Muhammed Yasir YAĞMUR
A Master’ s Thesis
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THE EFFECT OF LONGITUDINAL MASS DISTRIBUTION OF BLADES ON ENERGY EFFICIENCY IN WIND TURBINES

A THESIS
SUBMITTED TO THE DEPARTMENT OF SUSTAINABLE URBAN INFRASTRUCTURE ENGINEERING
AND THE GRADUATE SCHOOL OF ENGINEERING AND SCIENCE OF ABDULLAH GUL UNIVERSITY
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
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SCIENTIFIC ETHICS COMPLIANCE

I hereby declare that all information in this document has been obtained in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all materials and results that are not original to this work.

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M.Sc. thesis titled The Effect Of Longitudinal Mass Distribution Of Blades On Energy Efficiency In Wind Turbines has been prepared in accordance with the Thesis Writing Guidelines of the Abdullah Gül University, Graduate School of Engineering & Science.

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ACCEPTANCE AND APPROVAL

M.Sc.thesis titled The Effect of Longitudinal Mass Distribution of Blades o”n Energy Efficiency in Wind Turbines has been accepted by the jury in the Sustainable Urban Infrastructure Engineering Graduate Program at Abdullah Gül University, Graduate School of Engineering & Science.

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(Thesis Defense Exam Date)

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APPROVAL:

The acceptance of this M.Sc. thesis has been approved by the decision of the Abdullah Gül University, Graduate School of Engineering & Science, Executive Board dated ….. /….. / ……….. and numbered ………….……. .

……….. /……….. / ………..

(Date)

Graduate School Dean
Prof. İrfan ALAN

ABSTRACT

THE EFFECT OF LONGITUDINAL MASS DISTRIBUTION OF BLADES ON ENERGY EFFICIENCY IN WIND TURBINES

Muhammed Yasir YAĞMUR
MSc. in Sustainable Urban Infrastructure Engineering
Advisor: Asst. Prof. CİHAN ÇİFTCİ
May, 2024

The purpose of this thesis is to examine the effect of mass distribution on wind turbine energy, which may occur for any reason along the length of the wind turbine blade, through experimental studies. In this regard, first of all, a wind turbine blade without any extra mass along the blade length was randomly selected, and it was determined to be used as a reference sample in the comparisons of this study. Additionally, the other four different sample types with extra mass along the blade length were also produced to be used in comparisons. All these sample types were produced three times to be used for the experimental studies. Each of these sample types was produced in three times to be used for the experimental studies. After the production of these samples, they were subjected to wind tunnel tests at the Department of Energy Systems Engineering at Erciyes University. According to the experimental results, it was revealed that the inertia of the blades in rotation is related to the number of turns of the blades under wind. In other words, the results of these tests show that the inertia in rotation is directly related to the mass distribution along the length of the blades. Therefore, lighter blades can accelerate faster against the wind force, and the maximum number of turns they can reach is higher. As a result, the industry must keep the rotational inertia of the produced blades lower in order to produce blades for wind turbines that rotate at higher speeds and maximize energy efficiency.

Keywords: Wind turbine, Blade prototype, wind tunnel, longitudinal mass distribution

ÖZET

RÜZGÂR TÜRBİNLERİNDE KANATLARIN BOYUNA KÜTLE DAĞILIMININ ENERJİ VERİMLİLİĞİNE ETKİSİ

Muhammed Yasir YAĞMUR
Sürdürülebilir Kentsel Alt Yapı Mühendisliği Ana Bilim Dalı Yüksek Lisans
Tez Danışmanı: Dr. Öğr. Üyesi Cihan Çiftci
Mayıs, 2024

Bu tez çalışmasının amacı rüzgâr türbin kanadında kanat uzunluğu boyunca her hangi bir sebeple oluşabilecek kütle dağılımının rüzgâr türbin enerjisine etkisi deneysel çalışmalar ile irdelenecektir. Bu doğrultuda, öncelikle kanat uzunluğu boyunca herhangi bir ekstra kütleye sahip olmayan bir rüzgâr türbini kanadı rastgele seçilmiş ve bu çalışmanın karşılaştırmalarında referans örnek olarak kullanılmasına karar verilmiştir. Ayrıca, karşılaştırmalarda kullanılmak üzere bıçak uzunluğu boyunca ekstra kütleye sahip diğer dört farklı numune tipi de üretilmiştir. Bu numune türlerinin her birinden de deneysel çalışmalarda kullanılmak üzere üçer adet üretilmiştir. Üretilen bu numuneler Erciyes Üniversitesi Enerji Sistemeler Mühendisliği Bölümü bünyesinde bulunan rüzgâr tünelinde tünel testlerine tabi tutulmuşlardır. Yapılan deney sonuçlarına göre, kanatların dönmedeki eylemsizlikleri rüzgâr karşısında atacakları tur sayısı ile ilişkili olduğu ortaya çıkarılmıştır. Bu testlerin sonucunda dönmedeki eylemsizliğinin de kanat yapısının boyu doğrultusundaki kütle dağılımı ile doğrudan ilişkili olduğunu göstermektedir. Daha hafif kanatların rüzgâr kuvveti karşısında daha hızlanabildiği ve ulaşabileceği maksimum tur sayısının da daha yüksek olacağıdır. Bu kapsamda, endüstri tarafından üretilecek rüzgâr türbinleri kanatlarının daha yüksek turlarda dönebilmesi ve enerji verimliliğinin de makimize edilmesi amacıyla, üretilen kanatların dönmedeki eylemsizliğinin düşük tutulması gerekmektedir.

Anahtar kelimeler: Rüzgar türbini, kanat prototipi, rüzgar tüneli, boyuna kütle dağılımı

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My deepest appreciation goes to my cherished family for their unwavering love and support throughout my life, particularly during my master's degree studies. Their belief in my dreams and their encouragement to pursue my aspirations have been the bedrock of my success. I am truly blessed to have such wonderful parents (Süreyya and Çetin). I am especially grateful to my brother, İsmail Emre Yağmur, for his constant encouragement and assistance throughout this long journey, and to my sister, Zeynep Sude Yağmur, who has been a source of inspiration and motivation.

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LIST OF ABBREVIATIONS

CFD	Computational Fluid Dynamics
HAWT	Horizontal Axis Wind Turbine
NACA	National Advisory Committee for Aeronautics
VAWT	Vertical Axis Wind Turbine
MPH	Miles Per Hour
AWEA	American Wind Energy Association

To my wife, daughter and family.

Chapter 1

1. Introduction

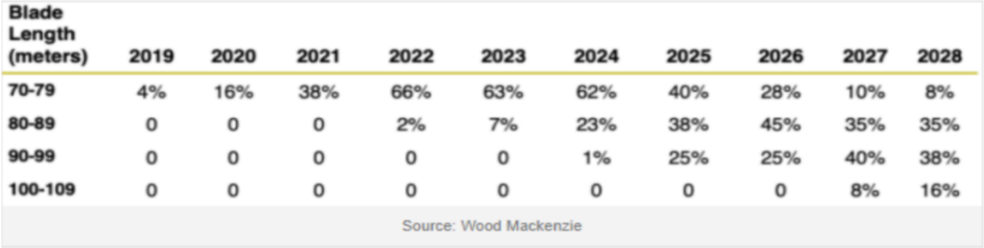
1.1 General Information & Objectives and Scope

The increase in energy need in the developing world order is an important source of problems and opportunities on a global scale. The world population is constantly increasing, and industrialization, technological advances and economic growth are increasing the demand for energy (Usenobong & Godwin, 2012).This situation makes the need for sustainable energy sources even more urgent. Technological advances and economic growth lead to an increase in energy demand. The expansion of sectors of industry, transportation and information technologies increases dependence on fossil fuels and triggers environmental problems. However, these challenges also bring the opportunity to turn to clean and sustainable energy sources. Renewable energy stands out as an important solution to meet this increasing energy need and reduce environmental impacts. Renewable resources such as sun, wind, water, geothermal and biomass can be used unlimitedly and support environmentally friendly energy production by keeping carbon emissions to a minimum. (Raihan & Tuspekova, 2022)

The increase in energy need in the developing world order also accelerates research and development in the energy sector. Innovations in areas such as high-efficiency energy storage systems, smart grid technologies, and energy efficiency solutions aim to optimize energy use and establish a sustainable energy future. As a result, while the increasing energy need brings with it environmental and economic challenges, it also carries with it a growing demand and innovation opportunity for renewable energy. This is a time when significant transformations are taking place in the energy sector, and sustainable energy solutions are gaining wider acceptance around the world.

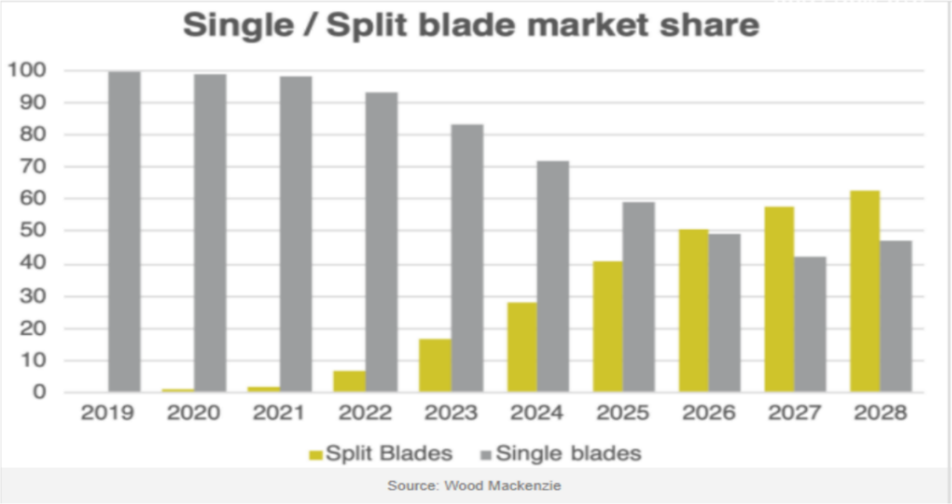
Today, with the increasing need for energy, the demand for sustainable energy resources is also increasing rapidly (Chien et al., 2023). To meet this demand, wind energy stands out as an environmentally friendly and renewable energy source. The most common and effective use of wind energy is through wind turbines (Olabi et al., 2023).

Wind turbines are an energy field that converts wind energy into electrical energy. It is located in large and open areas where wind intensity is high. It produces electrical energy by using the kinetic energy of the wind and through a generator. The most important components of wind turbines are the generator, turbine blades and tower. Turbine blades capture wind energy and mechanical energy is produced as a result of the rotation of the rotor. This rotational movement is converted into electrical energy through the generator. One of the important factors of the performance of turbine blades is the aerodynamic design of the blades. In recent years, technological developments in blade designs and dimensions have advanced considerably. In addition, the segmented production of blades and the widespread use of modular designs can both reduce transportation costs and enable easier optimization of assembly and maintenance. The use of lightweight materials increases the aerodynamic performance and increases the turbine weight and energy range.



Blade Length (meters)	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028
70-79	4%	16%	38%	66%	63%	62%	40%	28%	10%	8%
80-89	0	0	0	2%	7%	23%	38%	45%	35%	35%
90-99	0	0	0	0	0	1%	25%	25%	40%	38%
100-109	0	0	0	0	0	0	0	0	8%	16%

Source: Wood Mackenzie



Source: Wood Mackenzie

Figure 1. 1 Change of the segmented and single blade production ratio year by year

The aim of this study is to observe the contribution of mass distributions at different points on the blade to energy efficiency in the partial production of turbine blades. In the first part of the study, wind turbine blade prototypes with mass distribution at different points were produced. As can be seen from the Figure 1.2 below, extra mass was created by using iron powder at different points on the turbine blades. These blades were then tested in the wind tunnel to test their energy efficiency. It will be observed what effect the longitudinal mass distribution of the turbine blades has.

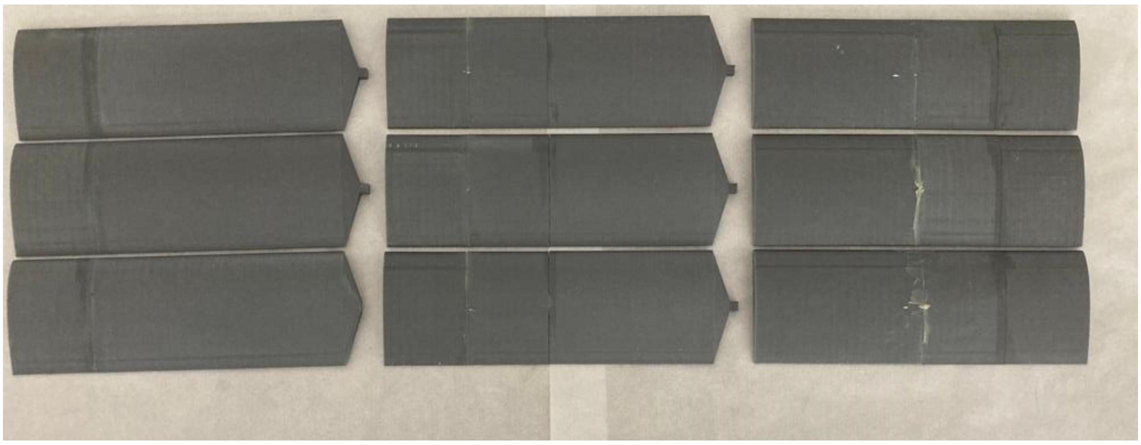


Figure 1. 2 Turbine Blade Prototypes

Chapter 2

Literature Review

2.1 Wind Turbines

The energy resulting from the exchange of hot air and cold air is called wind energy. Wind energy is generated from the physical differences on the earth and the different heating of the atmosphere by the sun. In short, wind energy, which occurs from pressure differences in the atmosphere, is a different type of solar energy. Wind energy is a resource that plays an important role in sustainable energy production today. Wind energy has made significant progress over time and has become an important player in the energy sector.

