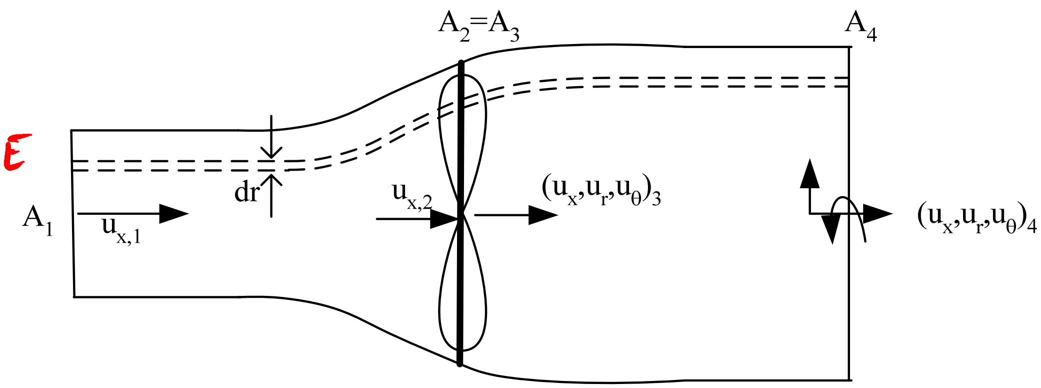
Wind Turbine Aerodynamics

C. Wake Rotation Effects

1. Theory



NON-DIMENSIONALIZE TO DETERMINE INCREMENTAL POWER COEFFICIENT

$$dC_p = \frac{dP}{\frac{1}{2}\rho A_2 U_{1,x}^3}$$

$$dC_p = 8a'(1-a)\frac{\lambda_r^3}{\lambda^2}\,d\lambda_r$$ ← INTEGRATE TO DETERMINE C_p

NEED RELATIONSHIPS AMONG a', a, λ_r

OUR INTEREST IS MAXIMUM POWER → MAXIMIZE $(1-a)a'$

APPROACH

1) DEFINE $f = a'(1-a)$

2) DIFFERENTIATE w.r.t. a & SET $= 0$

$$\frac{df}{da} = (1-a)\frac{da'}{da} - a' = 0$$

YIELDS

$$\frac{da'}{da} = \frac{1-2a}{1+2a'}\frac{1}{\lambda_r^2}$$

3) NEED $\frac{da'}{da}$ → USE $\lambda_r^2 a'(1+a') = a(1-a)$

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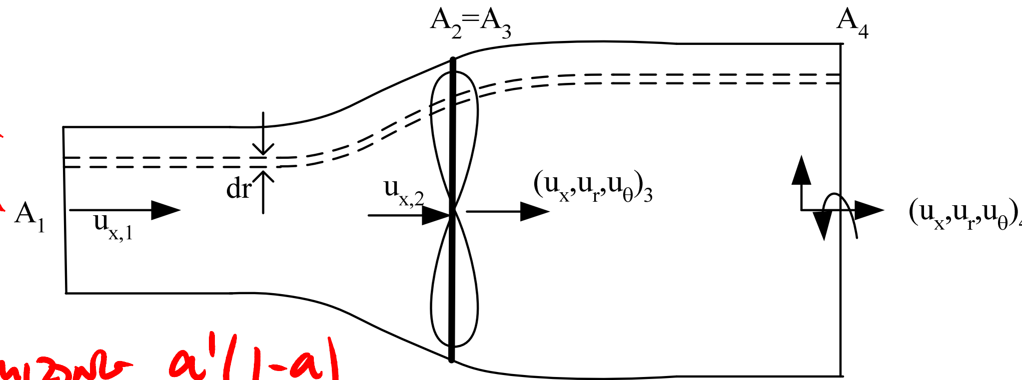

4) SUBSTITUTE INTO EQ. FOR $\frac{df}{da}$

$$a' = \frac{1-3a}{4a-1}$$

↑ CONDITION FOR MAXIMIZING $a'(1-a)$

5) SUBSTITUTE INTO λ_r^2 RELATION TO WRITE λ_r IN TERMS OF a

$$\lambda_r^2 = \frac{(1-a)}{(1-3a)}(4a-1)^2$$

6) DIFFERENTIATE TO GET $d\lambda_r$

7) SUBSTITUTE INTO dC_p EQUATION & INTEGRATE

$$C_{p,max} = \frac{24}{\lambda^2}\int_{a_1}^{a_2}\left[\frac{(1-a)(1-2a)(1-4a)}{1-3a}\right]^2 da$$

a_1 IS INDUCTION FACTOR FOR $\lambda_r = 0$
$r = 0$

a_2 IS INDUCTION FACTOR FOR $\lambda_r = \lambda$
$r = R$

NUMERICALLY INTEGRATE FOR DIFFERENT λ's

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INCREASE TIP SPEED RATIO TO
→ DECREASE WAKE ROTATION
→ INCREASE POWER AVAILABLE TO BLADE ROTATION

