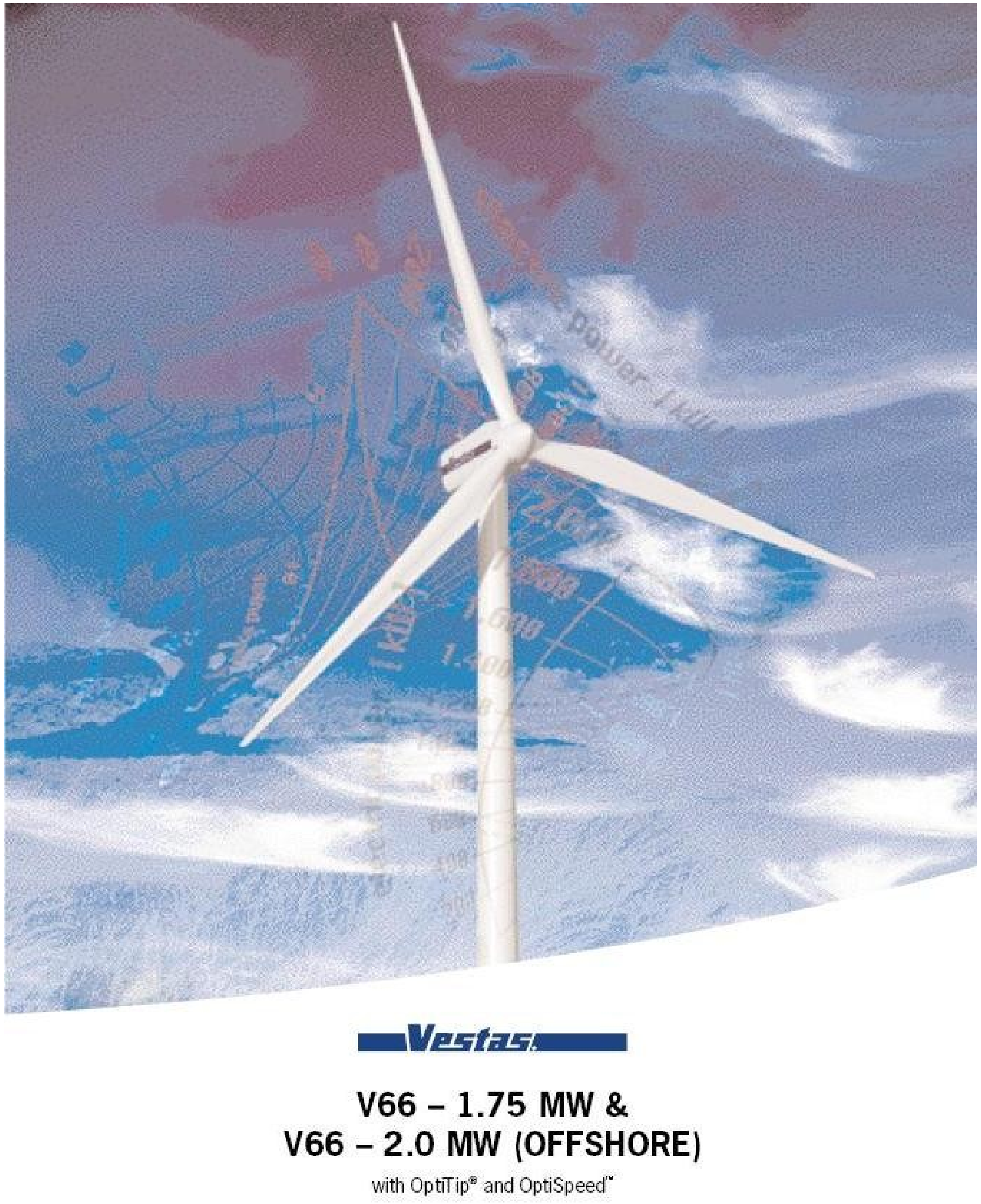
.../Papers/Review_3.pdf

Original paper on Jensen wake model:

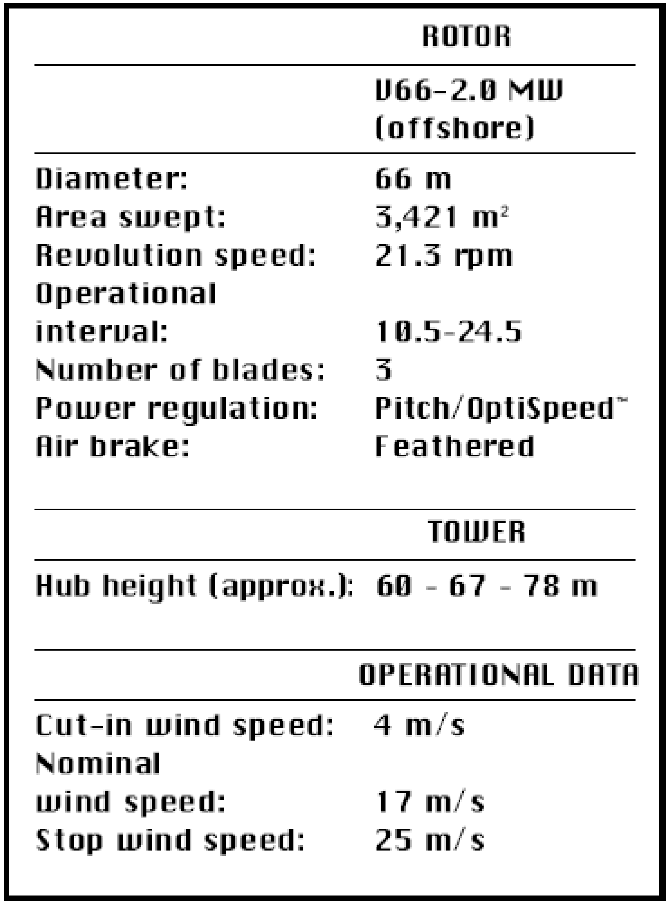
.../Papers/Paper_3.pdf

Etc...

