Aerodynamics and Structural Analysis of Wind Turbine

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PURPOSE-

This report aims to explore the fundamental principles and methodologies of structural analysis in wind turbine engineering. Enhancing sustainability by refining the aerodynamic and structural design of wind turbines, thereby advancing renewable energy adoption and reducing reliance on fossil fuels. It also focuses on ensuring structural integrity through comprehensive analysis of turbine components, mitigating risks of premature failure. Additionally, the report seeks to optimize performance by leveraging aerodynamic principles to enhance turbine efficiency, leading to heightened energy output and cost-effectiveness.

INTRODUCTION-

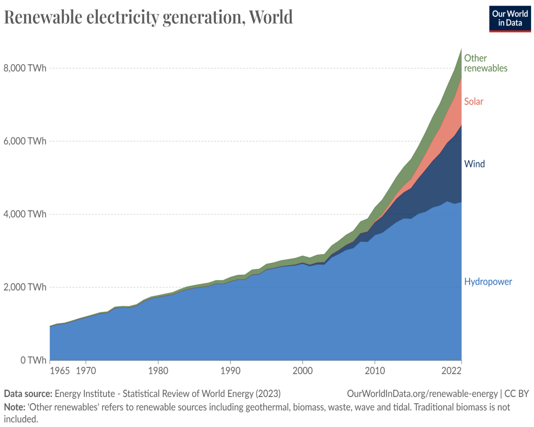
Wind energy has emerged as a key player in the global transition towards sustainable and renewable energy sources. The structural analysis of wind turbines is a critical field within renewable energy engineering, focusing on ensuring the durability, reliability, and safety of these towering structures.

The structural integrity of these turbines is paramount, as they must withstand the dynamic forces exerted by wind loads, turbulence, and other environmental factors over their operational lifespan.This examination involves thorough assessment of various components, including blades, towers, and foundations, to ascertain their ability to withstand the dynamic forces exerted by wind and environmental factors.

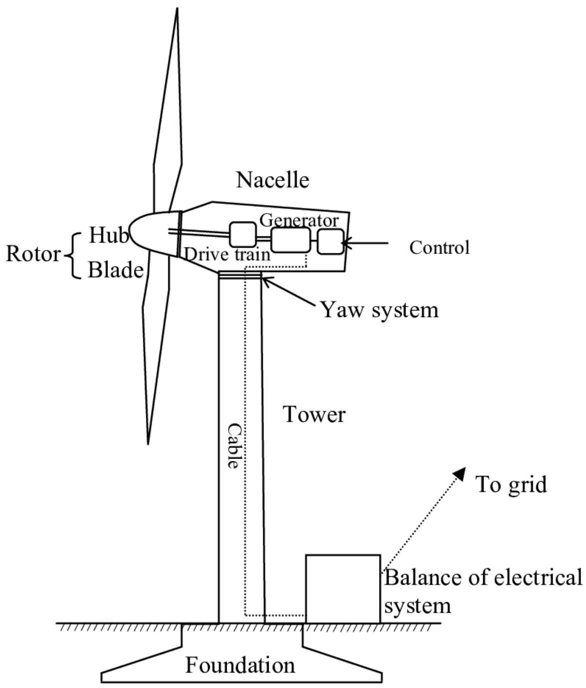
By employing sophisticated engineering techniques and computational models, researchers aim to optimize the structural design, enhance performance, and prolong the operational lifespan of wind turbines.

OVERVIEW-

Breakdown of renewable technologies by their components – hydropower, solar, wind, and others:



1. <u>Components of Wind Turbines:</u> Wind turbines consist of several key components, each playing a crucial role in converting wind energy into electrical power. The blades, usually made of fibreglass or carbon fibre-reinforced composites, capture the kinetic energy of the wind. The tower supports the nacelle, which houses the gearbox, generator, and control systems. The foundation anchors the turbine to the ground, providing stability and support.