Early Period (Pre-Mid-20th Century): Wind energy has been used for centuries in domestic applications such as water pumping and grain milling. However, the use of wind energy for electricity generation did not occur on a large scale until the mid-20th century (Shahan, 2019).

- **1970s and 1980s: First Commercial Wind Farms:** Modern use of wind energy began in the 1970s and 1980s. During this period, the first commercial wind farms began to be established around the world. These farms, using low-capacity turbines, represented the early stages of the technology (Shahan, 2019).
- **1990s: Technological Advances and Growth:** Beginning in the early 1990s, technological development of wind turbines resulted in higher efficiency and lower cost production. During this period, the wind energy sector experienced significant growth (Shahan, 2019).
- **2000s: Increased Investments and Offshore Wind Farms**: Since the early 2000s, investments in wind energy projects have increased. Additionally, attempts to establish offshore wind farms have also begun.

Offshore wind farms have contributed to energy production by increasing the capacity of terrestrial wind energy (Shahan, 2019).

- **2010s: Competitive Costs and Increasing Installed Capacity:** Towards the mid-2010s, the costs of wind energy projects continued to decrease, and this type of energy became competitive. Additionally, the installed power of wind turbines has increased, and more technologically advanced models have been introduced to the market (Shahan, 2019).
- **2020s and the Future: Renewable Energy Transformation:** With the increasing global demand for renewable energy, the wind energy sector has grown further and played a key role in the energy transition. As technological developments continue, wind energy is becoming an increasingly sustainable and competitive energy source (Shahan, 2019).

Wind turbines are facilities that convert wind energy into electrical energy. This technology stands out as an environmentally friendly and sustainable energy source. The process of generating electricity from wind energy is done by converting the kinetic energy of the wind into electrical energy. This energy is generally obtained using wind turbines. Wind turbines are equipped with large blades placed at high places. By turning these blades, the wind turns a generator inside the turbine, which produces electricity.

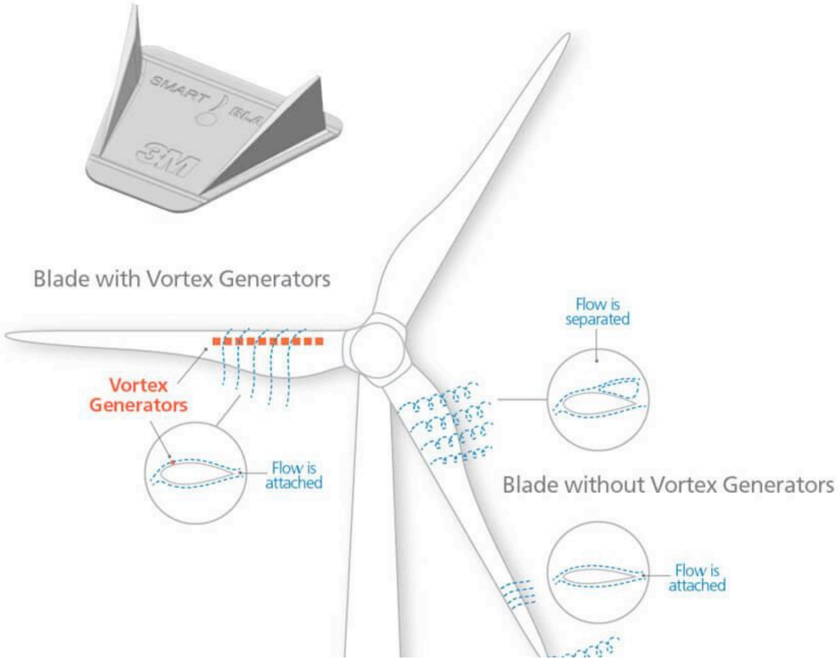


Figure 2. 1 Wind turbine operating principle (www.power-technology.com/news/newsedf-rs-and-3m-collaborate-to-deploy-wind-vortex-generators-across-wind-projects-in-us-5821866/?cf-view)

Wind turbines come in a variety of designs. Horizontal axis turbines (HAWT) are one of the typical and widely used models. Vertical axis turbines (VAWT) stand out with their more compact design and can be effective at low wind speeds. Special designs such as Savonius and Darrieus rotors are also available. (Eftekhari et al., 2021)

Offshore wind turbines benefit from more stable and stronger winds by being located offshore. These types of turbines are generally larger and more powerful than land turbines. While offshore projects offer the potential to increase energy production, they also present the challenge of assessing their impact on the marine environment.

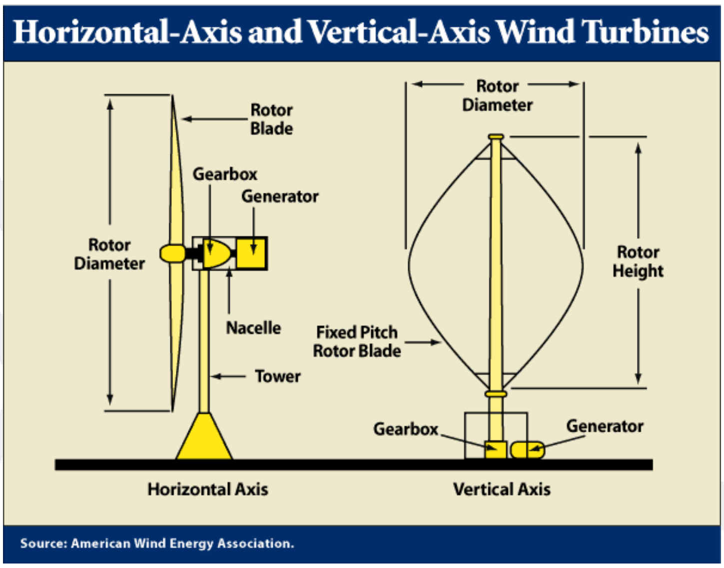


Figure 2. 2 Wind turbine types (AWEA)

- **Horizontal Axis Wind Turbines (HAWT):**

Single Rotor HAWT (Single Mast): These turbines operate with a single rotor mounted on a single mast. The most commonly used wind turbines generally fall into this category.

Double Rotor HAWT (Double Mast): These are turbines containing two or more rotors. Different rotors allow the wind to act at varying speeds and directions.

Figure 2. 3 Single-blade, double-blade and multi-blade turbine (www.dolcera.com/wiki/index.php?title=Different_Types_and_Parts_of_Horizontal_Axis_Wind_Turbines)

- **Vertical Axis Wind Turbines (VAWT):**

Savonius Turbines: They have a design consisting of two radiuses and rotating around a vertical shaft. It is effective at low wind speeds and is often used for low power applications.

Darrieus Rotors (Eggbeater or Umbrella Turbines): They have a double-bladed, vertically rotating design. It is more effective at higher wind speeds and is often used in small-scale applications

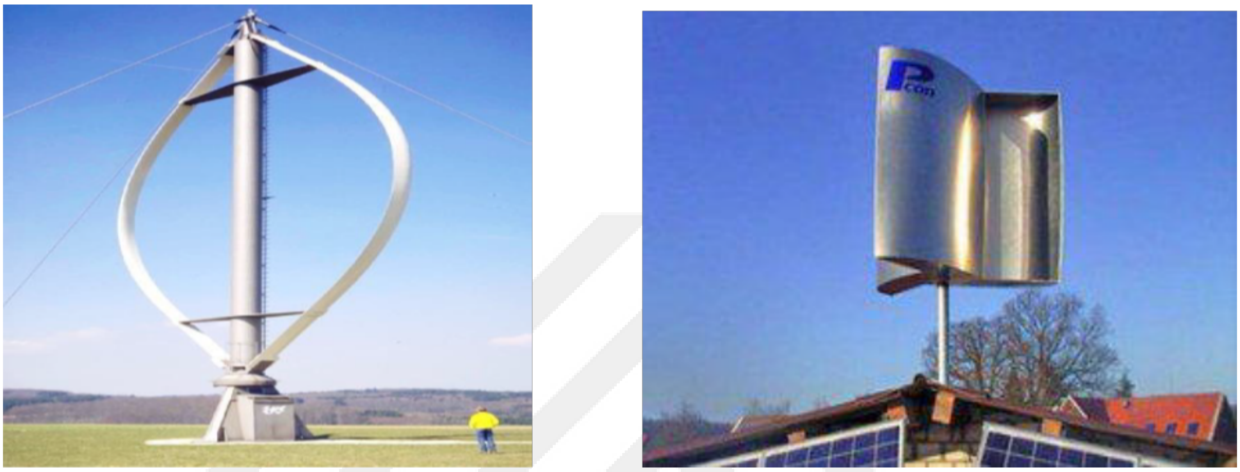


Figure 2. 4 Savonius and Darrieus (Brighthub, n.d)

- **Offshore Wind Turbines**

Fixed Base Offshore Turbines: These are turbines fixed to the sea bed. They are generally used in shallow waters.

Floating Offshore Turbines: These are turbines that float on the surface of the water and are positioned in deep sea areas. They have the potential to produce energy in deeper waters.

- **Wind Turbine Defences**

Actuator Disc Defences: Defence systems added to the tips of the blades or the entire rotor can increase performance by reducing the effect of wind.

Yawing Defences: These are systems that enable the turbine to adapt to the wind direction. As the wind direction changes, the route of the turbine is adjusted.

- **Innovative Designs:**

Twin Rotor Wind Turbines: Two-rotor designs provide higher efficiency by taking advantage of wind speeds at different altitudes.

Rotary Blade Wind Turbines: They are designed to be lighter and using less material compared to traditional fixed-blade turbines.

This diversity provides customized solutions for different wind conditions, residential areas and energy needs. With advancing technology and engineering developments, wind turbines will continue to become more effective, economical and environmentally friendly.

Peng et al. (2023) said that the internal mechanism of wind turbines has a very complex structure and includes a number of critical components. These components carry out the process of converting wind energy into mechanical energy. Here is the detailed internal mechanism of the wind turbine:

- Tower:

The height of wind turbines is important to take advantage of the tendency of wind to be faster in higher layers. The tower is usually made of durable materials such as steel or concrete and carries the wind turbine to a high point.

- Rotor:

A rotor is a rotating structure usually consisting of three or more long blades. These blades rotate under the influence of the wind and produce mechanical energy. The aerodynamic design of blades is important to provide more effective energy capture and conversion.

- Rotor Shaft:

The blades are attached to the rotor shaft. The rotor shaft serves as a shaft that transmits the rotational movement of the blades to the generator.

- Generator:

The rotor shaft is usually connected with a generator. The generator converts mechanical energy into electrical energy. This is the main electricity generation mechanism of the wind turbine.

- Transmission (Optional):

Some wind turbines use a gearbox to optimize the rotation speed at the rotor shaft and ensure that it runs at a speed suitable for the generator. However, low-speed direct drive systems are more common in modern designs.

- Control System

Wind turbines are generally sensitive to wind direction and speed. The control system adjusts the orientation of the rotor and/or turbine to ensure optimal performance of the turbine.

- Brake system:

Wind turbines have a braking system that is used when they need to be stopped in extreme wind conditions or during maintenance.

- Control Panel:

There is a control panel used to monitor, control and maintain the operation of the wind turbine. This panel can monitor and control data to optimize the performance of the turbine.

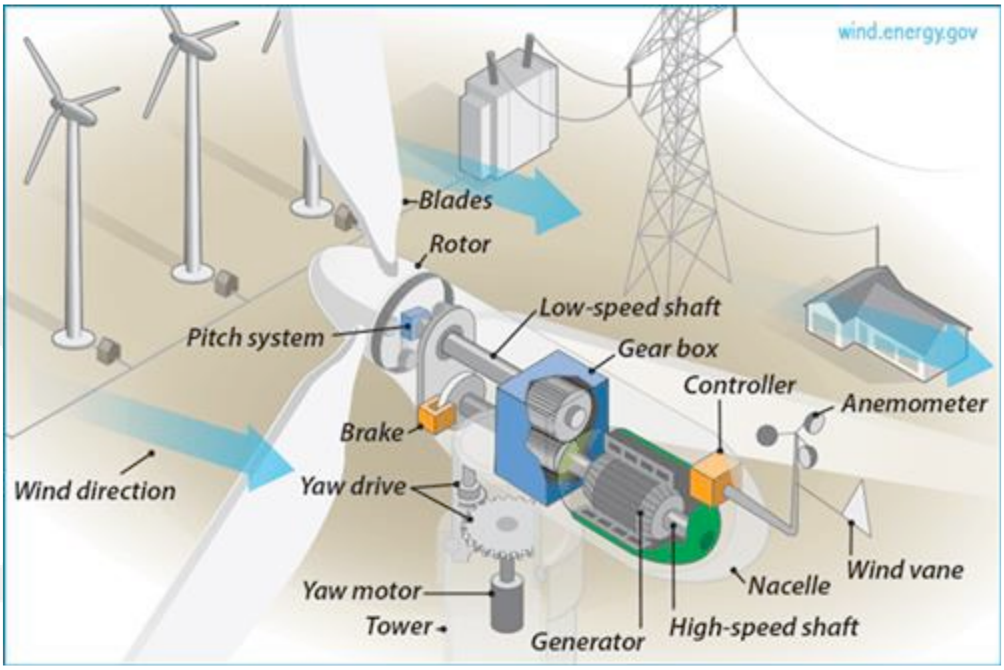


Figure 2. 5 The Inside of a Wind Turbine (Tajhau, 2002)

These components represent the main structure that forms the internal mechanism of wind turbines. Herbert et al. (2007) stated that thanks to advanced technology and engineering, wind turbines have become more efficient, durable and economical. They also said that these continuous developments enable more sustainable and environmentally friendly energy production in the wind energy industry.

