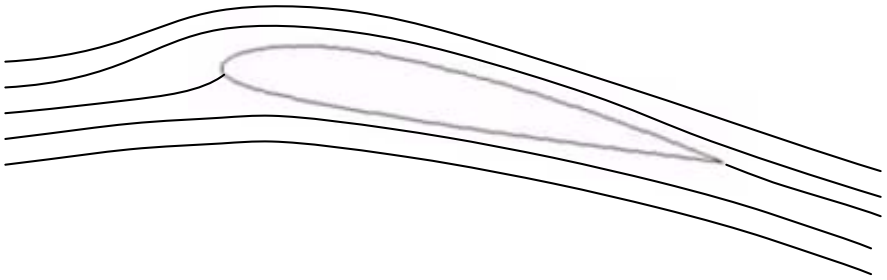
Wind Turbine Aerodynamics

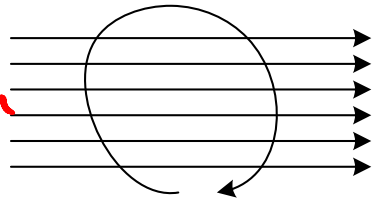
E. 3-D Blade Aerodynamics

1. Finite Wing Effects



AN ADDITIONAL CONCEPT IS THAT OF A BOUND VORTEX

FLOW AROUND WING MAY BE REPRESENTED BY ADDING A VORTEX TO THE FREE STREAM FLOW



$L = \rho U \times \Gamma$

KUTTA-JOUKOWSKI EQUATION

Γ ← STRENGTH OF VORTEX

FOR A 3-D WING, A SERIES OF VORTICES IS NEEDED TO ACCOUNT FOR CHANGING LIFT ALONG WING SPAN

$L = \phi$ AT TIP

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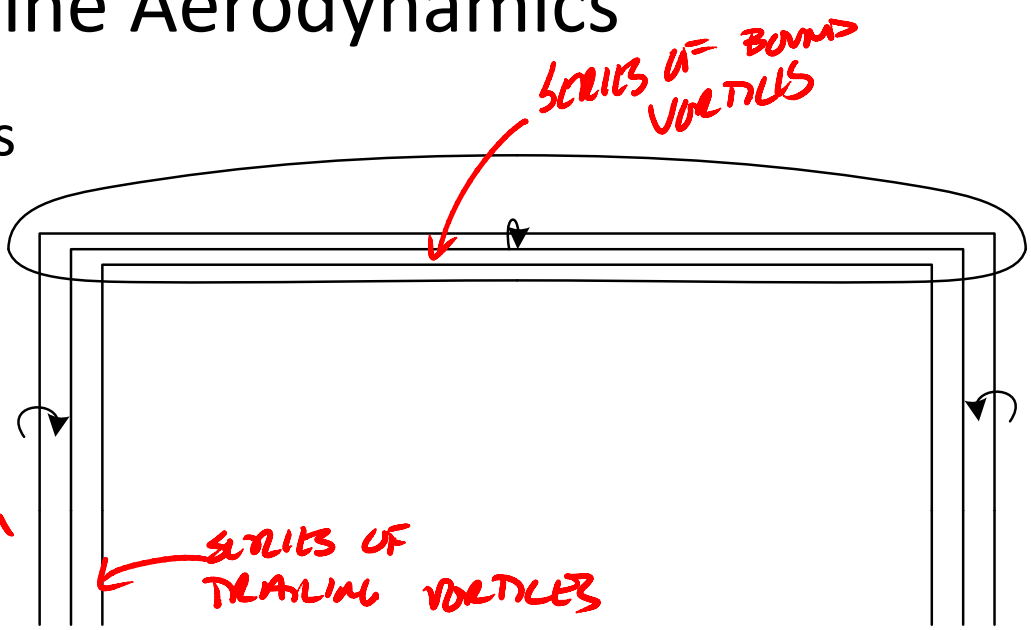
2. Lifting Line Theory



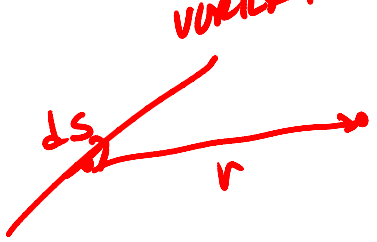
HOWEVER, VORTICES CANNOT JUST END IN SPACE