A Typical Offshore Wind Turbine

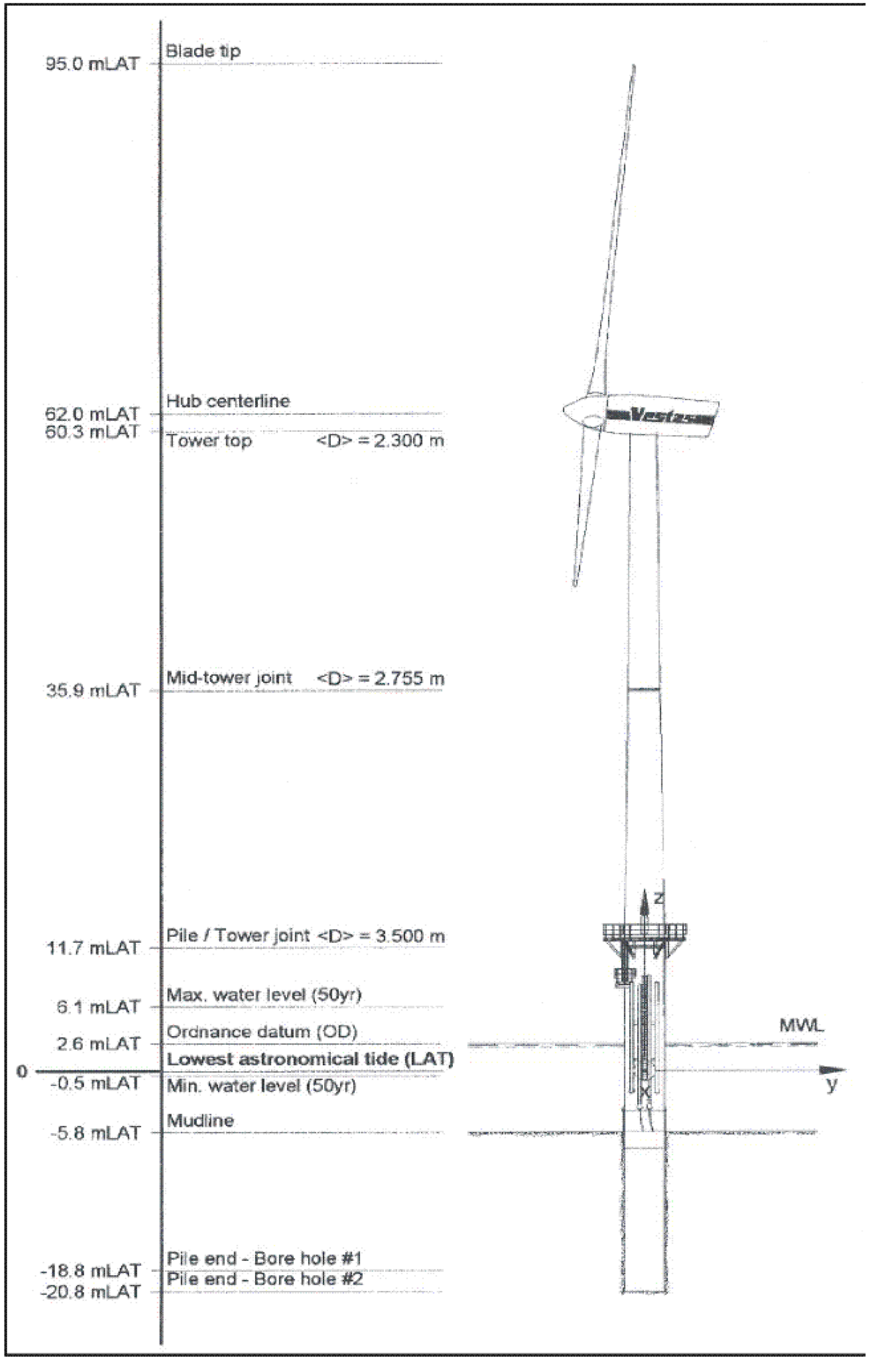


V66 – 1.75 MW &
V66 – 2.0 MW (OFFSHORE)
with OptiTip® and OptiSpeed™

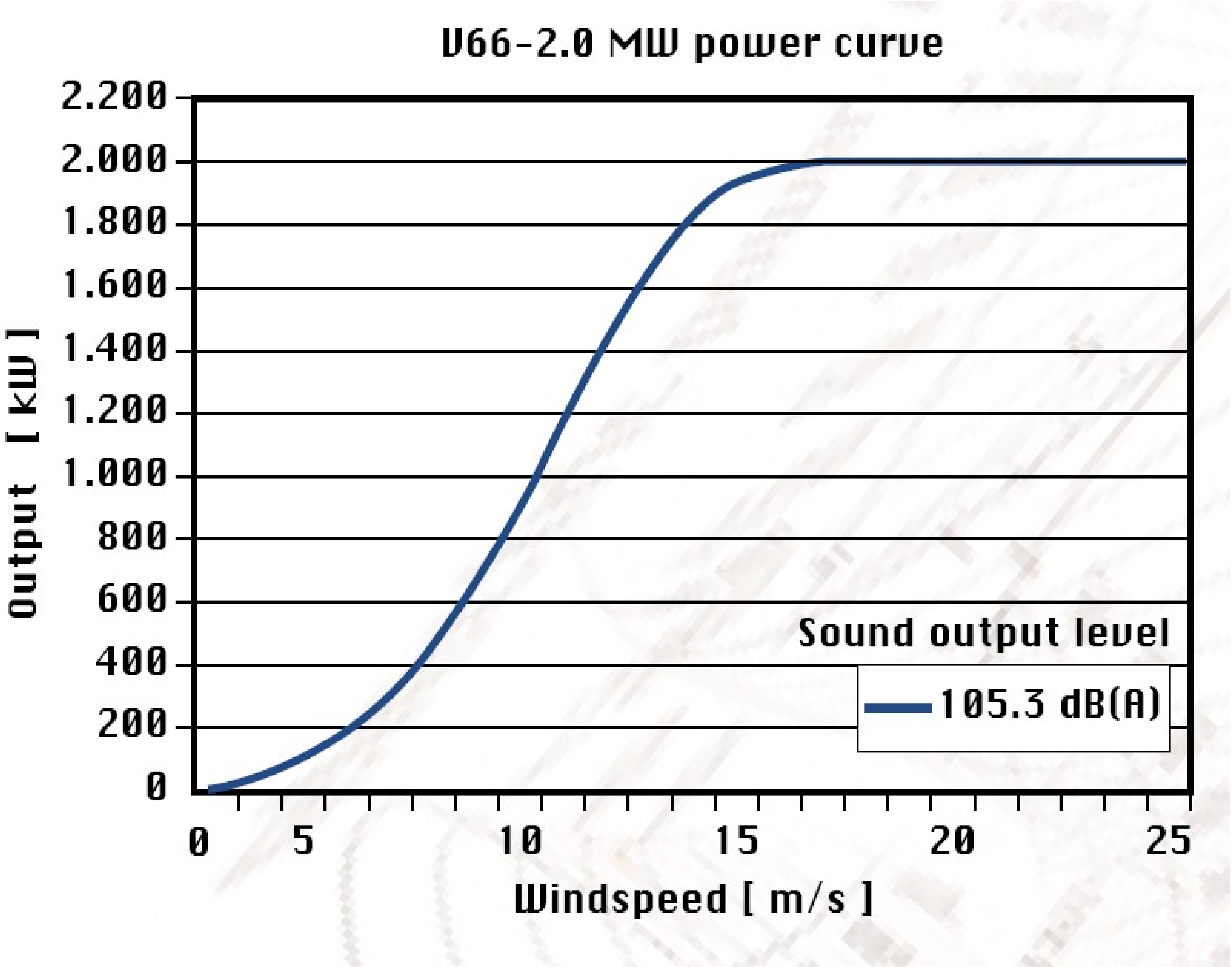


	ROTOR
	V66-2.0 MW (offshore)
Diameter:	66 m
Area swept:	3,421 m^2
Revolution speed:	21.3 rpm
Operational interval:	10.5-24.5
Number of blades:	3
Power regulation:	Pitch/OptiSpeed™
Air brake:	Feathered
	TOWER
Hub height (approx.):	60 - 67 - 78 m
	OPERATIONAL DATA
Cut-in wind speed:	4 m/s
Nominal wind speed:	17 m/s