Landis, F. and Budenholzer, Roland A. (2024) mentioned that turbines are devices that play an important role in energy conversion and are generally used to convert mechanical energy into electrical energy. Also main purpose of a turbine is to rotate a shaft by using the energy in the fluid. To understand this general principle, let's consider the example of a steam turbine. (Poljak et al., 2021)

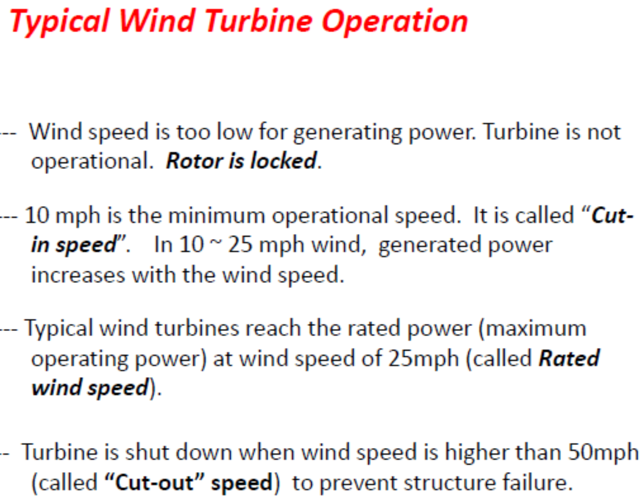
- **Thermodynamic Perspective:**

We can examine this perspective under three headings. These are the pressure and temperature of the fluid, expansion of the working fluid, and kinetic energy of the fluid.

- **Pressure and Temperature of the Fluid:** Turbine operation generally begins with steam or gas being taken from a source at high pressure and temperature and directed into the turbine (Furbish, 1997).
- **Expansion of the Working Fluid:** The fluid expands inside the turbine, and during this expansion, the pressure and temperature decrease. This is a thermodynamic expansion process (Furbish, 1997).
- **Kinetic Energy of the Fluid:** The potential energy lost during expansion turns into kinetic energy. This causes the fluid to rotate around the rotor of the turbine at high speeds (Furbish, 1997).
  - **Mechanical Perspective:**

We can examine this perspective also under three headings. These are rotation of the rotor, connection with generator, and electrical energy production.

- **Rotation of the Rotor**: The impact of the fluid at high speed rotates the rotor of the turbine. Pazarlama, (2023) said that the rotor is usually located on a shaft and is the point where kinetic energy is converted into mechanical energy.
- **Connection with Generator**: The rotation of the rotor also rotates a generator. The generator converts mechanical energy into electrical energy. Usually this conversion is based on the principle of electromagnetic induction (Pazarlama, 2023).
- **Electrical Energy Production**: Electrical energy produced by the generator is used as electrical energy depending on the facility or network (Pazarlama, 2023).



Typical Wind Turbine Operation

0 ~ 10 mph --- Wind speed is too low for generating power. Turbine is not operational. ***Rotor is locked***.

10 ~ 25 mph --- 10 mph is the minimum operational speed. It is called "***Cut-in speed***". In 10 ~ 25 mph wind, generated power increases with the wind speed.

25 ~ 50 mph --- Typical wind turbines reach the rated power (maximum operating power) at wind speed of 25mph (called ***Rated wind speed***).

> 50 mph --- Turbine is shut down when wind speed is higher than 50mph (called **"Cut-out" speed**) to prevent structure failure.

- .

Figure 2. 6 Typical Wind Turbine Operation

In this way, turbines achieve energy conversion using a combination of thermodynamic and mechanical principles. This description is a general framework used to understand the basic operating principles of the turbine. Wind turbines can often be oriented to be sensitive to wind strength and direction. Control systems ensure that the turbine optimally adapts to wind conditions and achieves maximum efficiency. This process explains the basic working principle of wind turbines. Wind energy is considered an environmentally friendly energy source and wind turbines contribute to sustainable energy production.

2.2 Obstacles

There are a number of factors that affect the performance of wind turbines. These factors have a significant impact on the turbine's efficiency, energy production and maintenance requirements. Here are the main factors that affect the performance of wind turbines:

- **Wind speed:**

The performance of wind turbines is directly related to wind speed. As the wind speed increases, the turbine can produce more energy. However, extremely high wind speeds may exceed the safe operating limits of the turbine, and operation at excessive speeds may shorten the life of the turbine (Badran, O, & Abdulhadi, E. 2016).

- **Wind Direction and Swell:**

The fact that the wind does not blow in a constant direction and fluctuates affects the performance of the turbine. Wind turbines are generally most effective in a particular wind direction, so choppy winds can reduce turbine efficiency (Konstantinidis & Botsaris, 2016).

- **Height and Location:**

The location where wind turbines are placed has a significant impact on performance. Placing the turbine from a higher location can benefit from higher and more sustained wind speeds (Badran, O, & Abdulhadi, E. 2016).

- **Blade Length and Design:**

The length and aerodynamic design of the blades affect the efficiency of the turbine. Longer blades can capture more wind energy and optimize the rotational motion of the turbine.

- **Generator and Electrical System:**

The type and features of the generator determine the capacity of the turbine to produce electrical energy. An efficient electrical system can optimize the turbine's output.

- **Control and Guidance Systems**

Wind turbines must be optimized according to the speed and direction of the wind. A good control system is important to ensure optimum performance of the turbine and to stop safely in extreme wind conditions.

- **Environmental Conditions:**

Environmental conditions of wind turbines can have an impact on performance. For example, corrosion prevention measures may be required for offshore turbines located in a salty seawater environment (Konstantinidis & Botsaris, 2016).

- **Maintenance and Reliability:**

A good maintenance program and reliability extends the life of the turbine and ensures low maintenance costs. Additionally, regular maintenance helps the turbine maintain its optimum performance at all times (Konstantinidis & Botsaris, 2016).

- **Shipping and Transportation**

Shipping and transportation of wind turbines involves some difficulties due to the transportation of large and heavy equipment. Transportation costs have a significant share in terms of costs in the Wind Turbine industry. Here are the problems and solutions encountered in this regard:

  - **Large Dimensions and Weight:**

Wind turbines often have large blade diameters and tall towers, making transportation difficult. The large dimensions of turbine blades can strain the carrying capacity of transport vehicles. This requires careful analysis of the engineering properties

Figure 2. 7 An example of turbine blade transport (https://www.reddit.com/r/EngineeringPorn/comments/knpejd/67metre_wind_blade_being_transported_by_road/?rdt=53185)

of transport vehicles. Maintaining the aerodynamic properties of blades requires carefully planned support systems and safety measures during transportation. This includes delicate protection of the aerodynamic design to prevent deformation or damage to the blades during transport (Peeters et al., 2017).

- **Road Infrastructure:**

Wind turbines are generally built in wind areas with high wind energy potential, these areas sometimes have limited transportation infrastructure. Selection of the transport vehicle, safe transport of the blades and determination of the transport route increase the complexity of engineering and logistics planning. Selection of the appropriate means of transport, the width of the roads and the suitability of the route should be carefully calculated (Smith, 2001).

Figure 2. 8 Example of turbine blade transport (https://www.craneblogger.com/featured-articles/goldhofer-ftv-300-blade-transport-device-moves-wind-turbines-up-tough-terrain/2016/09/02/)

- **Sea Transportation Problems:**

Offshore wind turbines must be transported to offshore sites, and this requires specialized marine transportation equipment and operations. Developments in marine transportation technologies, the use of specially designed ships and offshore assembly teams are very important but increase the cost (Smith, 2001).

- **Logistics Planning:**

Transportation of wind turbines requires extensive logistics planning, especially when different components are transported from different places to the plant site. That's why good logistics planning and coordination ensures that all components are delivered on time and safely (Smith, 2001).

- **Road and Rail Transportation Restrictions:**

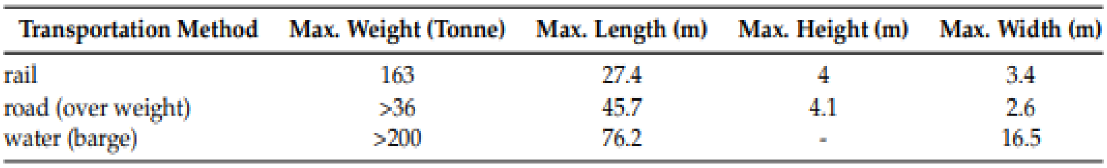
Certain road and rail routes may not be suitable for large and heavy transport. Therefore, choosing appropriate routes and improving infrastructure when necessary plays a major role in the transportation phase (Smith, 2001).

Figure 2. 9 One example of the difficulties experienced in turbine blade transportation. (https://www.youtube.com/watch?v=rxvuMv2MED0)

- **Environmental Monitoring and Permits**

Transporting wind turbines may require permits due to their environmental impact and safety precautions. It is very important to start permit processes at early stages, minimize environmental impacts, and communicate effectively with local authorities. [Smith, 2001].

Table 2.1 Wind components are transported using a variety of different modes, including ship, rail and truck.[Smith, 2001]



Transportation Method	Max. Weight (Tonne)	Max. Length (m)	Max. Height (m)	Max. Width (m)
rail	163	27.4	4	3.4
road (over weight)	>36	45.7	4.1	2.6
water (barge)	>200	76.2	-	16.5

The shipping and transportation processes of wind turbines require careful planning and cooperation. Despite these challenges, technological advances and experience in the renewable energy sector are making transportation processes more efficient and sustainable (Llc, 2024).

2.3 Additional Mass on Blade

Because it uses fossil fuels, which exacerbates climate change issues, the energy industry significantly contributes to greenhouse gas (GHG) emissions. Energy derived from fossil fuels is being replaced worldwide by cleaner sources including biomass, geothermal, solar, and wind energy. Being practical and reasonably priced, wind energy is one of the promising cleaner energy sources (Msigwa,2022). Innovation and optimizing strategies in the design of wind turbines have become a matter of curiosity to make wind energy a better option. Masses on the blades are the key factors that affect the performance of wind turbines. In this context, a detailed analysis of the additional masses added to the blades is crucially important. Mass distribution in wind turbines is also an important factor that affects the rotational movement of the turbine and therefore its efficiency for energy production. Changes in mass distribution can affect the aerodynamic performance of the turbine, its rotational speed, and therefore energy production.

The mass on the blade has a tendency to resist rotation, and this tendency is shown by the relationship between the mass on the blade and the moment of inertia. The resistance of an object to rotation is referred to as its moment of inertia, and it is determined by the mass distribution of the object as well as its distance around the axis of rotation. In most cases, the moment of inertia of a blade is proportional to the square of the length of the blade. When the length of the blade is increased, this results in an increase in the moment of inertia. In spite of this, it is essential to keep in mind that the square of the length is not the only component that determines this relationship; the mass distribution of the blade is also a factor. When it comes to the moment of inertia of the blade, another significant aspect that plays a role is the mass that is on the blade. It is the mass of an object that is the determining factor in determining its resistance to rotation. In general, the moment of inertia of a blade will grow in proportion to the distance that separates its center of mass from its axis of rotation.

With the following formula, the moment of inertia I of an object can be expressed mathematically.

$$I = m.r^2 \tag{2.1}$$

- The term of *I* represents the moment of inertia.
- m represents the mass of the object.
- r represents the distance between the object's center of mass and its axis of rotation.

A moment of inertia determined by this formula is exactly proportional to the square of the distance between the object's mass and its center of mass. Therefore, the mass distribution on the blade and the center of mass location are important factors that determine the blade's resistance to rotational motion.

In wind turbines, changing the mass of the blade tips alters the blades' rotational motion. Mass helps speed up the blade's rotation, but more mass also increases resistance to rotation. This requires balancing increasing blade speed with optimizing energy output, which design analysis could help with. Mass distributions at different points on the turbine blades may affect the aerodynamic performance, vibration and mechanical strength, control systems, imbalance, center of mass and height, and rotation axis stresses.