2. <u>Factors Affecting Structural Integrity:</u> Wind turbines are exposed to dynamic wind loads and turbulence, necessitating robust structural design to withstand these forces. Material selection is crucial, with engineers opting for materials possessing high strength and fatigue resistance. Fatigue analysis is employed to assess the impact of cyclic loading and vibrations on component lifespan, ensuring turbines can operate reliably over their operational lifespan.

3. <u>Optimization of Turbine Design and Performance:</u>

- Aerodynamic Considerations: Efficient turbine blade design is essential for maximizing energy capture and minimizing aerodynamic losses. Computational tools and experimental testing are employed to optimize blade shape, twist, and airfoil profiles, improving overall turbine performance.
- Structural Enhancements: Structural analysis identifies areas for design optimization to improve load distribution, reduce stress concentrations, and enhance fatigue resistance. Modifications such as reinforcement of critical components or adjustments to tower height and stiffness can enhance turbine reliability and longevity.

Aerodynamic Characteristics-

The rotational speed of the rotor determines how well a wind turbine works. The rotor's speed is governed by a variety of variables and varies depending on the type of rotor blades used. The spinning of the rotors is primarily caused by the action of lift or drag forces acting on the turbine blades. Several blades were created based on this concept. Various aspects such as the capacity of a wind turbine blade to capture the influence of flowing air, structural integrity, and efficiency at varying wind speeds are evaluated while constructing a wind turbine blade.

The common terms that are studied are Coefficient of power, Tip speed ratio. The Coefficient of power describes the efficiency of the turbine. It is the ratio of the mechanical power acting on the turbine to the power produced by the turbine.

$$C_p = \frac{\text{Mechanical Power}}{\text{Turbine power}}$$

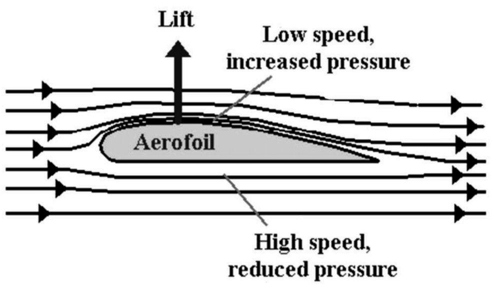
Similarly, the Tip Speed Ratio (TSR) is the ratio between the speed of the tip of the blade to the speed of the wind. TSR signifies the effectiveness of the blade design, i.e., the ability of the blade to capture the wind.

$$\text{TSR} = \frac{\text{Tip Speed of the blade}}{\text{Speed of the wind}}$$

The Cp and TSR values are affected by several factors, including rotational velocity, wind speed, rotor solidity, blade aspect ratio, and rotor disc area.

1. Horizontal axis wind turbines:

The design of HAWTs has become a key research issue as the need for large-scale power production utilising wind turbines has increased. The operation of a HAWT is based on forces generated by the pressure differential between the two sides of its blade, as seen in below fig:



This pressure differential propels the blade higher, while the limitation at one end of the blade causes a torque on the blade's loose end. This torque contributes to the rotation of the blade about the horizontal axis.

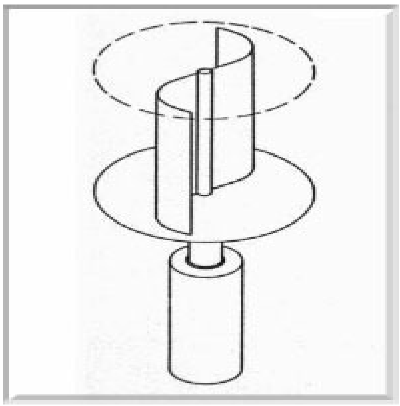
Wind turbine performance is determined by elements such as angle of attack, blade profile, and wake creation behind the turbines. The change in wind angle of attack has a substantial impact on the turbine's performance.When the angle of attack exceeds a certain limit, the value of the coefficient of lift drops dramatically while the value of the coefficient of drag rises. As a result, the coefficient ratio will be very low, lowering the turbine's power production. The turbine blade's power production varies due to the wind's uneven angle of attack. Thus, to overcome this issue, the blades of the turbine were designed in such a way that the blades align themselves automatically to the direction of the wind to achieve the maximum power output from the turbine.

