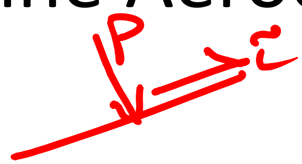
Wind Turbine Aerodynamics



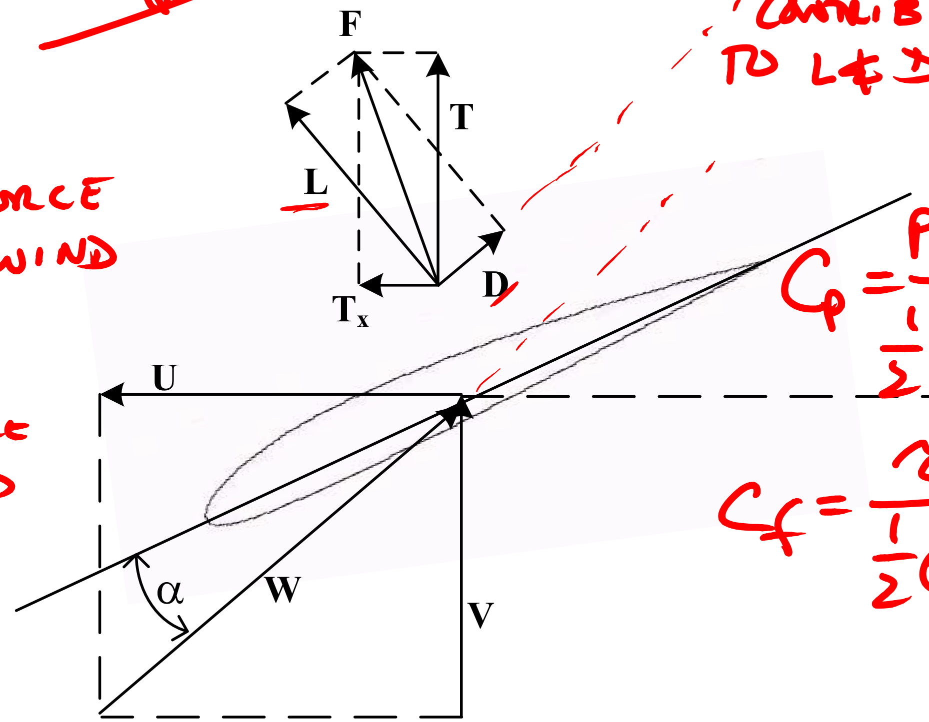
PRESSURE & SHEAR STRESS CONTRIBUTE TO L & D

D. Blade Aerodynamics

1. Terminology

LIFT - COMPONENT OF FORCE PERPENDICULAR TO WIND DIRECTION W

DRAG - COMPONENT OF FORCE PARALLEL TO WIND DIRECTION W



$$C_p = \frac{P - P_\infty}{\frac{1}{2}\rho W^2}$$

$$C_f = \frac{\tau}{\frac{1}{2}\rho W^2}$$

NON-DIMENSIONAL FORM

$$C_L = \frac{L/\ell}{\frac{1}{2}\rho W^2 c}$$

$$C_D = \frac{D/\ell}{\frac{1}{2}\rho W^2 c}$$

U - BLADE ROTATION VELOCITY $U = \Omega r$

V - WIND INFLOW VELOCITY AT ROTOR

W - RELATIVE FLUID VELOCITY w.r.t. BLADE

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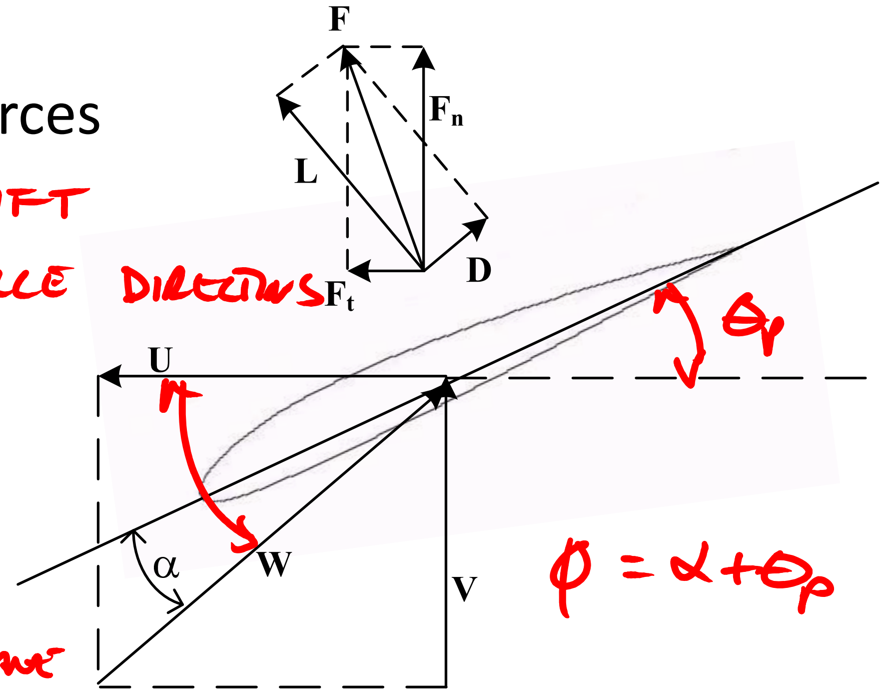
D. Blade Aerodynamics