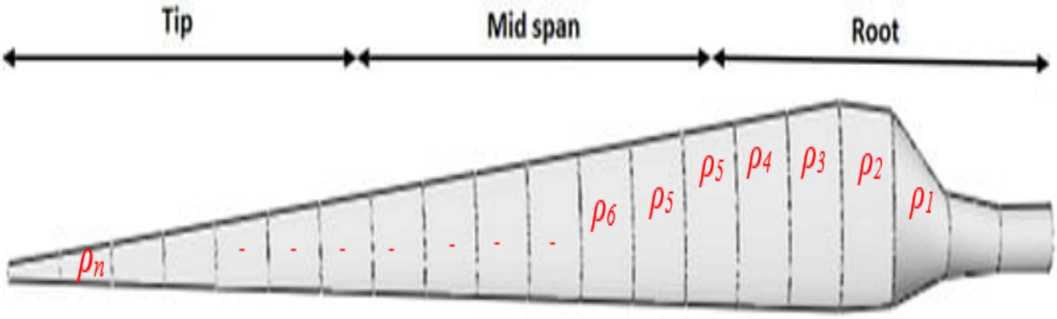


Figure 2. 10 Example representation of the mass distribution in the blade

Aerodynamically speaking, where and how the extra masses are located greatly affects air foil contact with the wind. The aerodynamic characteristics of the turbine can be studied with considerable benefit from CFD (Computational Fluid Dynamics). In-depth studies are required to determine, for example, how mass added to blade tips changes blade loads and how these changes affect energy capturing capacity. As was already said, the rotational motion of the turbine determines its aerodynamic performance. The faster the blades of the turbine spin, the more energy it produces. Inequalities in the mass distribution that influence the turbine's rotating speed can reduce its aerodynamic performance (Kaya et al., 2018).

The vibration characteristics of the turbine are normally studied using modal analysis and nonlinear simulations. These calculations evaluate how additional masses affect the resonance frequencies and blade vibration modes. Assessment of the stress and bending moments that additional masses exert on the blade material should also be done using material engineering methods. Mass imbalances in the turbine blades or other mechanical parts provide even another factor to vibrations and tiredness. Material wear and tear, fractures, and even mechanical breakdown may follow. The wear on mechanical parts may affect the turbine's life as well as maintenance costs (Awada et al., 2021).

Control systems are used to optimise and stabilise turbine rotating motion. In the meanwhile, increasing the mass may require re-evaluating control strategies. In this sense, adaptive control systems and techniques based on artificial intelligence could be applied. Another important topic is how the balancing mechanisms that rectify imbalances will be changed to take bigger weights. The turbine can become unstable with more masses. Rotation of the turbine in unfavourable locations may be the consequence of imbalance making control systems work harder. These changes need quick and accurate reaction from control systems (Awada et al., 2021).

Where additional masses are placed will affect the turbine's height and center of mass. High center of mass allows the turbine to react to changes in wind speed more quickly, even if it can also increase vibrations and spin axis stresses. Moreover, extra masses could generate loads on the rotating axis of the turbine. These additional loads affect the turbine durability and the rotational mechanism. This could affect the mechanical parts on the rotation axis' lifespan and long-term performance. (Scheurich et al., 2011).

Chapter 3

Experimental Study

3.1 Introduction

The effect of the mass distribution on the wind turbine energy, which may occur for any reason along the length of the wind turbine blade, will be examined through experimental studies in this section. In this regard, three samples without extra mass were produced along the blade in duplicate to be used as a reference in comparisons. Afterwards, 4 different sample types were determined with extra mass placed in various parts of the blade, and these samples were produced in 3 repeated numbers. Therefore, a total of 15 samples were produced for this experimental study, including 3 reference samples and 12 other samples. These produced samples were subjected to tunnel tests in the wind tunnel within the Department of Energy Systems Engineering at Erciyes University. The data obtained from these tests were collected and shared in the results section of this thesis.

3.2 Design and Production of Blades

The cross-section of all blade samples to be used in the experiments in this chapter was designed as the NACA 4412 airfoil, which is frequently preferred in the literature (see Figure 3.1). In these samples produced for the experiment, both the airfoil type and chord length do not change along the length of the blade. Additionally, no twist angle is used along the length of the blade. The main reason why the blade samples do not change

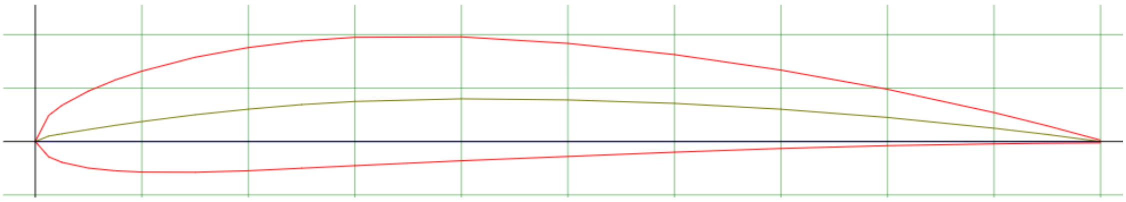
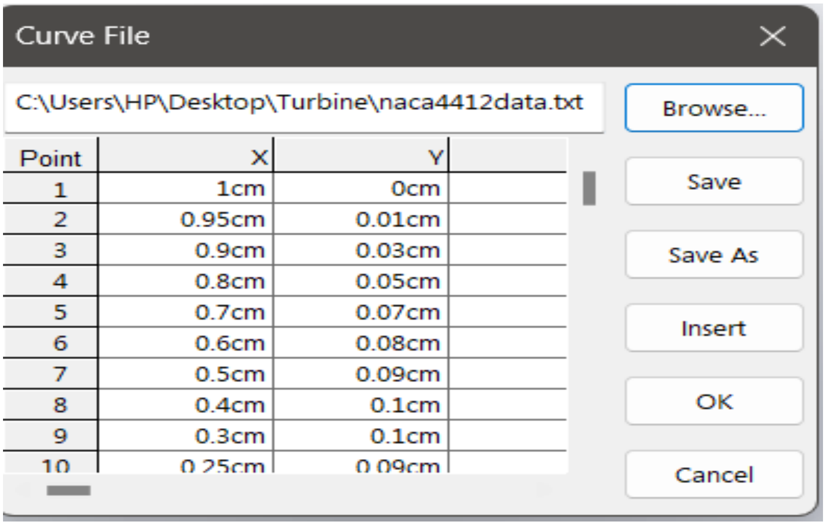


Figure 3. 1 NACA 4412 airfoil type

in chord length and do not contain twist angle is that this research is only an experimental comparison study. By comparing the parametric samples produced in these experimental studies with the reference sample, the effect of the differences created in the parametric samples will be investigated. In this context, since this experimental study was only for comparison as a kind of parametric study, there was no need for pre-production aerodynamic design of the blade samples; NACA 4412 airfoil cross-sectional area, which is frequently preferred in the literature, was randomly selected to be used in blade samples.

Drawings of the blade samples, whose cross-sectional area was determined by the NACA 4412 airfoil type, were created using SolidWorks software. For these drawings, first of all, the x-y coordinates of the cross-sectional area for the NACA 4412 airfoil type must be determined. For this, the website "airfoiltools.com/airfoil", which provides open source x-y coordinates for many airfoil cross-sectional areas used in the literature, was used. In this context, data containing specialized x-y coordinates for NACA-4412 on this site was taken. This data was created as a curve by entering x, y and z coordinates with the curve definition feature in SolidWorks, a package program (see Figure 3.2). In Figure 3.2, the values in all lines of the z axis are shown as zero, and the two-dimensional NACA 4412 airfoil cross-sectional area is defined in the z plane. Then, the offset feature of the SolidWorks program is used to transform the section curve into a drawing. Then, this drawing was shaped according to the desired chord length and the stations on the blade were created.



C:\Users\HP\Desktop\Turbine\naca4412data.txt

Point	X	Y
1	1cm	0cm
2	0.95cm	0.01cm
3	0.9cm	0.03cm
4	0.8cm	0.05cm
5	0.7cm	0.07cm
6	0.6cm	0.08cm
7	0.5cm	0.09cm
8	0.4cm	0.1cm
9	0.3cm	0.1cm
10	0.25cm	0.09cm

Figure 3. 2 x-y coordinate values used in SolidWorks software for the NACA 4412 airfoil cross-sectional area

In order to make the NACA 4412 airfoil cross-sectional area 3-dimensional in the Solid works drawings, the length of the blades must first be designed, and the blade length is designed based on the dimensions of the wind tunnel where the experiments will be carried out after production. The diameter length of the sweep area of a wind turbine, which will consist of a turbine tower and 3 blade samples to be produced, must be at least twice the length of the blade samples used in the turbine. Therefore, the swept area of the wind turbines to be constructed must fit into the cross-sectional area (50x50 cm2) of the wind tunnel where the tests will be carried out.

In this context, the total length of the blade samples to be produced was determined as 21.50 cm. In this way, 3D solid works drawings of the samples whose blade length was determined could be created as shown in Figure 3.3. As can be seen from the drawing in Figure 3.3, the total length of the region with NACA 4412 airfoil type cross-sectional area is 20 cm, and the other region with a length of 1 cm will be called the continuous transition region in this study. This transition zone is a part created using the "loft drawing" element during solid works drawings. As indicated in Figure 3.3, the initial cross-sectional area of the transition zone starts with the NACA 4412 airfoil and ends with the square cross-sectional area at the end of 1 cm length. The cube-shaped piece (a cube with a side of 0.5 cm) located at the end of the root of the blade samples is designed to allow the blade samples to enter the hub part, called the Hub, while the wind turbine is being created. In addition, the chord length of the blade profile is highlighted in the 3D visual of the drawn blade samples shown from another angle (see Figure 3.4). As mentioned before, this chord length continues unchanged throughout the blade, and this value is determined as 7 cm.

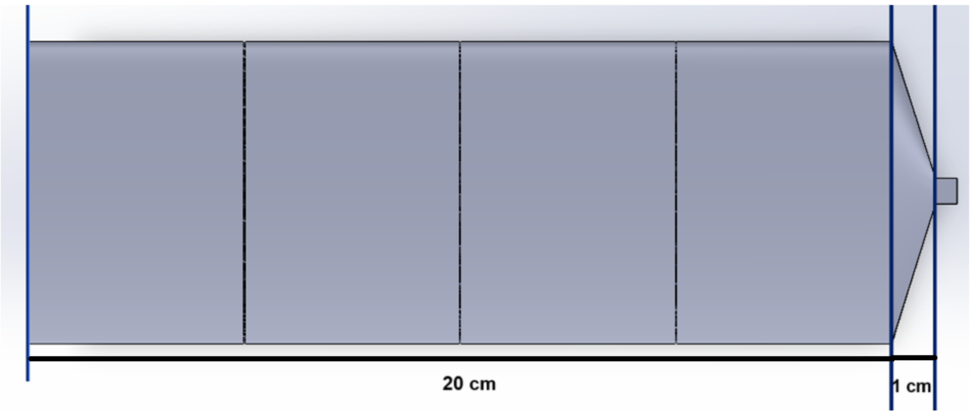


Figure 3. 3 Image of blade samples created by drawing with SolidWorks software

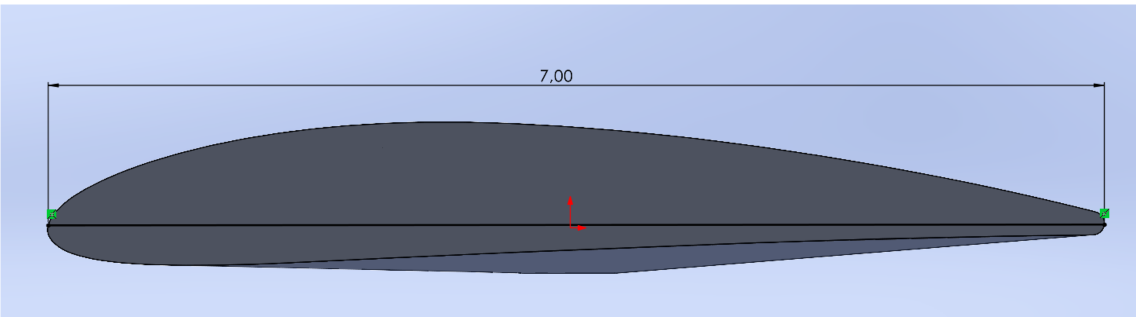


Figure 3. 4 3D visual of blade samples created by modeling in SolidWorks

A 3D-Printer (3D Loop Pro-X model) was used to make both the aerodynamic structure and mass distribution values of the blade samples drawn above more stable. The g-codes (stl files) created for 3D-printers are given in Figure 3.5 below, in order to produce an equivalent structure in this printer and then to ensure that the samples differ from each other in mass in a controlled manner.

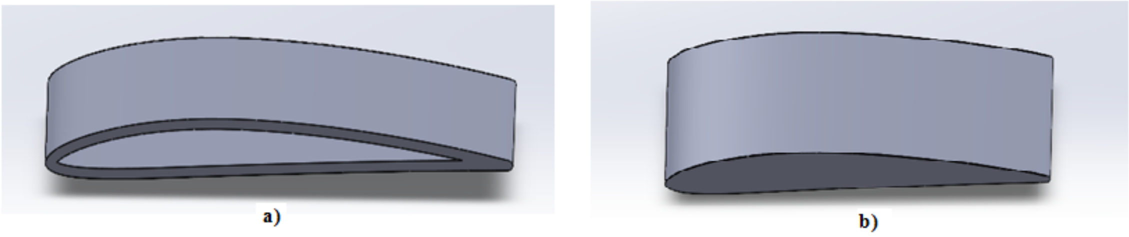


Figure 3. 5 Modeling the shell design with SolidWorks software. a) 5 cm long blade piece with a hollow shell structure, b) 5 cm long blade piece printed with 25% filling inside with a 3D printer.