Wake creation behind the turbine is another important aerodynamic property that influences the performance of a HAWT. The wake created by the turbine may be divided into two types: close wake and far wake.The wake created will be made up of vortexes that can exert force in the opposite direction of the turbine's spin. From the points of each blade, a wake will develop. As a result, as the number of blades grows, the wake creation will become more pronounced. This problem can be remedied by changing the geometry of the blade tips. The final consideration is the turbine's blade profile. Choosing a blade profile is entirely dependent on the coefficient of drag and coefficient of lift. To boost performance, blades with a high coefficient of lift are desired. Because of its high coefficient of lift value, the NACA44 series blades are the most widely utilised.

2. Vertical axis wind turbines:

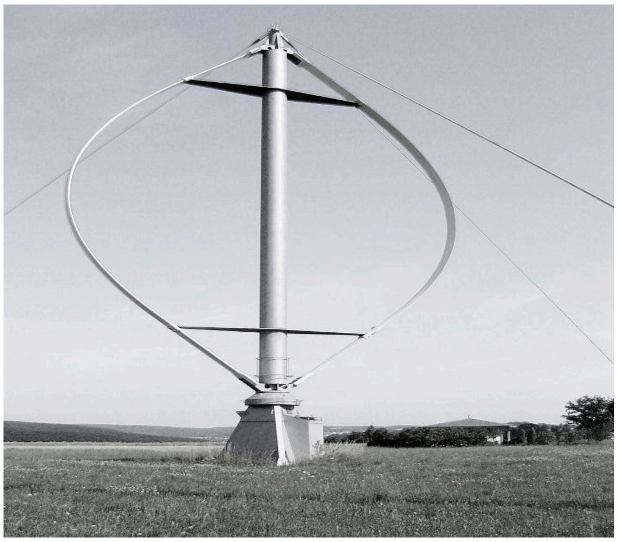
Vertical axis wind turbines can be classified into drag based and lift base wind turbines. The classification is based on the types of driving force used to rotate the rotor along the vertical axis.A drag-based wind turbine is intended to enhance the drag force acting on the rotor's surface. The drag force is employed to rotate the turbine blades in the case of a wind turbine. The surface area of the blade is expanded to enhance the drag force acting on the blade surface.

Based on this, numerous forms were developed to boost the rotor's rotating speed. The Savonius turbine, which employed an S-shaped blade design to collect the moving air, was one of the most prevalent forms developed. Because of its S-shape, dynamic pressure from moving air is caught on one side while the smooth flow is experienced on the other.



The lift-based wind turbine is the second type of VAWT. The turbine operates on lift force, which is caused by a pressure differential across a blade. A lift-based turbine's blades feature an aerofoil profile. When a fluid flows through an aerofoil-shaped device, pressure acts on both surfaces of the blade. The fast-moving air on the blade's top surface generates a low-pressure zone, while high-pressure operates on the blade's bottom surface. This pressure differential causes the blade to raise.

The aerofoil shaped blades of a vertical axis wind turbine, such as a Darius Turbine, are positioned vertically. The lift force acting on the blades causes a centrifugal force along the rod that links the blade to the central rotating axis, causing the vertically mounted blades to revolve. Increasing the number of blades increases the centrifugal force operating on the rod, increasing the blade's properties.



Several designs, including H-Darrius and Darrius turbines, were proposed as a result of the Darrius turbine study. The performance of each of these turbines depends on the effectiveness of the aerofoil shape of the blade.