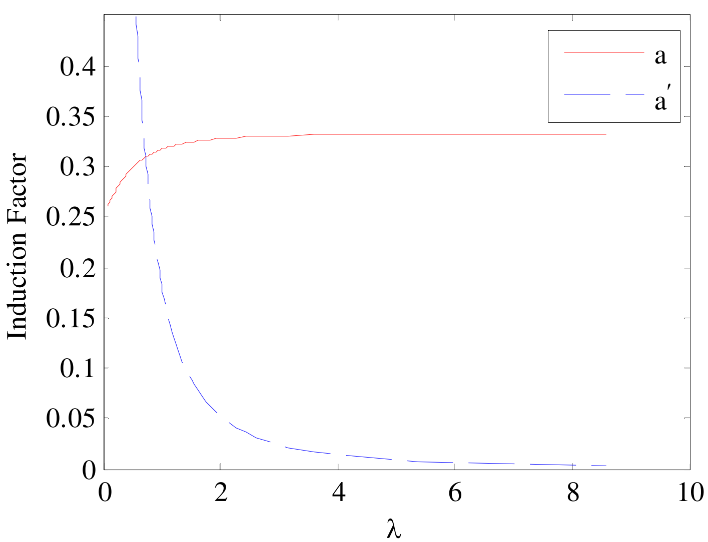
OBSERVATIONS

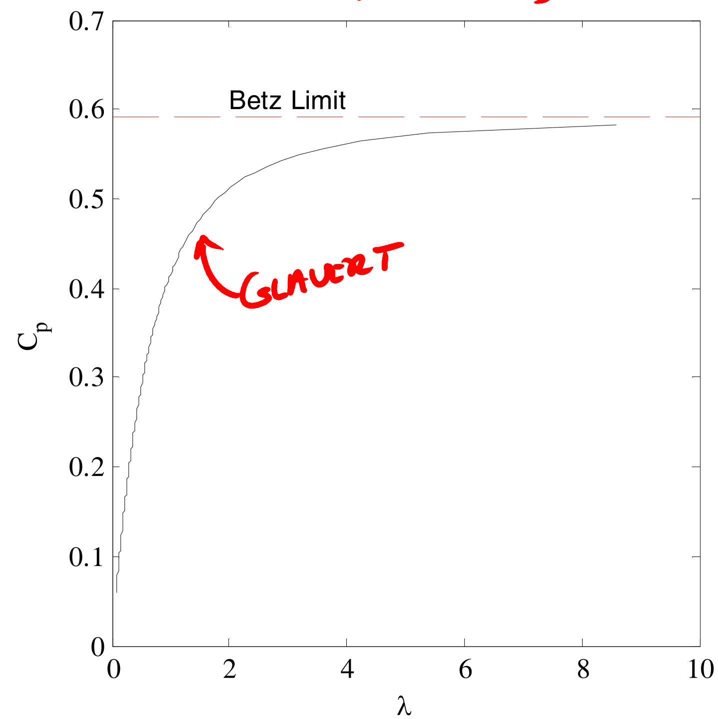
a' HIGHEST FOR LOW λ

a LEVELS OF WITH INCREASING λ

Cp CURVE DEMONSTRATES THE IMPROVEMENT WITH INCREASING λ

Cp APPROACHES BETZ LIMIT ONLY AT HIGH TIP SPEEDS





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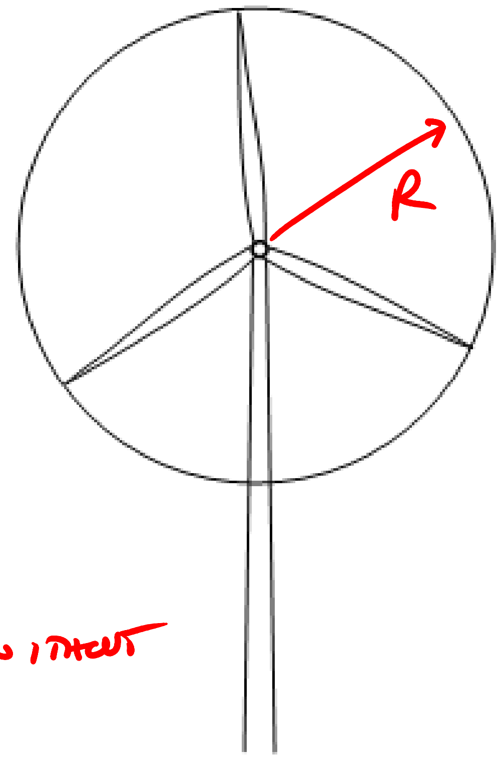
2. Practical Consideration