According to these g-codes, the part of the blade samples after the transition part was divided into 4 equal parts. The length of each of these separated pieces is 5 cm. Some of these parts were produced in a shell structure, as shown in Figure 3.5.a, in order to fill the inner parts homogeneously with a certain mass in a controlled manner. The wall thickness of this shell structure was determined as 1.6 mm for easy printing by the 3D printer. Some of them are produced with 25% filling inside, as in Figure 3.5.b. The weight of each compartment with 25% filling was measured as 14.65 grams. he reason why iron powder is used is that it contains more weight in less volume due to its high density. The iron powder used was first sieved to ensure its weight stability when used in each blade structure. A 0.3 mm sieve was used for this. The reason for using epoxy resin is to obtain more stable data by remaining fixed in the blade samples in order to prevent the iron powders from creating vibrations during the experiment in the part to be weighted. The liquid resin components used are LR 285 and LH 287.

These liquid resins are commercial and were purchased from Dost Kimya Endüstri Hammaddeler Sanayi Ticaret Limited Şirketi. The mixing ratio of these liquid resins is 2/3 by mass. The weight of the produced shell printer blade parts before the material is put into them is 10.6 grams. First, iron powder was added to the parts to be weighted until the total weight reached 33.08 grams. In the second step, epoxy resin was added to the added iron powder until the total weight reached 33.75 grams. Then, 24 hours were waited for the epoxy to dry. A representative drawing of the production of weighted partitions in a laboratory environment is given in Figure 3.6.

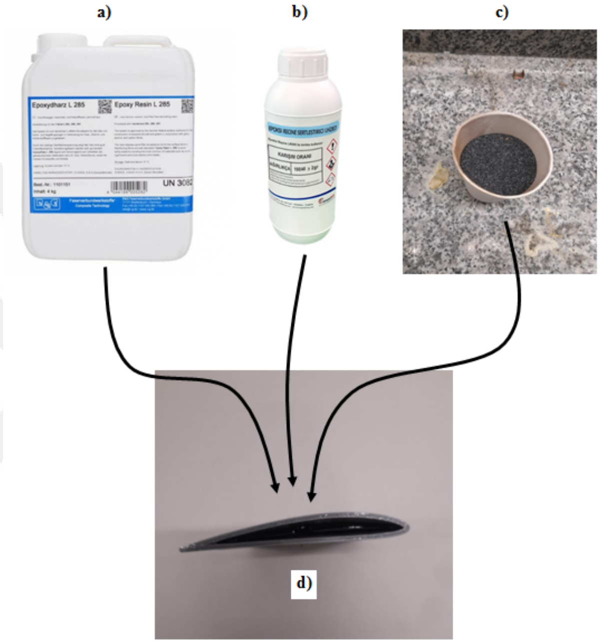


Figure 3. 6 Production process of weighted parts found in blade samples. a) LR 285 liquid resin material, b) LH 287 liquid resin hardener, c) 0.3 mm sieved iron powder, d) Weighted piece found in blade samples.

The blade sample types created during the process of combining the 5 cm long parts printed on a 3D printer with a shell structure (see Figure 3.5.a) and 25% filling (see Figure 3.5.b) with the help of epoxy material are given separately in Figure 3.6. The representative drawing in Figure 3.7.a belongs to the reference blade sample. All parts in this reference sample drawing (transition and all other sections with NACA 4412 airfoil cross-sectional area) were printed on a 3D printer with 25% infill as in Figure 3.5.b. The representative drawing in Figure 3.7.b belongs to the blade sample, whose first 5 cm long section after the transition zone is weighted with an iron powder-epoxy mixture (see Figure 3.5.a). This blade sample was named “Specimen-1 type” for this study. Similarly, “Specimen-2 type”, “Specimen-3 type”, and “Specimen-4 type” blade samples are drawn representatively as in Figure 3.7.c, Figure 3.7.d and Figure 3.7.e, respectively. In the

"Sample-2 type" blade sample, the region weighted with iron powder-epoxy mixture covers the second 5 cm length after the transition zone. In the "Specimen-3 type" and "Specimen-4 type" blade samples, these weighted regions cover the third and fourth 5 cm long pieces after the transition zone, respectively.

As mentioned in Figure 3.7, 5 different sample types were used in this study. A total of 9 samples of each sample type were produced to be used in experiments. In this context, a total of 45 blades (5x9 = 45) were produced in this study. Since 3 blades were placed on a wind turbine in the wind tunnel experiments, 15 tests could be performed (45/3 = 15). It was created by repeating these 15 tests 3 times for 5 different sample types. In other words, the tests of wind turbines containing 5 different sample types were repeated 3 times to obtain an average value of the test results.

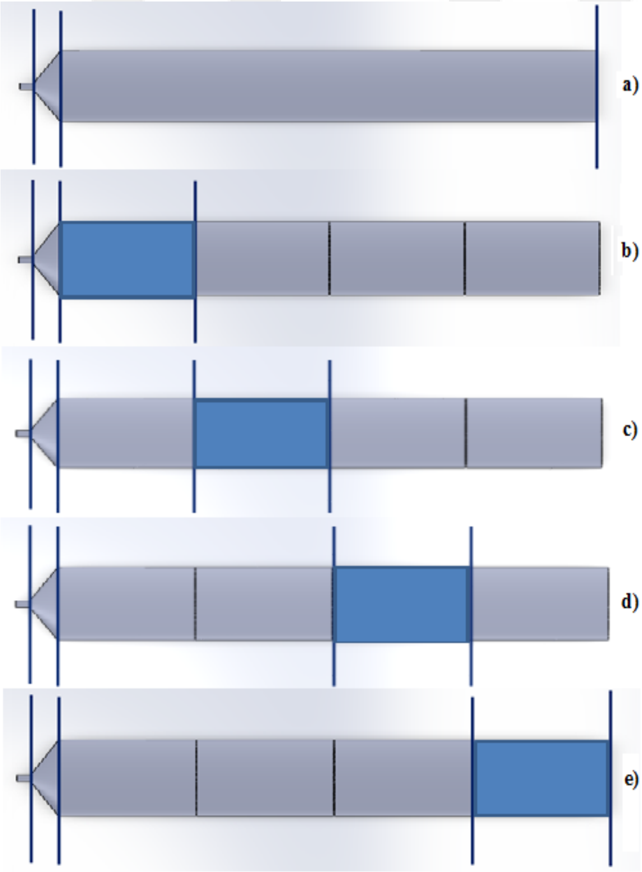


Figure 3. 7 Types and nomenclature of blade samples. a) Reference sample: It is a sample type printed on a 3D printer with all other parts, including the transition zone, filled with 25% filling. b) Sample-1 type: only the 5 cm piece highlighted in blue is weighted with a mixture of iron powder and liquid resin. c) Sample-2 type: only the 5 cm piece indicated in blue color is weighted with a mixture of iron powder and liquid resin, d) Sample-3 type: only the 5 cm piece indicated in blue color is weighted with a mixture of iron powder and liquid resin. and e) Sample-4 type: only the 5 cm piece highlighted in blue is weighted with a mixture of iron powder and liquid resin

The samples produced for each of the sample types, whose names are specified in Figure 3.7, are shown in Figure 18. When you focus carefully on the samples in Figure 3.8, it is clear from the color difference which parts are the weighted parts, and they are depicted in accordance with the order of the sample types in Figure 3.7.

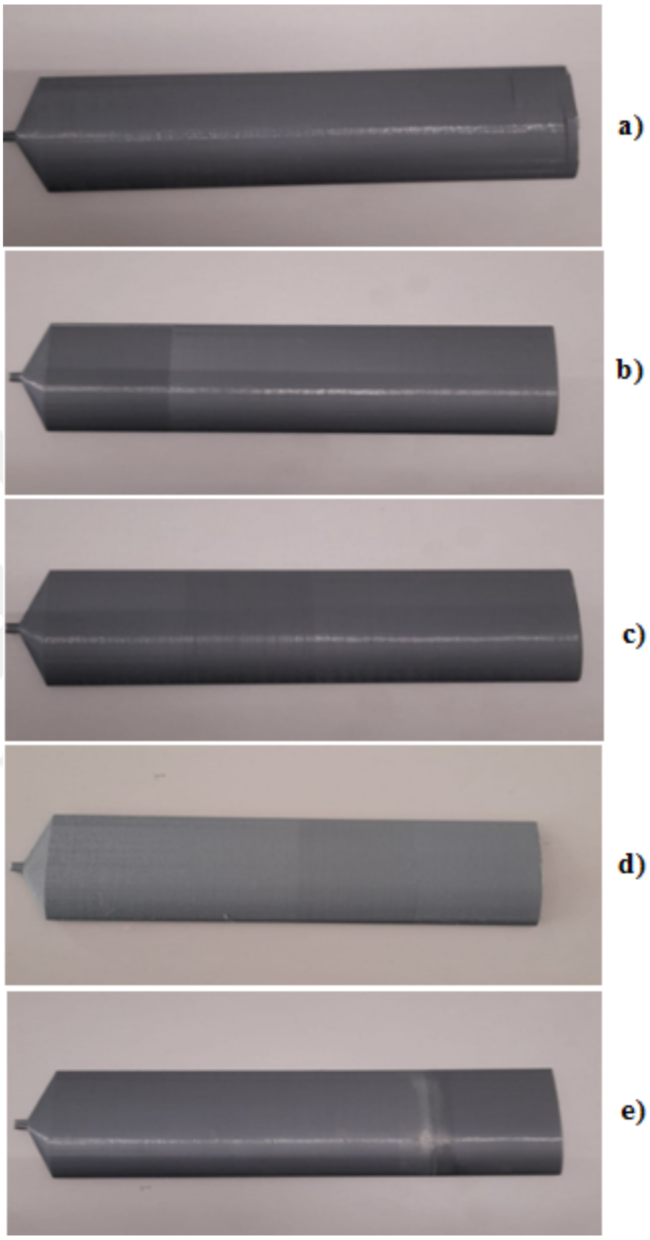


Figure 3. 8 Produced turbine blade sample types. a) Produced reference sample, b) Produced sample-1 type, c) Produced sample-2 type, d) Produced Sample-3 type, and e) Produced sample-4 type.

Nine samples of each sample type given in Figure 3.8 were produced. In order to test these produced blade structures in the wind tunnel and to simulate a realistic wind turbine, blades produced of the same type were mounted on a tower in threes. In this tower structure, a 3D printer was used to produce the blades. A photo of the tower is shared in Figure 19. The dimensions of this tower, which has 3 blades attached, were adjusted according to the tunnel dimensions for wind tunnel tests. In addition, this tower, which has a plastic structure produced with a 3D printer, has been produced in an unusual structure so that it can stand stable and not break during wind tunnel tests. In this context, shear walls representing shear walls were designed between the legs of this tower structure consisting of 3 legs, in order to carry the moment (see Figure 3.10). The most important reason for designing this shear wall structure is to prevent unwanted movements that may mislead the observer in wind tunnel tests and to obtain more stable test results. In addition, instead of producing separate towers for each test, a hub structure with a mechanism that can easily mount and remove the produced blades on the tower has been designed so that one tower can be used in all tests. A picture of this produced hub structure is given in Figure 3.9. In order for the blade root to fit perfectly into the hub, a hexagonal hub was designed instead of a cylindrical design. A connecting element is also used between the hub and the blade (see Figure 3.9).

Figure 3. 10 3D printed wind turbine tower structure with three legs and a curtain wall system between the legs

Figure 3. 9 Hub connection element designed to hold three blade structures

Figure 3. 11 Sample wind turbine produced for wind tunnel tests

Figure 3.11 shows an example of one of the 15 wind turbines to be used for wind tunnel tests, assembled and ready for testing. As seen in Figure 3.11, the blades in the picture are of sample-1 type structure. By using a bearing in the center of the hub connection element, rotation of the blades was ensured in wind tunnel tests. In addition, by keeping the surface area of the ground part of the manufactured tower structure wide, an attempt was made to create sufficient shear capacity on the ground against the wind force on the horizontal axis in wind tunnel tests.

3.2 Testing Process

All wind tunnel tests were carried out in the wind tunnel within the Department of Energy Systems Engineering, Faculty of Engineering, Erciyes University. The wind frequency selected for all turbine samples is 14 Hz. Moreover, the tests were repeated 3 times to obtain more stable data for all sample types. Wind frequency was kept constant throughout the experiment. The experiment process was recorded in slow motion with a camera, and then the number of rotations of the blades was obtained in time by watching these recordings. Figure 3.12 is an example of a total of 15 wind tunnel tests.