2. Lift, Drag and Related Forces

FROM BLADE'S PERSPECTIVE, LIFT & DRAG ARE "NATURAL" FORCE DIRECTIONS



FOR A WIND TURBINE

FORCE IN ROTOR PLANE

F_t - TANGENTIAL FORCE

FORCE NORMAL TO ROTOR PLANE

F_N - NORMAL FORCE

$\phi = \alpha + \theta_p$

RELATIONSHIP AMONG FORCES

$$F_N = L\cos\phi + D\sin\phi$$

$$F_T = L\sin\phi - D\cos\phi$$

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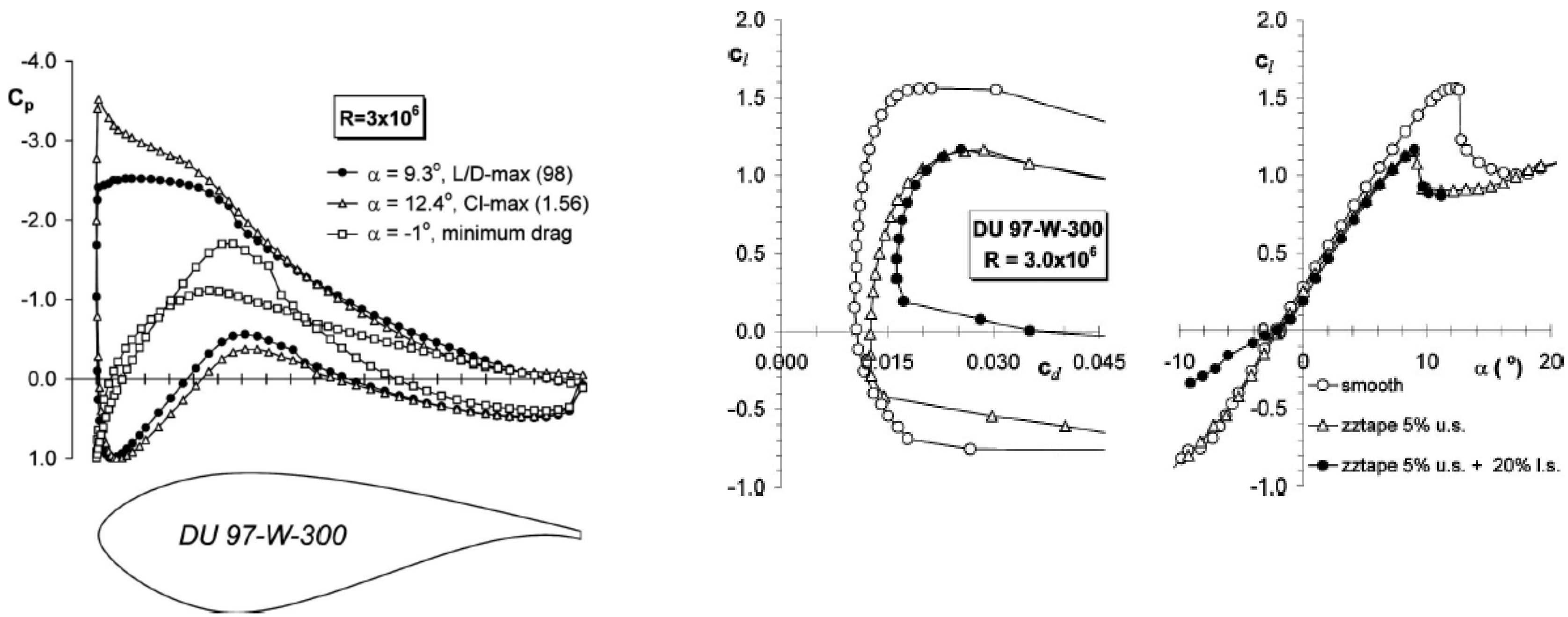
2. Lift, Drag and Related Forces