Stop wind speed:	25 m/s

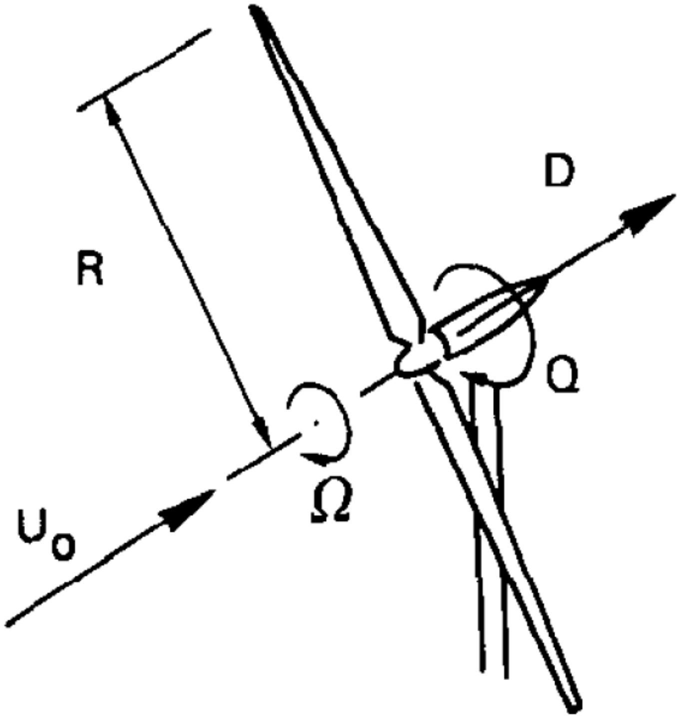
A Typical Offshore Wind Turbine



A Typical Offshore Wind Turbine



Non-dimensional Parameters



$\lambda = \Omega R / U_0$ (tip-speed ratio),

$C_Q = Q / (\frac{1}{2} \rho U_0^2 R S_{ref})$ (torque coefficient),

$C_P = P / (\frac{1}{2} \rho U_0^3 S_{ref})$ (power coefficient),

$C_D = D / (\frac{1}{2} \rho U_0^2 S_{ref})$ (rotor-drag coefficient)

N (number of blades)

$Re = U_0 R / \mu$ (Reynolds number)