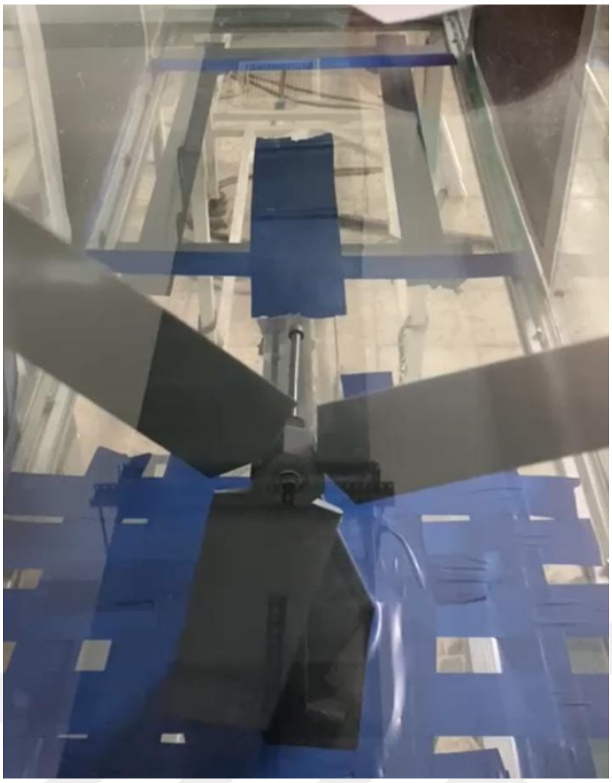


Figure 3. 12 Experimental study in wind tunnel

Chapter 4

Planar Kinetics of Three Blades in Wind Energy

4.1 Mass Moment of Inertia

Given that a body possesses a distinct size and shape, the application of a nonconcurrent force system can induce both translational and rotational motion in the body. While the equation F = ma governs the translational component of the motion, the equation in the form of M = IA governs the rotational part of the motion, resulting from a moment M. Within this equation, I and A represent the mass moment of inertia and angular acceleration, respectively. According to these equations, while the moment of inertia serves as a quantification of a body's opposition to angular acceleration, mass quantifies the body's resistance to translational acceleration.

The moment of inertia is defined as the calculation of the integral of the "second moment" around an axis, considering all the mass parts dm that make up the body. As an illustration, the moment of inertia of the body with respect to the z-axis can be observed in Figure 4.1.

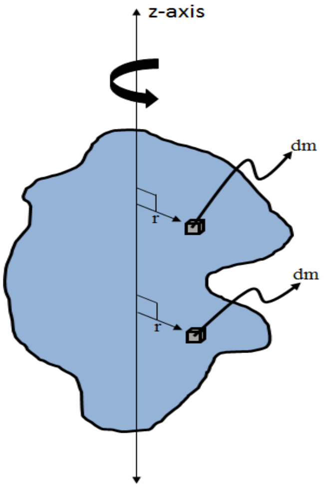


Figure 4. 1 Rotational motion of a particular mass dm around an axis passing over the center of mass of the rigid body.

$$I_z = \int r^2 dm \qquad \text{Eq. 4.1}$$

In Figure 4.1 and Eq. 4.1, the "moment arm" (denoted as *r*) represents the perpendicular distance between the rotational movement axis and the hypothetical element dm. In the field of planar kinetics, it is customary to select an axis for analysis that intersects the mass center *G* of the rigid body and is consistently oriented perpendicular to the plane of motion. The indicated symbol for the moment of inertia about this axis is IG. Considering a rigid body composed of material with a variable density, denoted as as $\rho = \rho\ (x, y, z),$ it is possible to describe the elemental mass dm of the body in relation to its density and volume as $dm = \rho dV$.. By substituting the value of dm into Equation 4-1, the moment of inertia of the rigid body is subsequently calculated as follows:

$$I_G = \int r^2 \rho dV \qquad \text{Eq. 4.2}$$

In the specific scenario where ρ is a constant, it is possible to factor out this term from the integral, resulting in the integration being solely dependent on the geometry. Therefore, Eq. 4.2 can also be written as:

$$I_G = \rho \int r^2 dV \qquad \text{Eq. 4.3}$$

4.2 Parallel-Axis Theorem

Utilizing the parallel-axis theorem, one can ascertain the moment of inertia of an object with respect to any other parallel axis, given knowledge of the object's moment of inertia about an axis passing through its mass center (see Figure 4.2). The z'-axis intersects the mass center G, whereas the parallel z-axis is positioned at a constant distance d. By choosing the differential element of mass dm, which is situated at coordinates (x', y'), and employing the Pythagorean theorem ($r^2 = (d + x')^2 + y'^2$), it is possible to calculate the body's moment of inertia with respect to the z-axis as

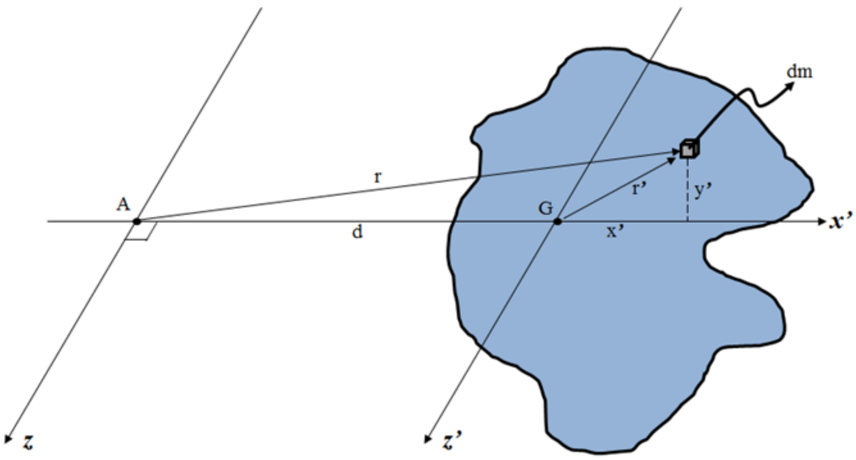


Figure 4. 2 The utilization of parallel axis theorem for the mass moment of inertia of the rigid body with respect to the z-axis.

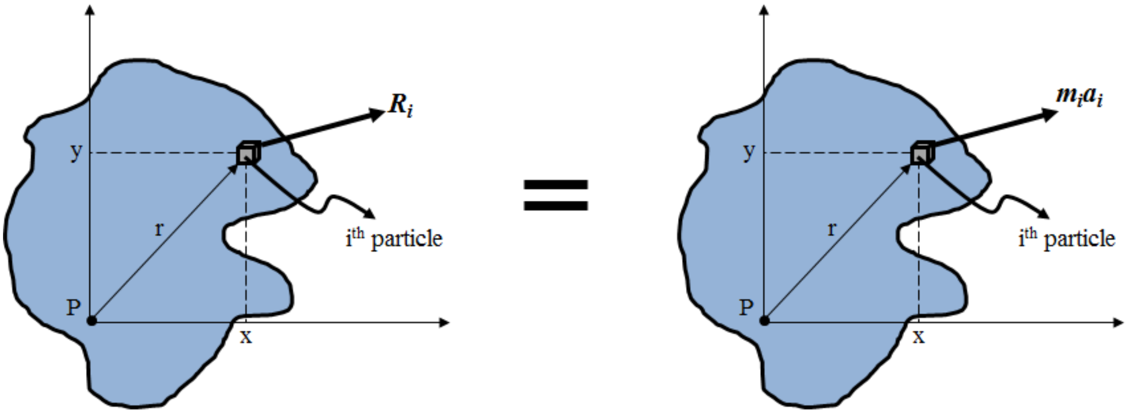
$$I = \int r^2 dm = \int ((d + x')^2 + y'^2)dm = \int (d^2 + x'^2 + 2dx' + y'^2)dm = I_G + md^2 \quad \text{Eq. 4.4}$$

in which IG is the mass moment of inertia about the z'-axis passing over the center of the mass of the rıgıd body. While m represents the total mass of the rigid body, the symbol of d is for the perpendicular distance between the parallel z and z' axes.

4.3 Planar Kinetic Equations of Rotational Motion for Rigid Bodies

This part of the chapter will look at how the moments caused by the external force system affect the rotational motion about the z-axis that is perpendicular to the plane of motion and goes through point P (see Figure 4.3). R_i is the resultant force exerted on the i^{th} particle, and the particle is supposed to have an acceleration of a_i and a mass of m_i. Under these circumstances:

$$(M_p)_i = r \times R = r \times m_i a_i \quad \text{Eq. 4.5}$$



a) Free-body diagram **b)** Kinetic diagram

Figure 4. 3 Particle free-body and kinetic diagrams for the rotational motion of rigid bodies

To recall the concept of relative motion analysis, as in Eq. 4.6 below, the translational acceleration at point B in a rigid body (a_B) is equal to the sum of the translational acceleration at point A (a_A), the tangential acceleration of point B relative to point A ($(a_{B/A})_t$), and the normal acceleration of point B relative to point A ($(a_{B/A})_n$).

$$a_B = a_A + \left(a_{B/A}\right)_t + \left(a_{B/A}\right)_n \qquad \text{Eq. 4.6}$$

Since the tangential and normal components of the relative acceleration represent the effect of circular motion observed from translating axes having their origin at point A, these components can be defined as in the equations given below.

$$\left(a_{B/A}\right)_t = \alpha \times r_{B/A} \qquad \text{Eq. 4.7}$$

$$\left(a_{B/A}\right)_n = -\omega^2 r_{B/A} \qquad \text{Eq. 4.8}$$

where α is the angular acceleration and ω is the angular velocity for the rotational motion. Combining these two equations with Eq. 4.6, the new equation can be derived as follows:

$$a_B = a_A + \alpha \times r_{B/A} - \omega^2 r_{B/A} \qquad \text{Eq. 4.9}$$

According to the equations (Eqs. 4.5 and 4.9), it is possible to express the resultant moment about point P in terms of the accelerations of point P as follows:

$$\left(M_p\right)_i = m_i \left(r \times a_p + r \times (\alpha \times r) - \omega^2 (r \times r)\right) \qquad \text{Eq. 4.10}$$

The last term in Eq. 4.10 should be zero ($\omega^2(r \times r) = 0$), because the cross product of the same vectors is zero. Using Cartesian components to express the vectors *r* and a_p, Eq. 4.11 can be derived as follows:

$$(M_p)_i \hat{k} = m_i \left\{ (x\hat{\imath} + y\hat{\jmath}) \times \left[(a_p)_x \hat{\imath} + (a_p)_y \hat{\jmath} + \alpha \hat{k} \times (x\hat{\imath} + y\hat{\jmath}) \right] \right\} \qquad \text{Eq. 4.11}$$

Performing cross-product operations in Eq.4.11, then it yields,

$$(M_p)_i \hat{k} = m_i \left\{ \alpha r^2 + x(a_p)_y - y(a_p)_x \right\} \hat{k} \qquad \text{Eq. 4.12}$$

According to Figure 4.2, m_i goes to *dm*. Therefore, by integrating with regard to the body's total mass (m), the resultant moment is obtained as below:

$$\circlearrowleft \sum M_p = \alpha \left(\int r^2 \, dm \right) + (a_p)_y \left(\int x dm \right) - (a_p)_x \left(\int y dm \right) \qquad \text{Eq. 4.13}$$

The first term in Eq. 4.13 represents mass moment of inertia about the z-axis (see Eq. 4.1 and Figure 4.1). The second and the third terms in this equation represents the location of the center of mass for the rigid bodies in x and y axes, respectively. Therefore, Eq. 4.13 can be written in a simpler mathematical form as follows:

$$\circlearrowleft \sum M_p = I_z \alpha + (a_p)_y \bar{x} m - (a_p)_x \bar{y} m \qquad \text{Eq. 4.14}$$

To calculate the resultant moment of the rigid body about the center of mass, the points P and G (the center of mass) coincide in the x-y plane. Thus, the simplest mathematical form of Eq. 4.14 can be derived as below:

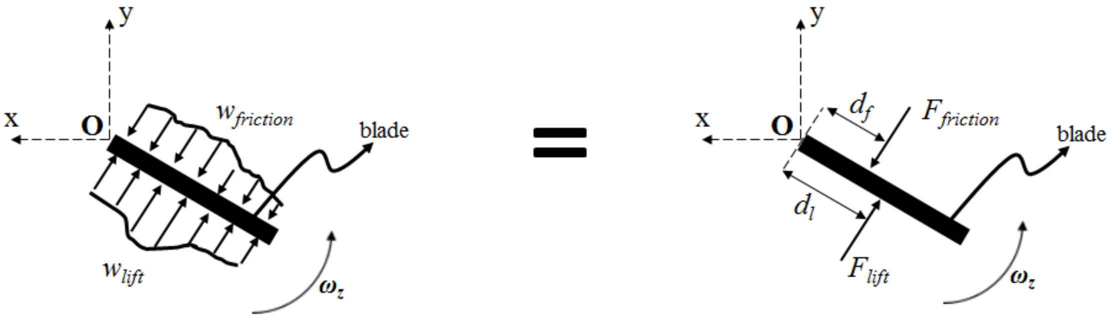
$$\circlearrowleft \sum M_G = I_G \alpha \qquad \text{Eq. 4.15}$$

4.4 Planar Kinetic Equations for the Rotational Motion of Wind Turbine Blades

Figure 4.4 shows the distributed lift and friction loads on a wind turbine blade. The resultant forces corresponding to these distributed loads in opposite directions are expressed as lift force and friction force. These forces will create a moment on the blade around the hub of the turbine (point O) as follows:

$$\circlearrowleft \sum M_o = F_l d_l - F_f d_f = I_o \alpha = (I_G + m d^2)\alpha \qquad \text{Eq. 4.16}$$

in which F_l and F_f are represents the lift force and the friction force subjected to the wind turbine blade, respectively. Furthermore, d_l and d_f are the corresponding level arms for the moments of the lift and the friction forces. In this equation, the mass moment of inertia about point O can be also calculated using the parallel-axis theorem (see Eq. 4.4).



a) **b)**

Figure 4. 4 Distributed loads and resultant forces subjected to wind turbine blades