HELMHOLTZ THEOREM

MODEL WING AS A SERIES OF VORTEX FILAMENTS

- BOUND VORTICES ON WING – MODEL LIFT
- TURN INTO TRAILING VORTICES – MODEL VORTICITY GENERATED AT TRAILING EDGE

VORTEX FILAMENT



VORTICES INDUCE VELOCITIES IN THE FLOW

BIOT SAVART LAW

$$\vec{u} = \frac{\Gamma}{4\pi}\int \frac{\vec{r} \times d\vec{s}}{r^3}$$

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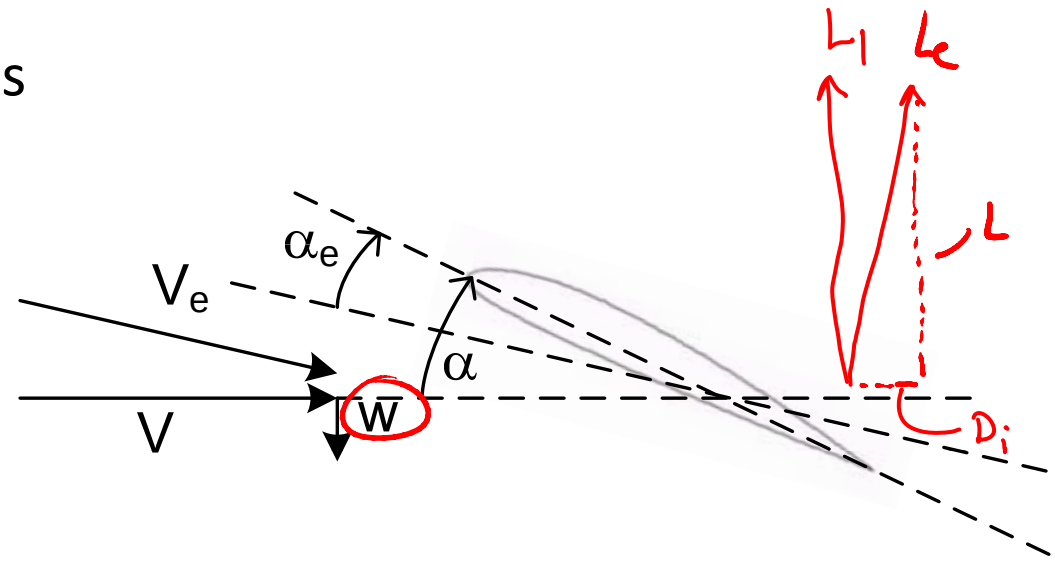
2. Lifting Line Theory



NET EFFECT OF ALL VORTICES IS TO PRODUCE AN INDUCED DOWNWARD VELOCITY → DOWNWASH

ADD DOWNWASH VELOCITY $\vec{w}$ AT POINT ON THE BLADE TO THE INCOMING WIND VELOCITY V YIELDS V_e

THE EFFECT OF DOWNWASH IS TO REDUCE THE EFFECTIVE ANGLE OF ATTACK THEREBY REDUCING LIFT

LIFT VECTOR ALSO ROTATES TO ALIGN WITH V_e

L - COMPONENT OF L_e ⊥ TO V

D_i - COMPONENT OF L_e ∥ TO V ⇒ INDUCED DRAG

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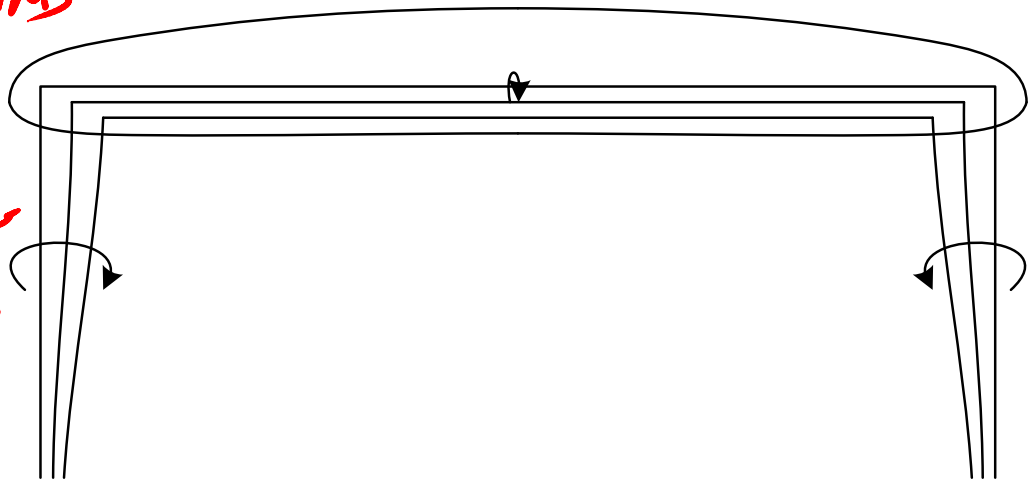
2. Lifting Line Theory