Actuator Disk Theory

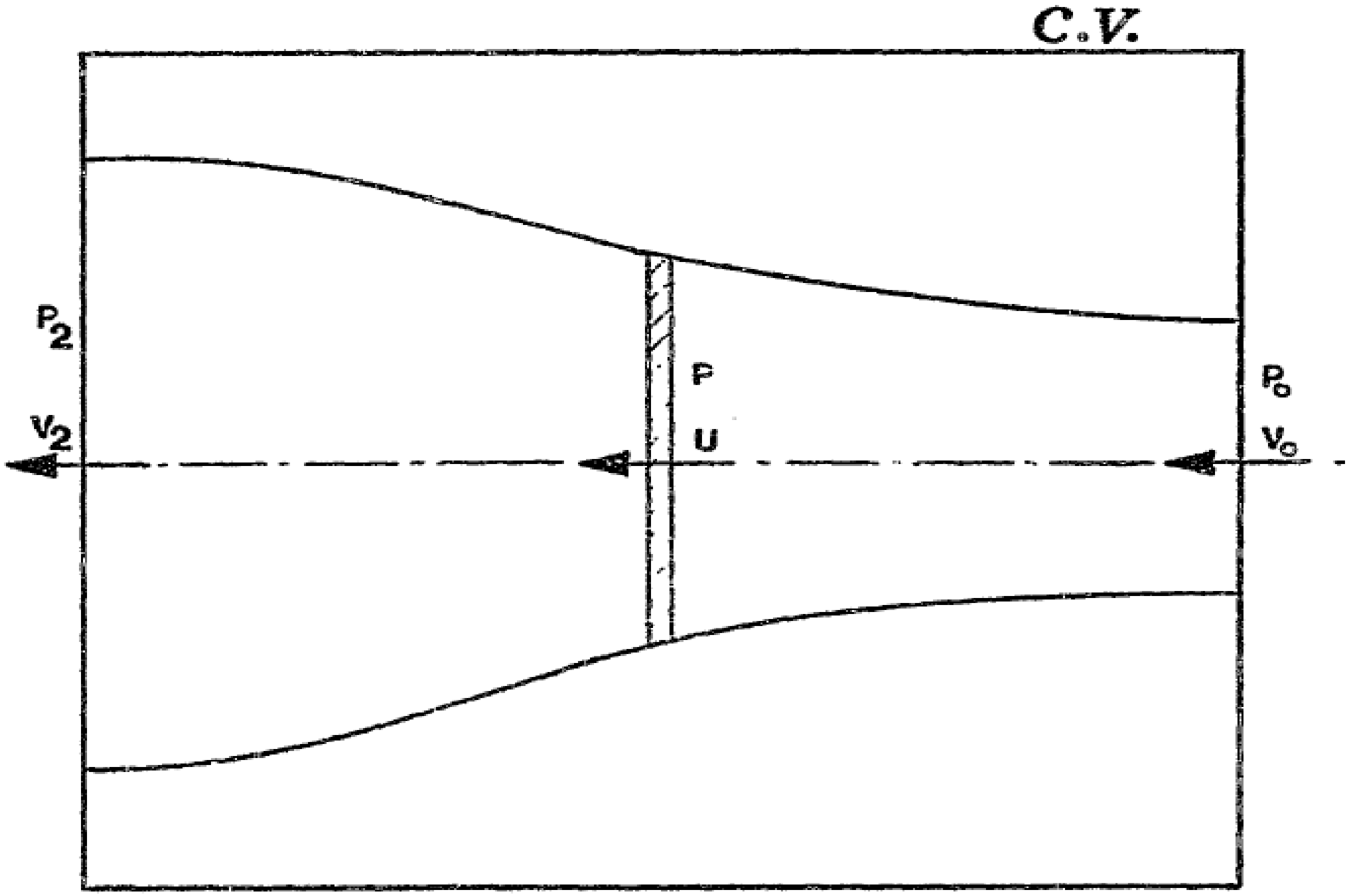
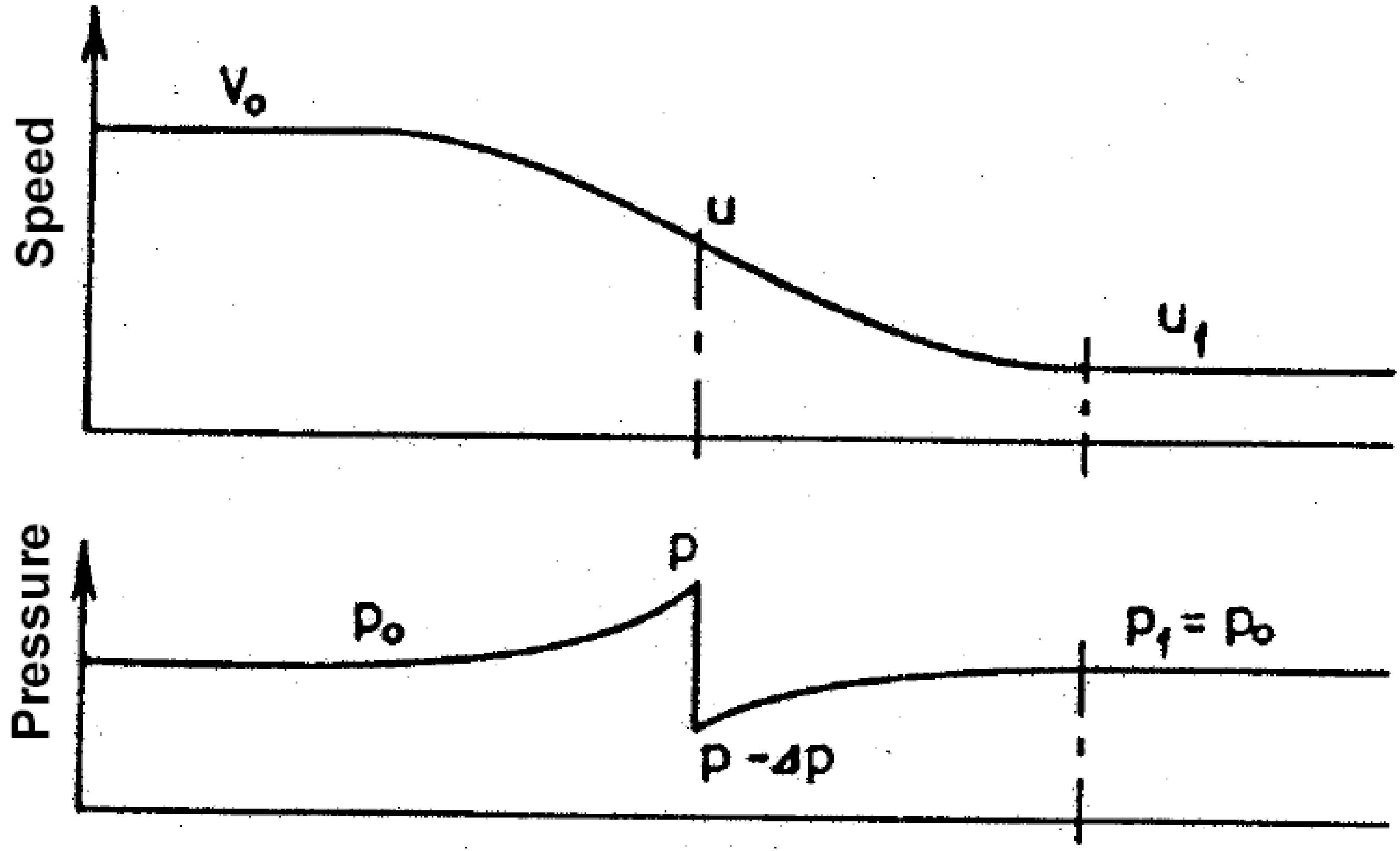


Fig. A-1 The flow field and control volume for momentum theory

Axial induction factor: $a = (V_0 – U) / V_0$

Actuator Disk Theory



Actuator Disk Theory

Power coefficient

$$C_P = \frac{\text{Power}}{\frac{1}{2}\rho U_\infty^3 A_\text{d}} \qquad C_P = 4a(1-a)^2$$