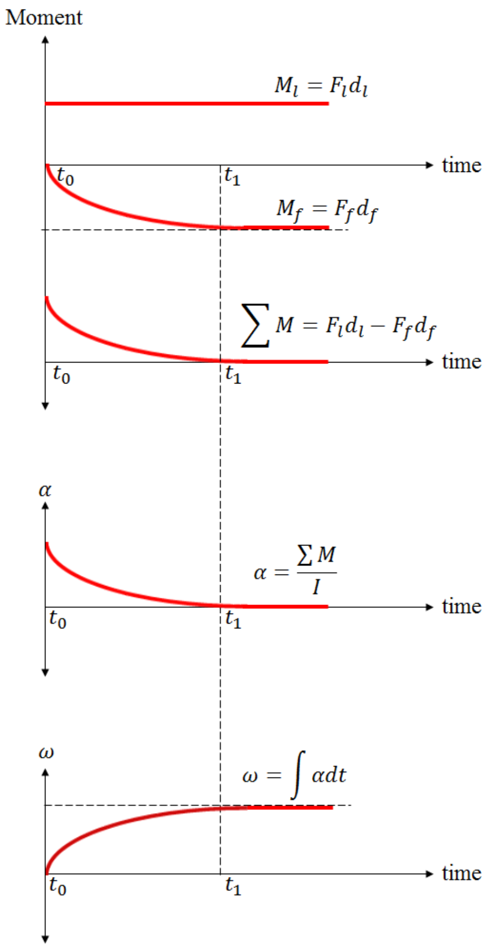


Figure 4. 5 Representative processes corresponding to both angular velocity and acceleration for wind turbine blades

If the moment of the lift force created by the wind speed exceeds the moment of the static friction force, the positive net moment on the blade will start to rotate the blade with a constant angular acceleration according to the formulation given by Eq. 4.16. This constant angular acceleration will cause the blade to rotate faster over time. Consequently, the dynamic friction force acting on this blade, which rotates faster and faster over time, will start increasing. The moment provided by this increasing friction force will also increase over time and become equal to the moment of the wind lifting force. If this equality is met, the net moment applied to the blade will be zero, and according to Eq. 4.16, the angular acceleration value of the blade will now reach to zero. The fact that the angular acceleration is zero means that the rotation speed of the blade remains constant. All these processes after the blade starts to rotate are represented with both the angular velocity and acceleration versus time plots in Figure 4.5. According to this figure, the blade starts to rotate with the initial time (t_0). The blade that starts to rotate continues its rotation by increasing its inherent velocity due to the maximum angular acceleration just after the initial time. However, the facts that the wind speed is constant and the friction force on the blade increases over time, cause the net moment on the blade gradually decreases. This net moment value, which decreases over time, causes the angular acceleration of the blade to gradually decrease. Until the time reaches t1, the net moment on the blade will be completely zero and the angular acceleration will become zero. Therefore, at time t_1, the speed of the blade will now be completely constant and will not increase in any way.

Chapter 5

Results and Discussion

5.1 Introduction

All constructed wind turbines mentioned in Chapter 3 were subjected to tests in the wind tunnel within the Energy Systems Engineering Department of Erciyes University Faculty of Engineering. All results and data obtained from these experiments are discussed in this chapter. All discussions about the interpretation of the experimental results are also discussed in this section of the thesis.

5.2 Experimental Results

A total of 15 tests were conducted in the wind tunnel. In total, 3 wind turbines with blades produced in the same type were created for each of 5 different sample types. In this context, 3 wind turbines with different blades produced in the same type were used to obtain average values. The wind tunnel tests mentioned were carried out by keeping the wind frequency constant at 14 Hz. The experiment process was recorded in slow motion with a camera, and then the number of rotations of the blades was obtained in time by watching these recordings. All these data obtained on the time axis are shared in Figures 5.1-5.3. The y-axis in these figures shows the number of turns the blades make against the wind force. The x-axis shows the elapsed time in seconds.

Table 5.1 Experiment 1 data

EXPERIMENT 1						
	s0	s1	s2	s3	s4	Time
Angular Velocity (rad/s)	0	0	0	0	0	0
	4,71239	3,13999	3,46189	3,60931	3,14159	4
	7,22566	4,29821	4,71647	3,34021	3,14159	6,6
	7,85398	5,73277	5,92206	4,98000	4,20973	9,6
	8,04248	7,16779	8,24312	7,09057	6,28319	17,4
	9,23628	10,52146	9,09816	7,72518	6,97434	24,2
	10,80708	10,92540	9,42009	8,75876	7,85398	30
	12,56637	10,90563	10,35091	9,04339	7,85398	35
	12,06372	12,61113	11,48407	10,54067	8,98495	40,2
	11,24690	11,25411	10,81202	9,69119	7,85398	45,8
	14,95398	12,53830	11,71103	9,97330	8,98495	50
	13,06903	12,71643	11,77681	6,78521	8,98495	54,8
	15,70796	13,06145	11,44418	10,28180	8,79646	57,6
	15,70796	13,12310	11,73775	10,30505	8,98495	58
	15,70796	12,76501	11,57126	10,57711	9,11062	62

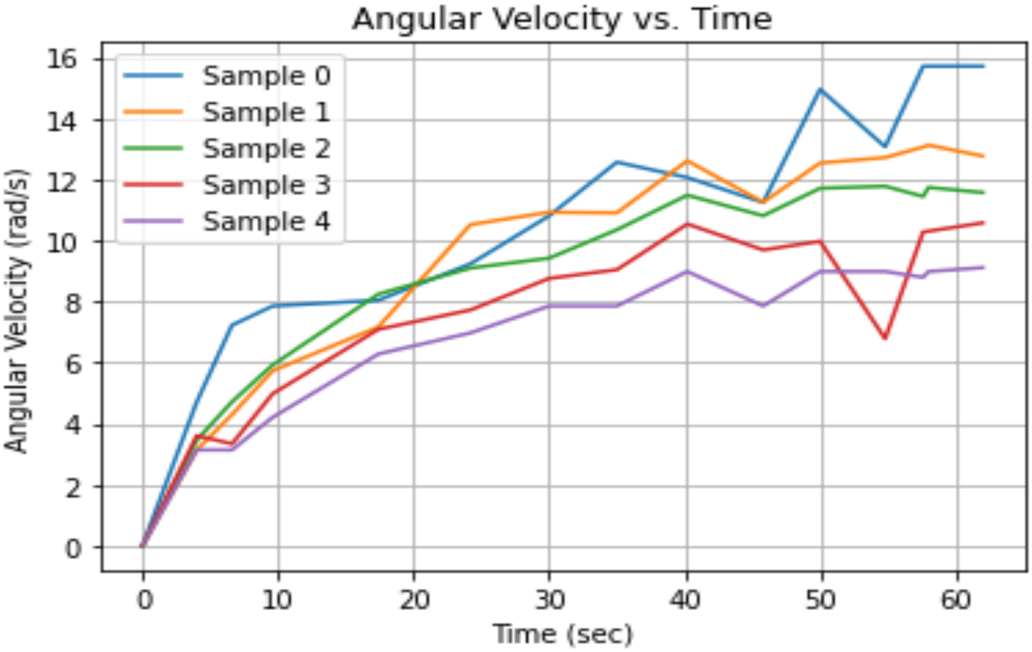


Figure 5. 1 Experimental result data with different types of blades for experiments in the first iteration. Blue, purple, yellow, orange and green colors represent the wind turbine with blades of the reference sample type, sample-1 type, sample-2 type, sample-3 type, and sample-4 type, respectively.

Table 5. 2 Experiment 2 data

EXPERIMENT 2						
	s0	s1	s2	s3	s4	Time
Angular Velocity (rad/s)	0	0	0	0	0	0
	4,9982924	4,3604	3,93161	4,305036	4,101020	4
	6,6924032	5,0403	4,48188	3,777499	3,434963	6,6
	7,6435659	6,0676	5,33147	4,669746	4,077967	9,6
	8,3898012	8,7394	8,13361	7,223314	6,676004	17,4
	9,8891623	9,1349	9,06789	7,832669	7,089460	24,2
	10,104845	10,571	9,08301	8,311244	7,206959	30
	13,358465	12,166	10,126	9,39404	8,450395	35
	12,478496	12,06	10,8356	10,36348	9,177887	40,2
	11,204260	12,101	10,5414	9,280786	7,938914	45,8
	14,831319	12,321	11,4471	10,2611	9,308693	50
	12,932299	12,857	11,6345	10,64176	9,149201	54,8
	15,517515	12,873	10,2921	9,918262	8,204906	57,6
	15,722443	13,151	11,4509	10,20262	8,882955	58
	15,740189	12,974	12,163	10,15919	9,018849	62

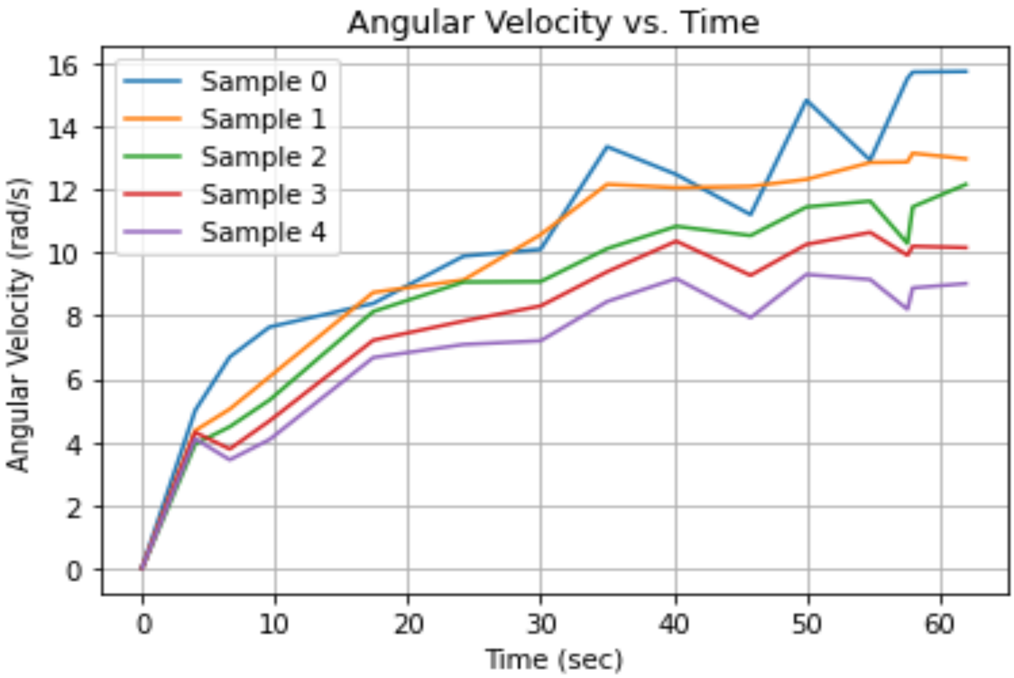


Figure 5. 2 Experimental result data with different types of blades for the experiments in the second iteration. Blue, purple, yellow, orange and green colors represent the wind turbine with blades of the reference sample type, sample-1 type, sample-2 type, sample-3 type, and sample-4 type, respectively.

Table 5. 3 Experiment 3 data

EXPERIMENT 3						
	s0	s1	s2	s3	s4	Time
Angular Velocity (rad/s)	0	0	0	0	0	0
	3,95599	3,45823	3,25924	3,07499	2,83941	4
	7,06610	4,58474	4,46133	4,08168	3,34737	6,6
	6,95634	5,73529	5,11148	5,02260	4,62740	9,6
	8,02937	8,14040	8,15012	7,20394	6,33671	17,4
	8,88401	9,88311	9,92563	8,39439	7,52785	24,2
	12,17542	10,02236	10,20238	8,94228	8,05706	30
	13,28169	11,42453	9,78003	8,45423	7,36129	35
	10,49488	11,62630	10,53940	9,08304	7,85061	40,2
	11,52420	12,68206	10,91685	10,11843	9,02177	45,8
	14,07551	12,61859	11,78600	9,66977	8,60512	50
	12,90877	13,07937	11,87646	10,34560	9,04990	54,8
	15,81126	12,30059	11,96378	10,30420	9,15031	57,6
	16,17778	12,51272	11,40595	10,35392	9,05633	58
	15,53640	12,81982	11,63488	10,09107	8,54216	62

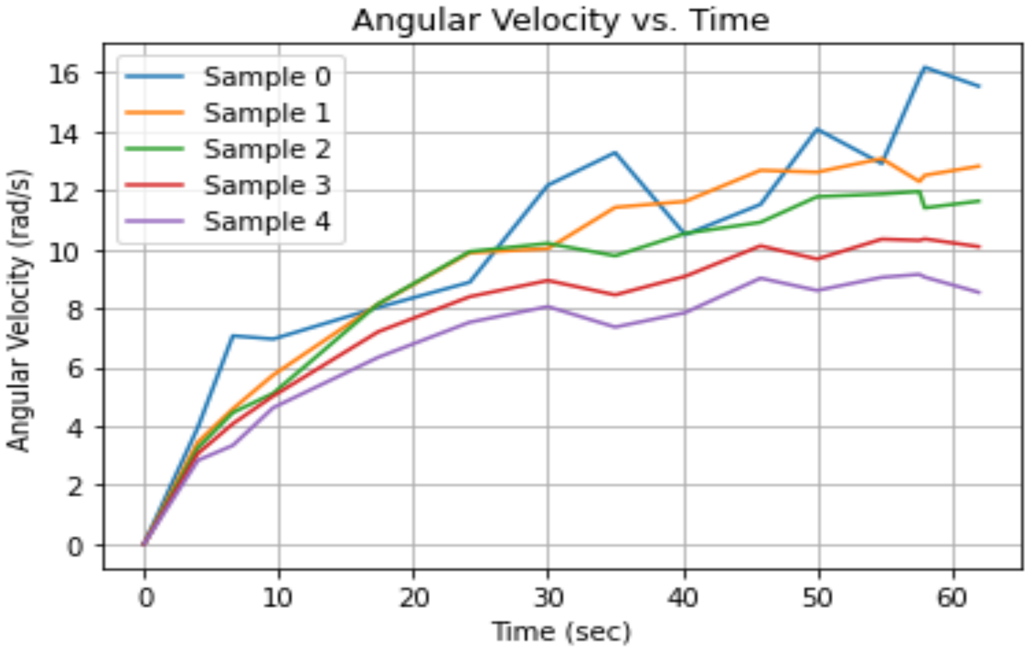


Figure 5. 3 Experimental result data with different types of blades for the experiments in the third iteration. Blue, purple, yellow, orange and green colors represent the wind turbine with blades of the reference sample type, sample-1 type, sample-2 type, sample-3 type, and sample-4 type, respectively.