CONSIDER A MULTI-BLADED WIND TURBINE

EFFICIENCY DECREASES IF

- BLADES ROTATE SO QUICKLY THAT BLADES PASS THROUGH TURBULENT WAKE OF PRECEDING BLADE
- BLADES ROTATE SO SLOWLY SUCH THAT MUCH OF THE AIR PASSES BY BLADES WITHOUT INTERACTING WITH THEM

DEFINE AN IDEAL TIP SPEED RATIO

$$\lambda_0 = \frac{2\pi R}{k n R}$$

R – ROTOR RADIUS

n – NUMBER OF B

kR – DISTURBANCE DISTANCE

TRAVEL DISTANCE BELOW WHICH BLADE WILL NOT FEEL EFFECTS OF PREVIOUS BLADE

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2. Practical Consideration

$$\lambda_0 = \frac{2\pi}{kn}$$

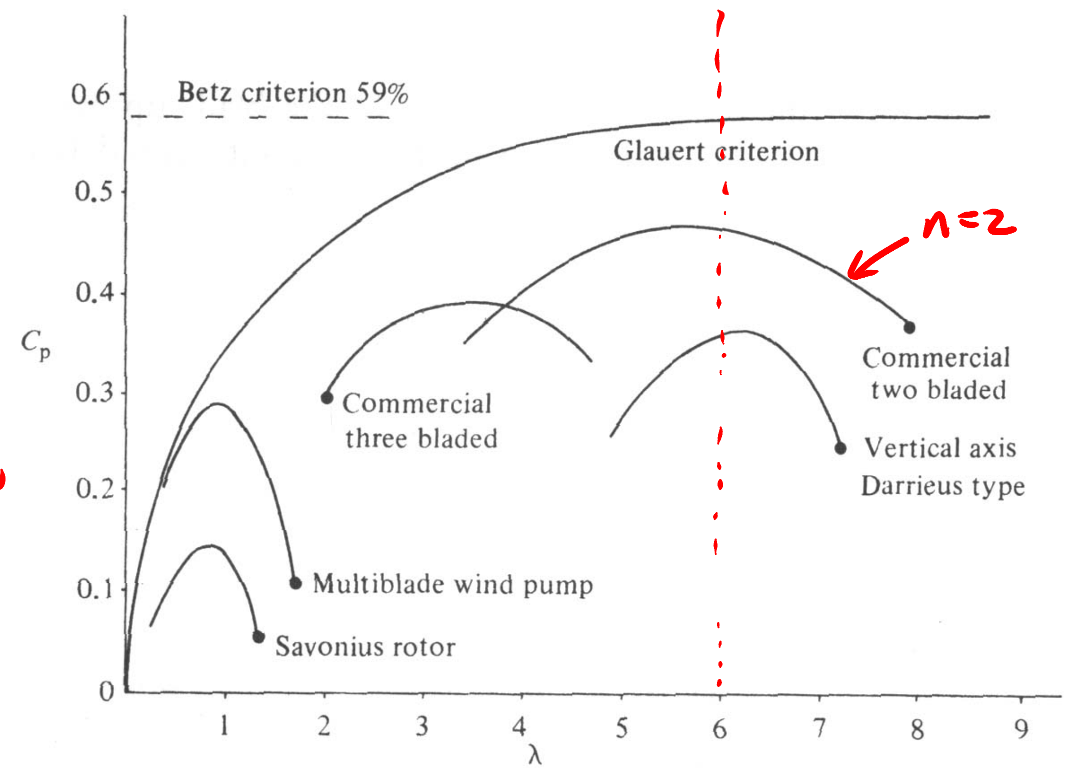
CONSIDER A 2-BLADED TURBINE

$k = \frac{1}{2} \quad n = 2$

$\lambda_0 = 2\pi \sim 6$

WITH CAREFULLY DESIGNED AIRFOILS, THE BEST TIP SPEED RATIO CAN BE INCREASED

$\lambda_{BEST} \sim 1.3\,\lambda_0$



LEADS TO UNDERSTANDING OF WHY WE SEE 2 & 3 BLADE MACHINES

Wind Turbine Aerodynamics

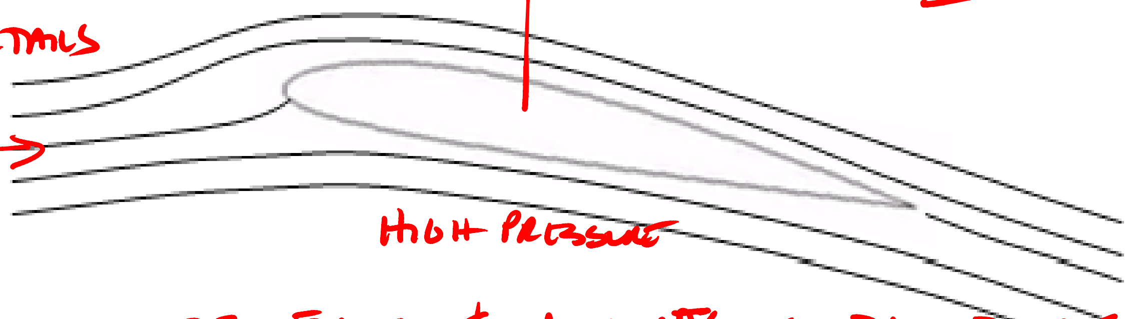
D. Blade Aerodynamics