Summary

- 3-D WING HAS REDUCED LIFT COMPARED TO 2-D COUNTERPART AT α EFFECTIVE
- LOCAL EFFECTIVE LIFT HAS A COMPONENT IN INFLOW WIND DIRECTION → INDUCED DRAG



REAL VORTEX SYSTEM – ALL TRAILING VORTICES END UP MERGING INTO ONE LARGE VORTEX

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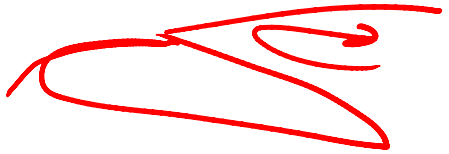
3. Other 3-D Effects



ROTATION ALSO CAUSES 3-D EFFECTS

ROTATION → CENTRIFUGAL FORCES

↓

CORIOLIS FORCE ← FLUID STARTS TO MOVE

MOST IMPORTANT WHEN FLUID MOMENTUM IS LOW → NEAR SEPARATION

- CENTRIFUGAL FORCES CAUSE FLOW TOWARDS TIPS
- CORIOLIS FORCE DEVIATES AIR TOWARD TRAILING EDGE

FORCES MODIFY POST STALL BEHAVIOR THAT IS OBSERVED IN 2-D BLADE

- COMPLEX BLADE FLOWS OBSERVED APPROACHING & AFTER STALL

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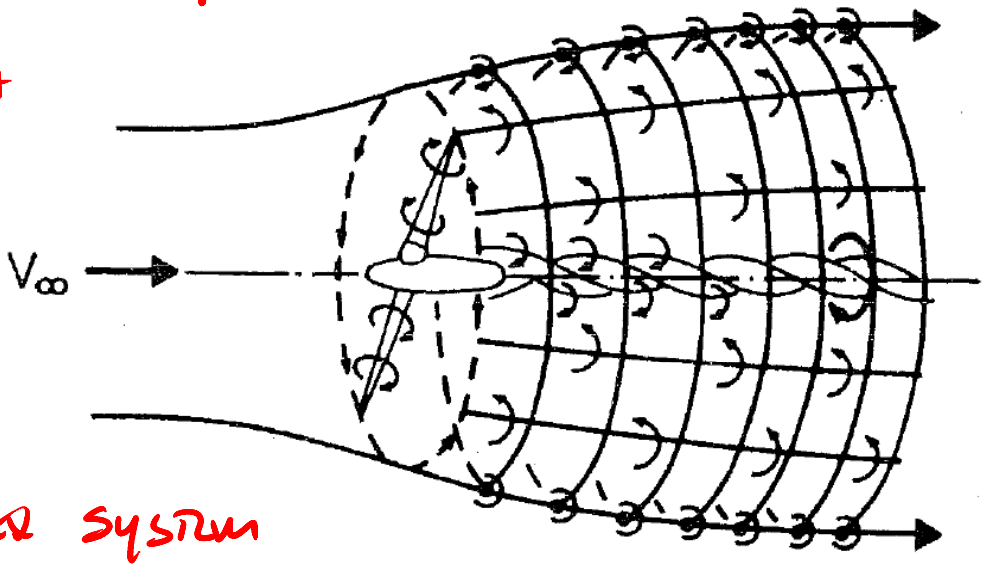
4. Vortex System Behind a Wind Turbine

LIKE AN AIRCRAFT WING, A VORTEX SYSTEM DEVELOPS BEHIND WIND TURBINE

THEY TAKE A HELICAL PATH DUE TO ROTATING BLADE

TIP VORTICES → EDGE OF WAKE

ROOT VORTICES → NEAR ROTOR AXIS



EFFECTS OF RESULTING VORTEX SYSTEM

1) INDUCES AXIAL COMPONENT OPPOSITE TO WIND INFLOW DIRECTION

2) INDUCES A TANGENTIAL COMPONENT OPPOSITE TO BLADE ROTATION

→ CAUSE THE OBSERVATIONS ARGUED ON A PHYSICAL BASIS EARLIER

Wilson and Lissaman
Applied Aerodynamics of Wind Power Machines, 1974