The maximum value of C_P occurs when

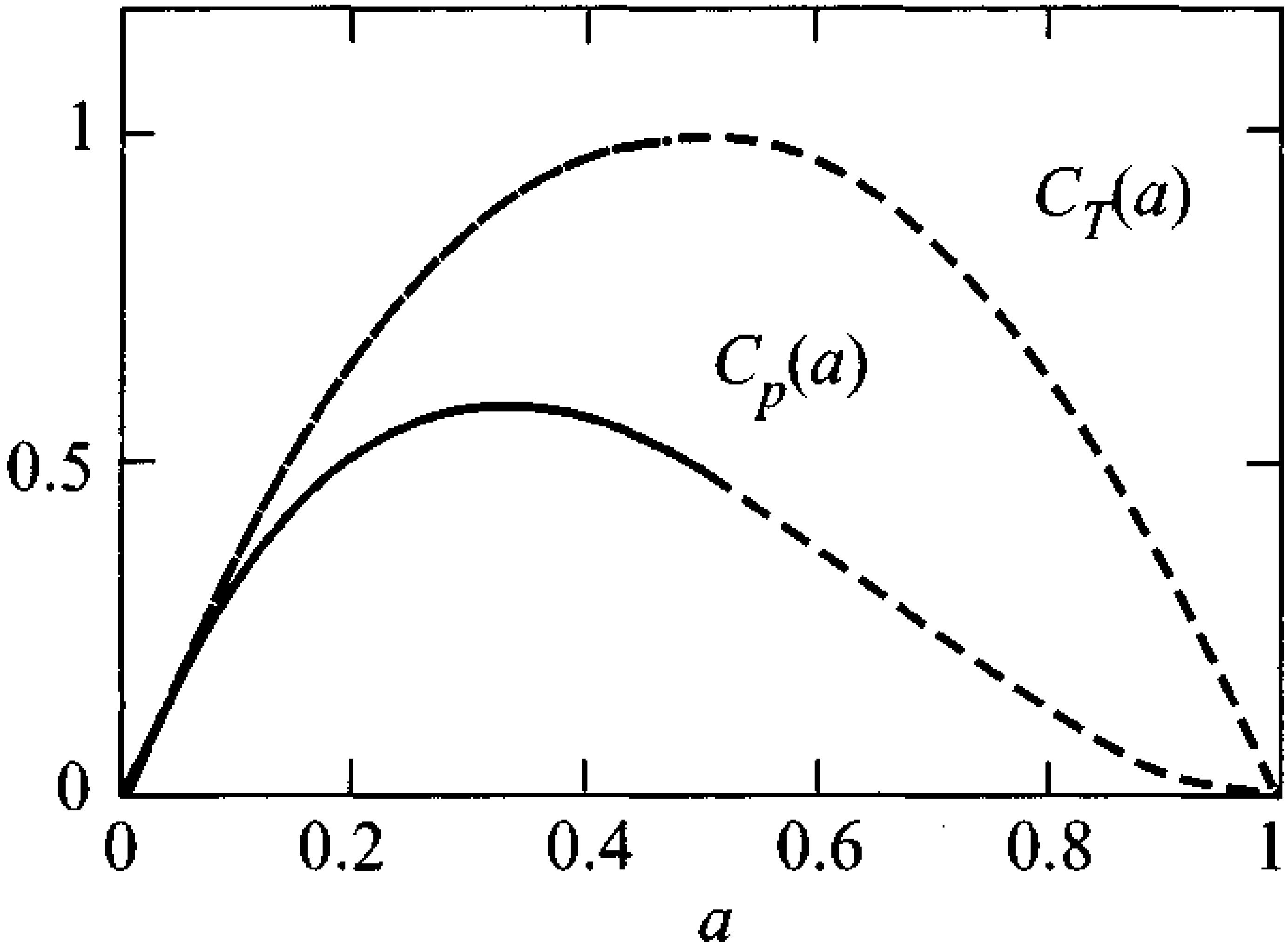
$$\frac{\mathrm{d}C_P}{\mathrm{d}a} = 4(1-a)(1-3a) = 0$$

The Betz limit $\quad C_{P_\text{max}} = \frac{16}{27} = 0.593$

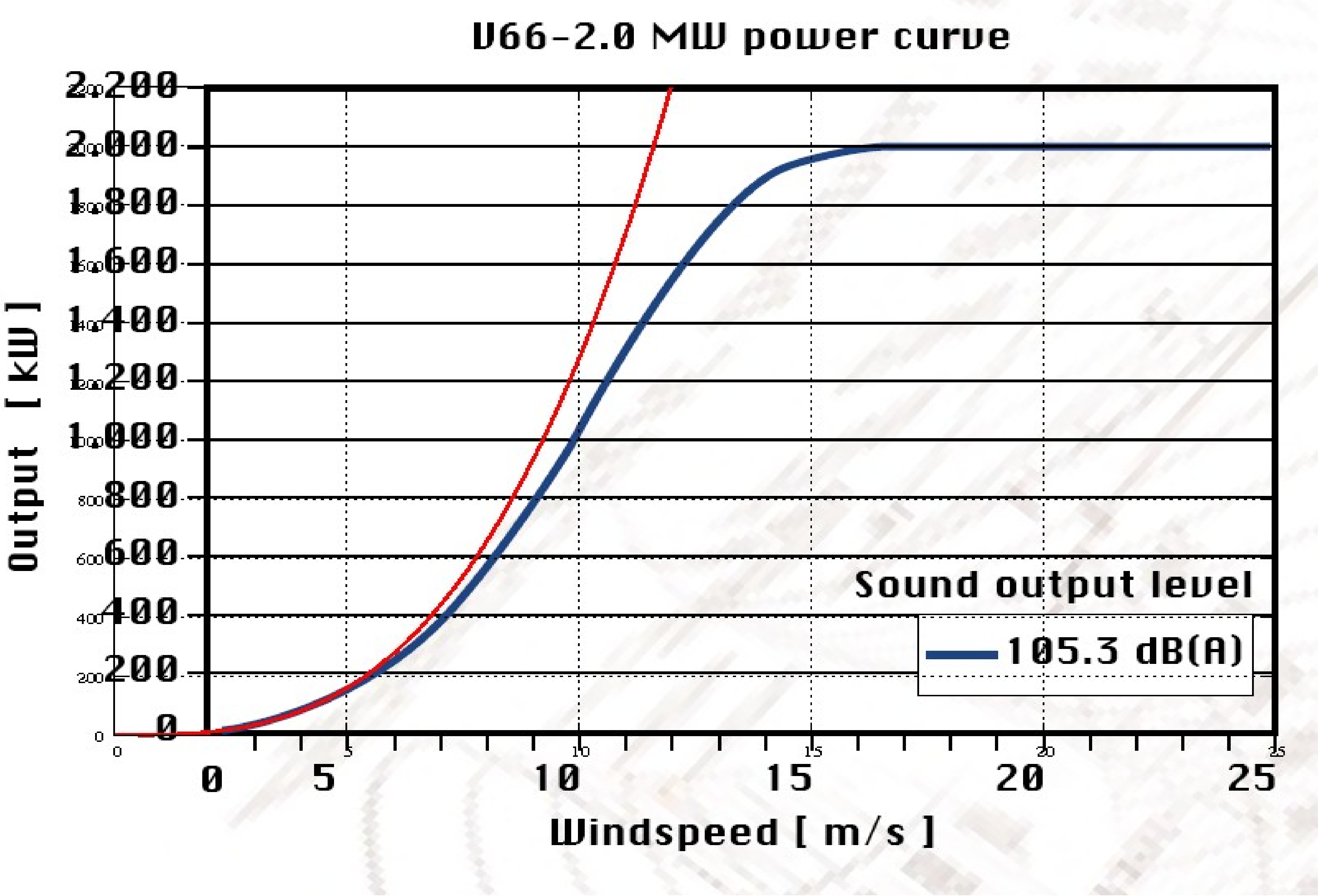
The thrust coefficient

$$C_T = \frac{\mathit{Thrust}}{\frac{1}{2}\rho U_\infty^2 A_\text{d}} \qquad C_T = 4a(1-a)$$