STRUCTURAL ANALYSIS-

1. <u>Turbine Blade:</u>

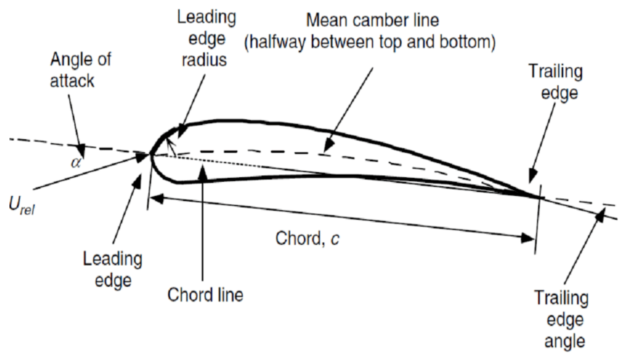
The wind turbine blade is a very important part of the rotor. Wind turbine provides an alternative way of generating energy from the power of wind. Extraction of energy depends on the design of the blade. Wind turbine blades are complex structures whose design involves the basic aspects of:

- Selection of the aerofoil shape
- Structural configuration
- Material selection (to ensure that the defined shape is maintained for the expected life)
- Density of blade material

<u>Airfoils:</u>

A number of terms are used to characterize an airfoil. The mean camber line is the locus of points halfway between the upper and lower surfaces of the airfoil.

The most forward and rearward points of the mean camber line are on the leading edge and trailing edges, respectively. The straight line connecting the leading and trailing edges is the chord line of the airfoil, and the distance from the leading to the trailing edge measured along the chord line is designated as the chord of the airfoil. The thickness is the distance between the upper and lower surfaces, also measured perpendicular to the chord line. Finally, the angle of attack α is defined as the angle between the relative wind and the chord line.



<u>Lift, drag and non-dimensional parameters:</u> The most important non-dimensional parameter for defining the characteristics of fluid flow conditions is the Reynolds number. Force and moment coefficients, which are a function of Reynolds number, can be defined for two- or three-dimensional objects. Rotor design usually uses two dimensional coefficients, determined for a range of angles of attack and Reynolds numbers, in wind tunnel tests. The two-dimensional lift coefficient is defined as:

$$C_l = \frac{L/l}{1/2\rho U^2 c}$$

The two-dimensional drag coefficient is defined as:

$$C_d = \frac{D/l}{1/2\rho U^2 c}$$

where ρ is the density of air, U is the velocity of undisturbed airflow, c is the airfoil chord length and l is the airfoil span. Other dimensionless coefficients that are important for the analysis and design of wind turbines include the power and thrust coefficients and the tip speed ratio, the pressure coefficient, which is used to analyze airfoil flow:

$$C_p = \frac{p - p_\infty}{1/2\rho U^2}$$

<u>Types of loads on Blade:</u>

For finding the maximum permissible wind speed of the turbine, the structural integrity of the turbine plays a major role. Different types of loads act on the blades flowing through the air stream. These forces induce stresses within the blade causing blade damage. Another major concern is the vibrations induced in the blade. All these issues can be solved by selecting a strong material that should withstand the continuous loading on the blade. The various types of loads that act on a blade are:

1. <u>Steady load:</u>

These Loads remain constant over a large period. A steady load is induced on the blade while a continuous flow of air at a constant velocity strikes the blades of the turbine.

2. <u>Cyclic load:</u>

Loads that vary periodically with time. These loads are induced due to the rotation of the rotor. The loads arise due to factors such as the weight, shearing of the wind, or the yaw motion.

3. Transient load:

Time-varying loads are called transient loads. These loads are induced due to transient variation of the wind that strikes the blades. The time-varying load can be represented in the form of a function.

4. Stochastic load:

These loads are also a type of time-varying load but they cannot be represented in the form of a function as the load value varies randomly with time.

5. Resonance-induced loads:

These are loads that are induced due to dynamic response from the blade. These loads arise when the wind turbine blade is excited to its natural frequencies.