Source:
Timmer and Rooij
J. Solar Energy Engineering
Vol. 125, November 2003



LIFT & DRAG CHARACTERISTICS DETERMINED BY STATICALLY AT KNOWN ANGLES OF ATTACK

Wind Turbine Aerodynamics

D. Blade Aerodynamics

3. Boundary Layers and Stall

REGION NEAR A SURFACE WHERE VISCOUS EFFECTS ARE IMPORTANT

$$Re_x = \frac{\rho U_\infty x}{\mu} = \frac{U_\infty x}{\nu}$$

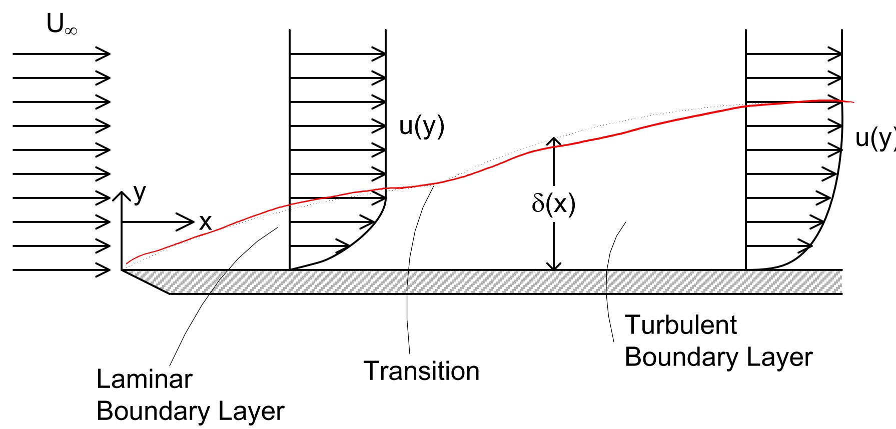
laminar boundary layer $\rightarrow$ transition $\rightarrow$ turbulent boundary layer

$\mathrm{Re}_x < 2 \times 10^4$ $\quad$ $\mathrm{Re}_x > 3 \times 10^6$

LIMITED TO HIGH Re FLOWS

$$\delta = y \quad \text{where} \quad u = 0.99 U_\infty$$

BOUNDARY LAYER THICKNESS



$$\delta^* = \int_0^\infty \left(1 - \frac{u}{U_\infty}\right) dy$$

DISPLACEMENT THICKNESS

REYNOLDS NUMBERS ON TURBINE BLADES IS VERY HIGH $\sim 6\times10^6$

$Re_c \sim 1\times10^5 - 2\times10^6$

$$\theta = \int_0^\infty \frac{u}{U_\infty}\left(1 - \frac{u}{U_\infty}\right) dy$$

MOMENTUM THICKNESS

LAMINAR, TRANSITIONAL, & FULLY TURBULENT FLOW

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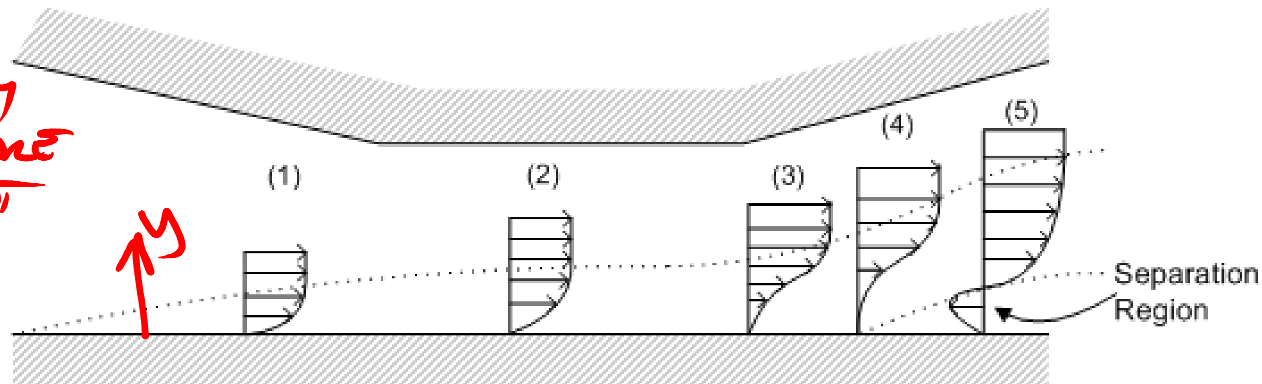
3. Boundary Layers and Stall