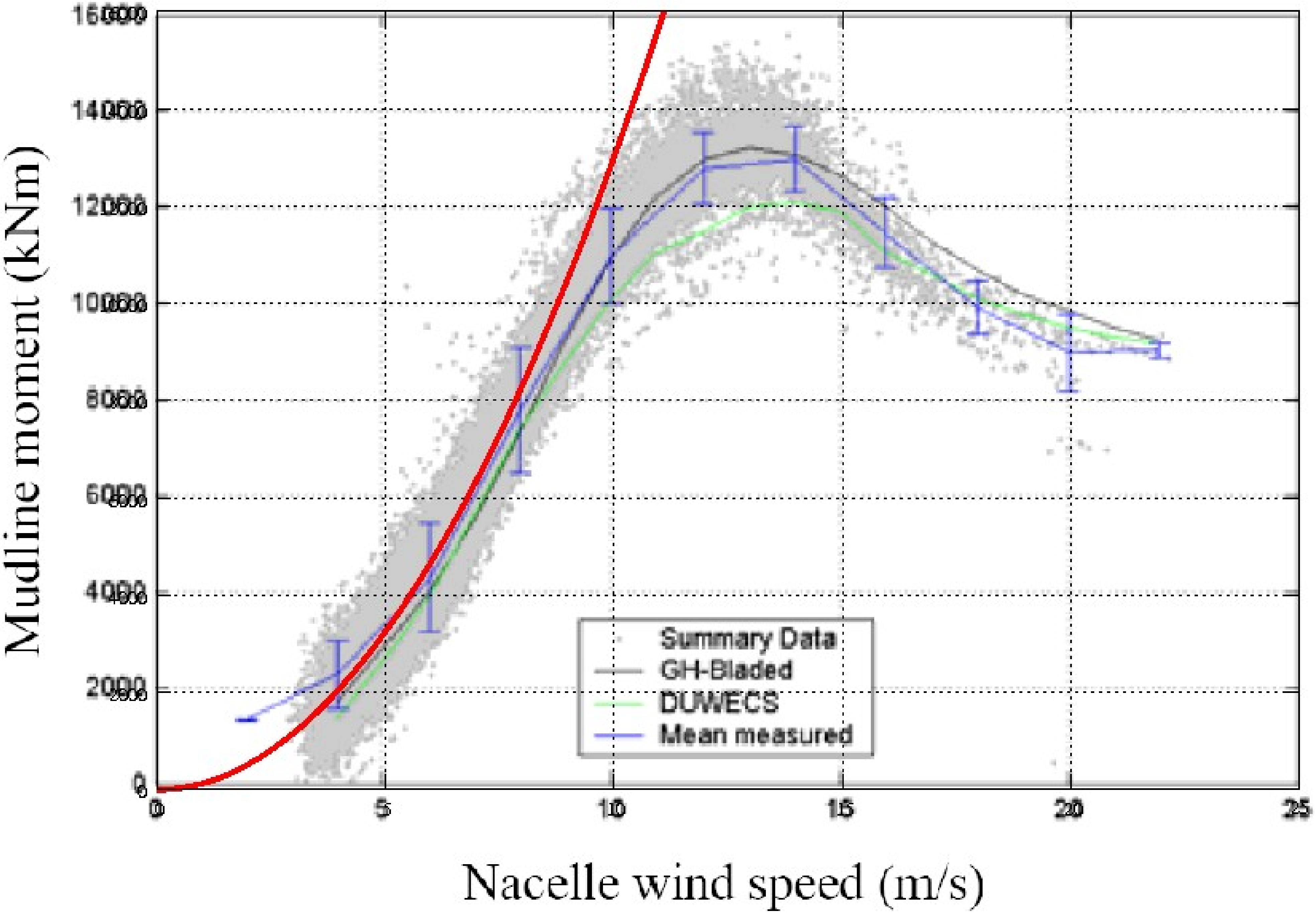
Actuator Disk Theory



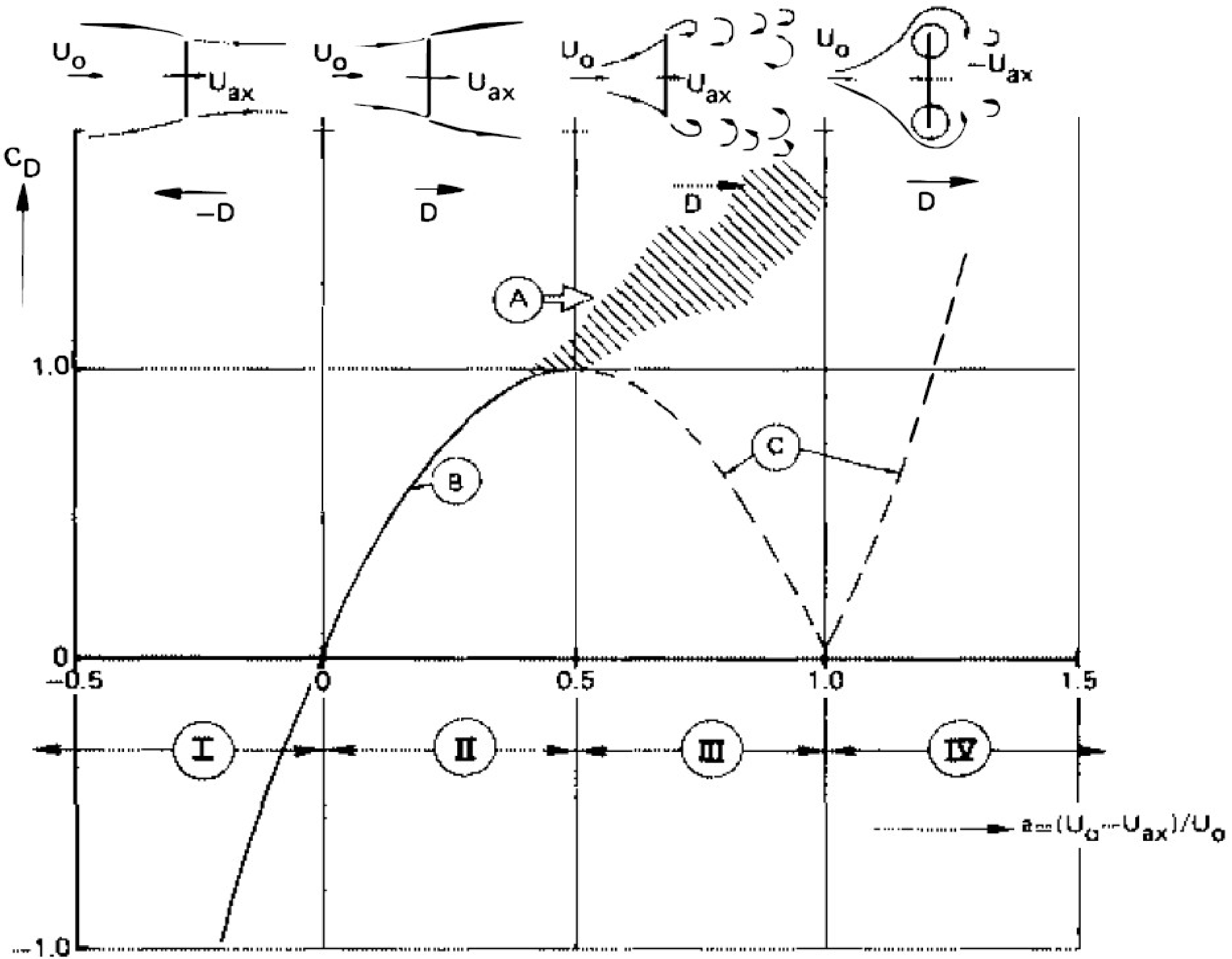
Theory vs Reality



Theory vs Reality

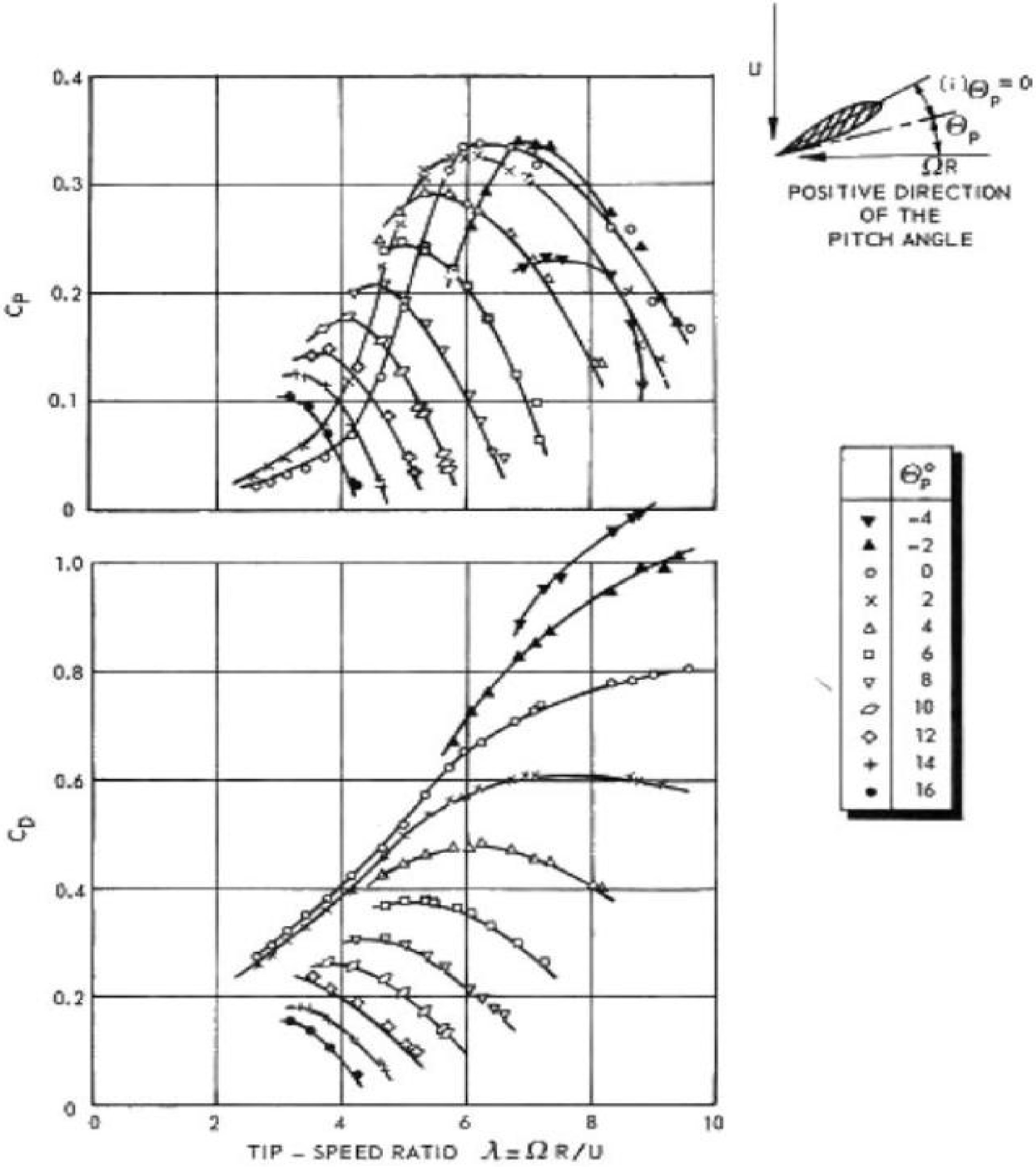


Theory Validity



Ann. Rev. Fluid Mech. 1983. 15:77–96

Real Turbine Performance



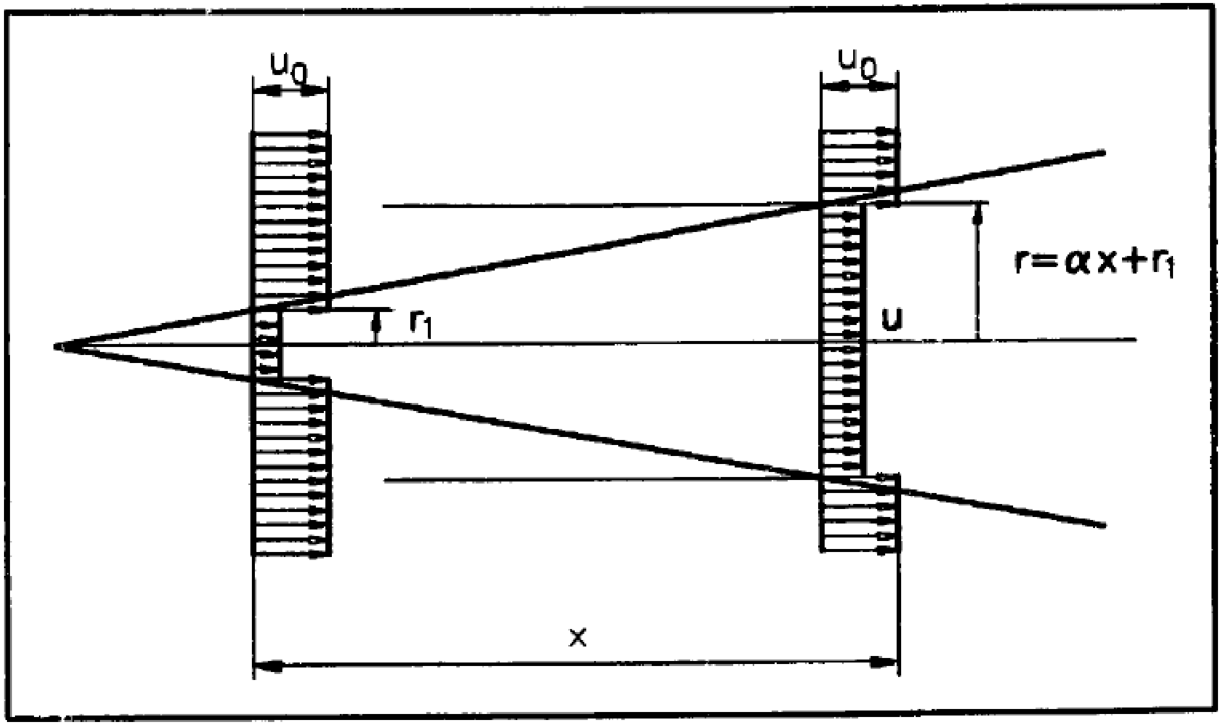
Problem 1

Estimate the maximal mudline moment generated by the rotor of an Vestas V66 2MW turbine for operational conditions. Compare your