UP UNTIL THIS POINT, WE HAVE NOT CONSIDERED DETAILS OF WHAT GOES ON IN ROTOR PLANE →

YIELDS AN UPWARD FORCE

LOW PRESSURE

LIFT



HIGH PRESSURE

THE FLOW AROUND AIRFOIL CREATES FORCES & MOMENTS ON THE BLADE

THESE FORCES & MOMENTS ARE USED TO PRODUCE USEFUL MOTION

WT BLADE → LIFT COMPONENT PRODUCES ROTATION

AIRPLANE → LIFT TO PROVIDE FORCE TO OVERCOME GRAVITY

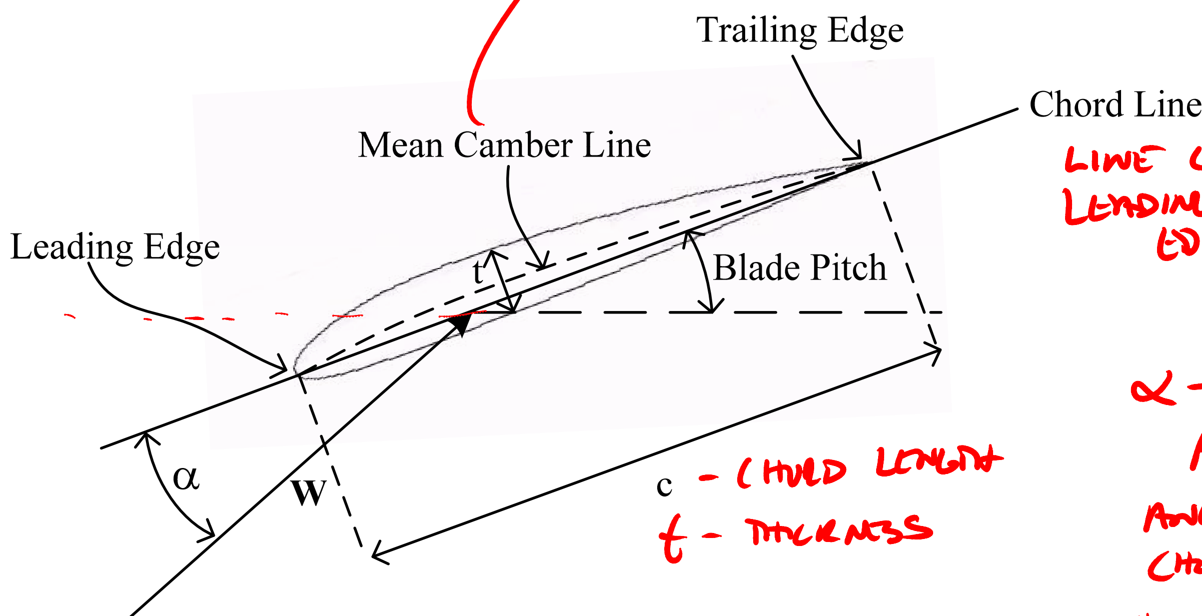
WE MUST DISCUSS THESE FORCES & MOMENTS & HOW THEY ARE CREATED & MANAGED IF WE ARE TO BUILD EFFECTIVE BLADES

Wind Turbine Aerodynamics

D. Blade Aerodynamics

1. Terminology

HALF WAY BETWEEN THE UPPER & LOWER SURFACES



LINE CONNECTING LEADING & TRAILING EDGES

ROTATE IN THIS DIRECTION

c - CHORD LENGTH

t - THICKNESS

α - ANGLE OF ATTACK - ANGLE BETWEEN CHORD LINE & "PERCEIVED" WIND DIRECTION W

AIRFOILS COME IN A WIDE VARIETY OF SHAPES & SIZES TO PERFORM DIFFERENT FUNCTIONS

BLADE PITCH - ANGLE BETWEEN CHORD LINE & ROTATION PLANE