These loads are generally induced at high winds and can cause serious damage to the turbine blade. Loads arise on the blades mainly due to aerodynamic force, gravity, dynamic vibrations, or the effect of secondary subsystems such as gears. But other than these loads can be induced due to inertia, and gyroscopic effect. Another major concern is the induced vibrations that can cause serious damage to the blades. The major cause of failure of turbine blades is material fatigue.

```python
#1.This function calculate the values of forces and moments
def calculate_aerodynamic_forces_and_moments(v_wind, v_rotor, yaw_error, vertical_wind_shear, yaw_rate):

    rotor_radius = 20  # meters (example value)
    density_air = 1.225  # kg/m^3 (example value)
    area_rotor = np.pi * rotor_radius**2

    # Wind speed components
    v_axial = v_wind * np.cos(yaw_error)
    v_crosswind = v_wind * np.sin(yaw_error) + v_rotor

    # Vertical wind speed correction
    v_vertical = v_wind * vertical_wind_shear

    # Aerodynamic forces
    lift_coefficient = 1.2  # Example lift coefficient
    drag_coefficient = 0.1  # Example drag coefficient
    lift_force = 0.5 * density_air * area_rotor * (v_axial**2) * lift_coefficient
    drag_force = 0.5 * density_air * area_rotor * (v_crosswind**2) * drag_coefficient

    # Aerodynamic moments (for simplicity, assuming only yaw motion)
    rotor_area = np.pi * rotor_radius**2
    yaw_moment_arm = 0.75 * rotor_radius  # Example distance from rotor center to yaw axis
    yaw_moment = 0.5 * density_air * rotor_area * rotor_radius * v_wind * yaw_rate * yaw_moment_arm

    # Additional factors
    # Tip speed ratio (TSR)
    tip_speed_ratio = (v_wind + v_rotor) / (2 * np.pi * rotor_radius)
    # Angle of Attack
    aoa = np.arctan(v_crosswind / v_axial)
    # Blade pitch angle
    blade_pitch_angle = 0.1  # example value
    # Wind turbine power coefficient
    power_coefficient = 0.5  # example value
    # Torque on the rotor
    rotor_torque = 0.5 * density_air * area_rotor * (v_axial**2) * (rotor_radius**2) * power_coefficient

    return lift_force, drag_force, yaw_moment, tip_speed_ratio, aoa, blade_pitch_angle, rotor_torque
```

2. Tower Analysis:

We are calculating the maximum bending stress on the tower due to wind load and comparing it with the yield strength of the steel material with a safety factor. We can adjust the parameters and equations according to our specific requirements and the actual design of the wind turbine tower.

For Cylindrical Tower Using the Python Code:-

Using some formula:

1. Area of Moment of Inertia(I):- I = $\pi d^4 / 64$

- The moment of inertia represents how the cross-sectional area of the tower resists bending. For a circular cross-section (which is assumed in this code), the formula calculates the moment of inertia based on the diameter D of the tower.

2. Maximum Bending Stress(B):- B=MH / 2I

- Calculates the maximum bending stress experienced by the tower due to a given load M (moment) at a certain height H. It's derived from the basic principles of beam bending (Euler-Bernoulli beam theory).

3. Safety Margin(SM):- SM = yield strength / safety factor*stress

- The safety margin is calculated by dividing the yield strength of the material by the product of the safety factor and the actual stress experienced by the material. It represents how much stronger the material is compared to the maximum stress it's subjected to.

The safety factor is typically chosen to ensure that the structure remains safe under various loading conditions and uncertainties.