BOUNDARY LAYERS BEHAVE DIFFERENTLY DEPENDING ON PRESSURE GRADIENT



FAVORABLE PRESSURE GRADIENT

$$\frac{dP}{dx} < 0$$

ADVERSE PRESSURE GRADIENT

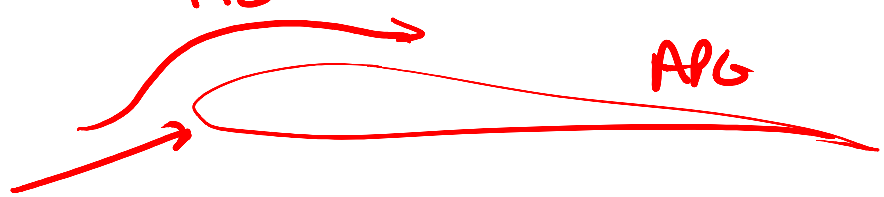
$$\frac{dP}{dx} > 0$$

ZERO PRESSURE GRADIENT

$$\frac{dP}{dx} = 0$$

SEPARATION

$$\left.\frac{du}{dy}\right|_w = 0 \ \& \ \tau_w = 0$$



APG GETS WORSE AS α INCREASES
LEADS TO SEPARATION

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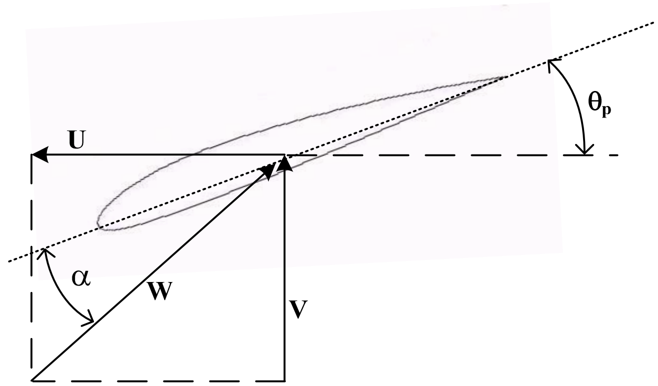
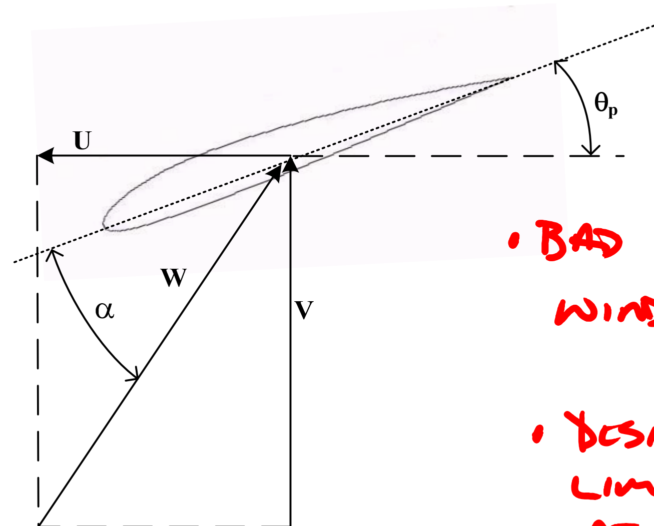
4. Various Effects on Angle of Attack

a. Variations in Wind Speed

IF α INCREASES ABOVE α_{STALL}, AIRFOIL COULD STALL





• BAD AT LOW WIND SPEEDS

• DESIGN TO LIMIT LOAD AT HIGH V BY STALLING

INCOMING WIND VELOCITY CHANGES

INCREASE IN V CAUSES INCREASE IN α

DECREASE DECREASE

WIND SPEED INCREASE THROUGH SHEAR

CHANGES IN WIND SPEED

GUSTS

STALL-REGULATED TURBINE