estimate with site measurements and discuss valifity of your solution. Suggest a method of improving your result.

Wind Farms and Wake Effects

Wake Model

Jensen wake model



momentum is conserved in the wake

$$u=u_0\left[1-2a\left(\frac{1}{1+\alpha(x/r_1)}\right)^2\right]$$

r_1 – *downstream* radius of Betz' stream tube

a – induction factor

u_0 – upstream flow speed

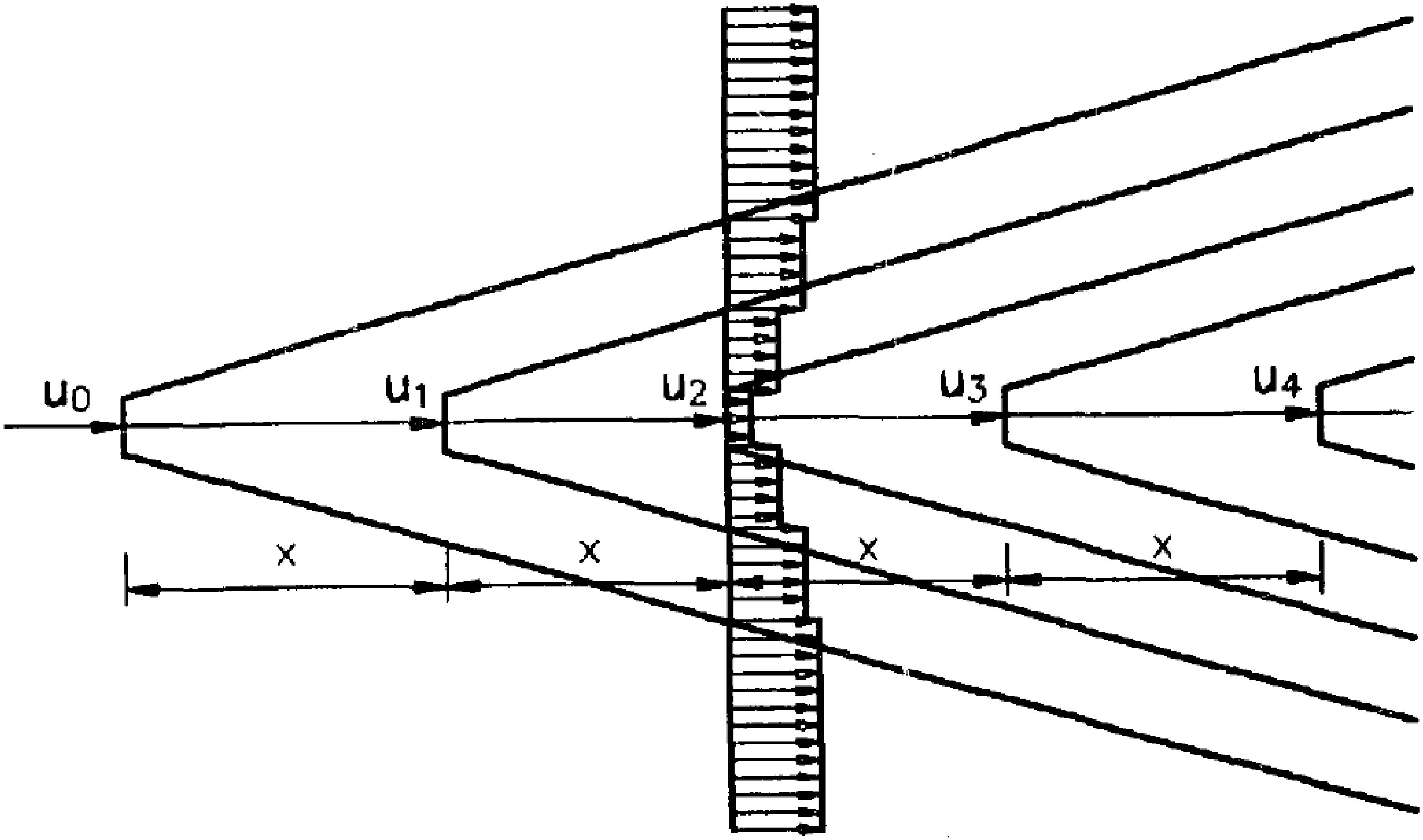
α – momentum entrainment constant

$$\alpha = 0.5/\ln(h/z_0)$$

h is hub height z_0 is surface roughness

$\alpha = 0.04$ for offshore systems

Multiple Wakes



Problem 2

A Blyth offshore wind farm consists of 2 Vestas V66 2MWt wind turbines placed 500 meters apart. Estimate the reduction of power generated by the wind farm when the wind blowing at 17m/s changes direction from *A* to *B* (Figure 1). Discuss the accuracy of your estimate and factors which could affect your result.