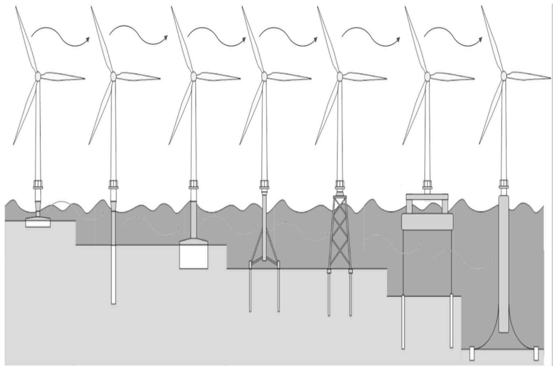
In this code we assumed a simplified linear elastic behaviour of the material and neglected other potential factors such as fatigue, non-linear behaviour, and dynamic effects, which would require more complex analysis.

```python
import math

# Material properties of steel
yield_strength_steel = 250 * 10**6  # Yield strength of steel in Pascals
safety_factor = 1.5  # Safety factor

# Tower dimensions
tower_height = 80  # Height of the tower in meters
tower_diameter = 4  # Diameter of the tower in meters

# Load on the tower (for example, wind load)
wind_load = 100000  # Wind load in Newtons

# Calculate the area moment of inertia of the tower cross-section
def calculate_moment_of_inertia(diameter):
    return math.pi * (diameter ** 4) / 64

moment_of_inertia = calculate_moment_of_inertia(tower_diameter)

# Calculate the maximum bending stress on the tower
def calculate_bending_stress(load, height, moment_of_inertia):
    return (load * height) / (2 * moment_of_inertia)

bending_stress = calculate_bending_stress(wind_load, tower_height, moment_of_inertia)

# Calculate the safety margin
def calculate_safety_margin(yield_strength, stress):
    return yield_strength / (safety_factor * stress)

safety_margin = calculate_safety_margin(yield_strength_steel, bending_stress)

print("Maximum bending stress on the tower:", bending_stress, "Pascals")
print("Safety margin:", safety_margin)
```

Fatigue Reliability on Support Structures-

As the capacity and height of wind turbines continue to increase, the safety problems regarding support structures increase accordingly, structural integrity analysis and evaluation of support structures have become an important technical subject in this field.

The load acted on the support structures of onshore and offshore wind turbines are different. For the onshore one, the cyclic load originates mainly from wind load. By using the orthogonal expansion method and the numerical-theoretical method of random dynamic action, expanded the random fluctuating wind field into a set of scattered points to calculate wind load. Then, a fatigue probability model based on the probability density evolution method was proposed and later utilised in a 1.5 MW wind turbine tower case.



Typical support structures of offshore wind turbines

<u>The Linearized Aerodynamics Model:</u>
By linearizing the equations, the complex nonlinearities present in the full fluid dynamics equations are neglected, simplifying the analysis.

```python
#2.Perform stress analysis
def stress_analysis(wind_speed, blade_length, elastic_modulus):
    wind_force = 0.5 * 1.23 * wind_speed**2 * np.pi * blade_length**2  # Assuming blade acts as a flat plate
    stress = wind_force / (blade_length * elastic_modulus)
    return stress

#3.Estimate fatigue life
def fatigue_life(max_stress, fatigue_strength):
    fatigue_life = 1 / (max_stress / fatigue_strength)
    return fatigue_life

#4.Conduct buckling analysis
def buckling_analysis(blade_length, elastic_modulus, buckling_load):
    critical_load = (np.pi**2 * elastic_modulus * blade_length**2) / 4
    if critical_load > buckling_load:
        return "Safe - No buckling expected"
    else:
        return "Critical buckling load exceeded"
```

CONCLUSIONS-

The structural analysis of wind turbines is essential for ensuring their reliability, safety, and efficiency in generating renewable energy. By comprehensively evaluating turbine components and their interactions with environmental factors, engineers can optimize design parameters and enhance performance. As the demand for clean energy continues to grow, structural analysis will play a pivotal role in advancing the development and deployment of wind power technologies, contributing to a more sustainable and greener future.

FUTURE SCOPE-

Designing new blades with different configurations or modelling a new type of blade can be one of the best methods to improve the output power from a wind turbine. Trying new modifications to check their effects on the performance of the turbine. The accuracy of the solution is a very important factor when it comes to numerically solving a problem. Improving the turbulence models, and other flow parameters can help in improving the accuracy of the result thus making it more reliable. Studying the effect of external features around the turbine to improve efficiency is another method for improving the performance of the turbine. Developing innovative techniques to observe the flow across the blade will aid in improving the accuracy of testing procedures.

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