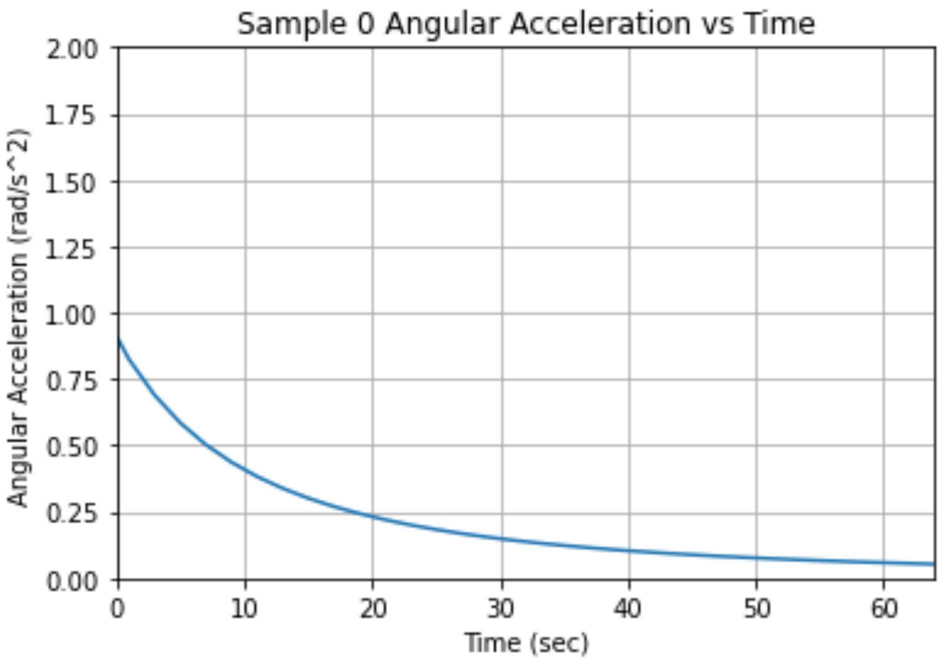


Figure 5. 4 Angular Acceleration vs Time for reference sample

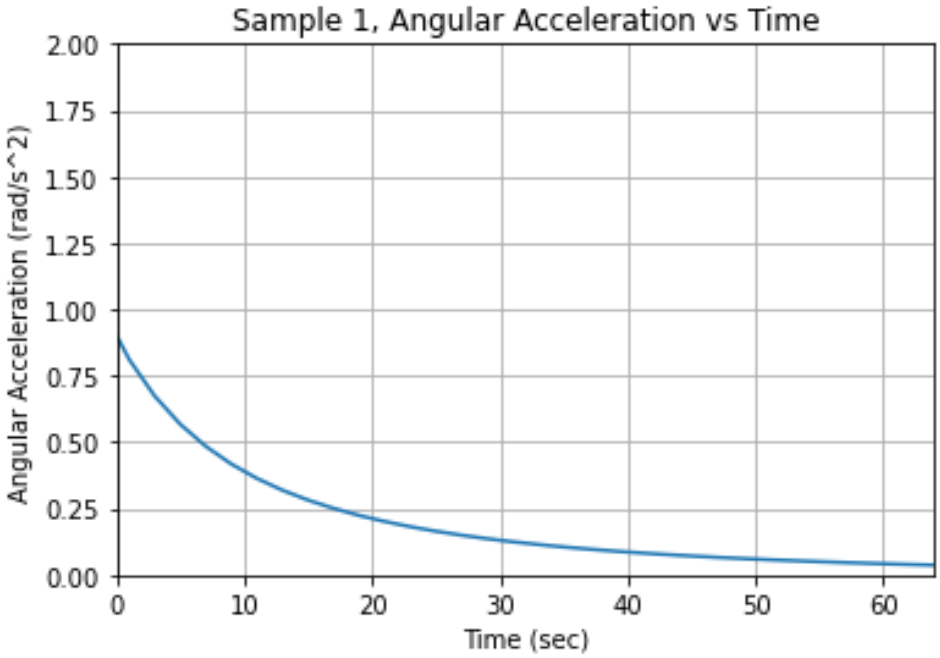


Figure 5. 5 Angular Acceleration vs Time for sample 1

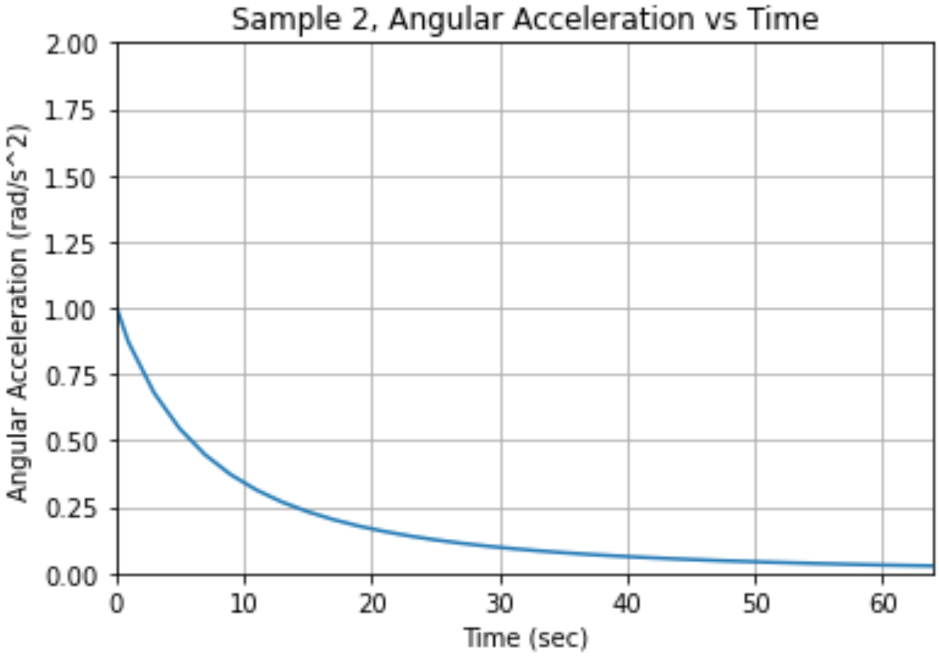


Figure 5. 6 Angular Acceleration vs Time for sample 2

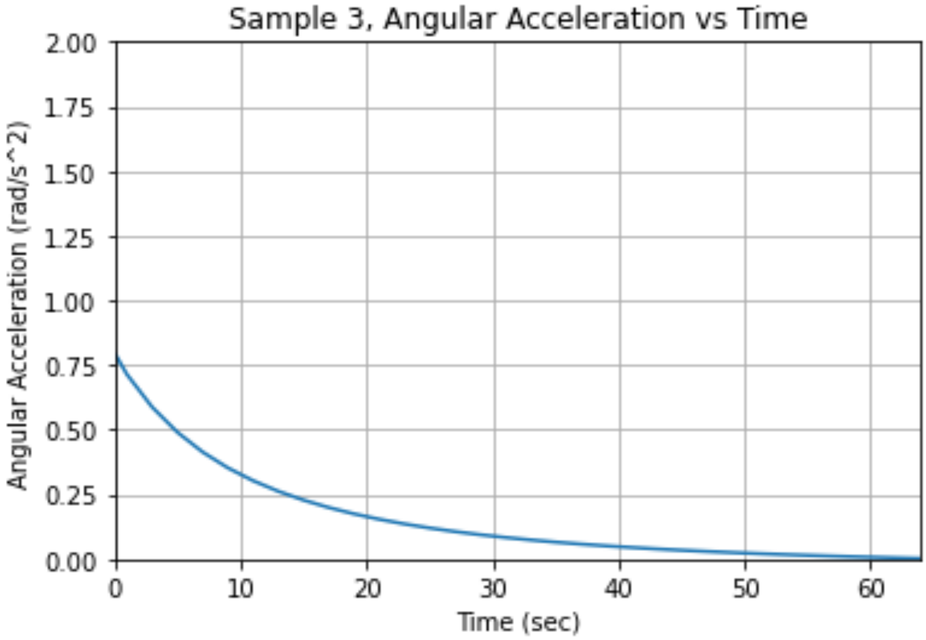


Figure 5. 7 Angular Acceleration vs Time for reference sample 3

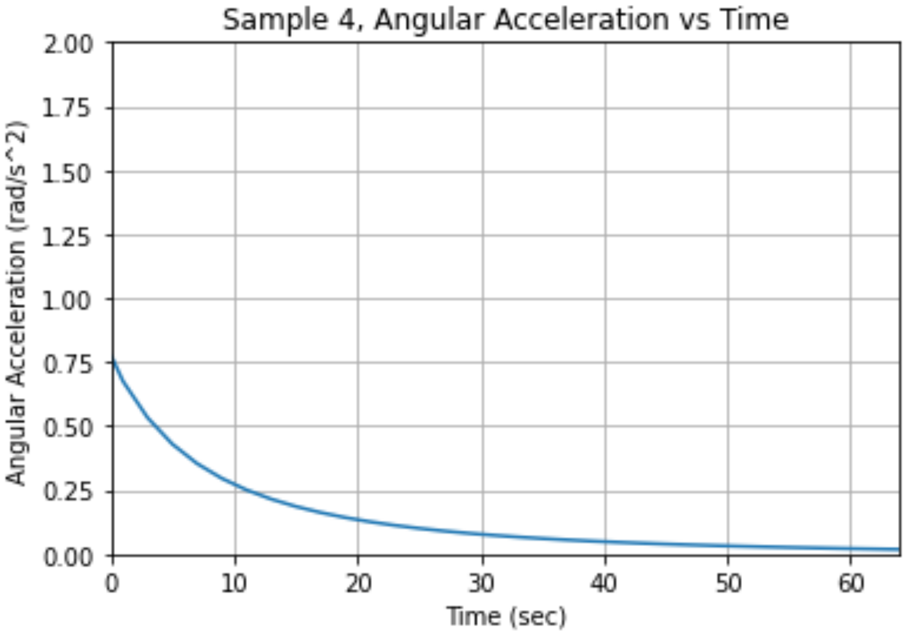


Figure 5. 8 Angular Acceleration vs Time for reference sample 4

As can be seen from the figures above (Figures 5.1-5.3), the blades of the reference sample type can accelerate faster and reach a higher number of turns compared to other blades. The main reason for this is that it has the lightest blades, as no weighted sections are used in the blade structure of the reference sample type. Since the inertia of light blades in rotation is lower than that of other weighted blades, it is thought that the blades of the reference sample type accelerate better and can reach higher rotation numbers despite the wind blowing at the same speed.

It was shown in the previous section of the thesis that, while going from sample type-1 to sample type-4, the weighted sections in the produced blade structures are further away from the rotation axis of the wind turbine (see Figures 3.7 and 3.8). In this case, when going from sample type-1 to sample type-4, the rate of increase of the number of turns, that is, the acceleration of the blades in rotation, decreases. In addition, when going from sample type-1 to sample type-4, the maximum amount of rotation reached by the blades also decreases. It is considered that the main reason for this result is that the inertia in rotation increases from sample type-1 to sample type-4.

Chapter 6

Conclusion and Future Prospects

6.1 Conclusions

According to the results of the experiments carried out in this thesis, it was revealed that the inertia of the blades in rotation is related to the number of turns they will make against the wind. Since it is known that the inertia in rotation is related to the mass distribution along the length of the blade structure, two basic results have emerged:

1. Blades with lower mass moment of inertia will accelerate faster against the wind force and the maximum number of rotations they can achieve will be higher.
2. When longitudinal mass distribution away from root to end part changed angular velocity also changed. The highest velocity was obtained in the sample close to the root
3. In order for the blades to be produced by the industry for wind turbines to rotate at higher speeds and to maximize energy efficiency, the rotational inertia of the produced blades must be kept low. When producing single or segmented turbine blades, it should not be overlooked that the effect of the longitudinal mass distribution on the inertia parameter should also be included in the calculations for aerodynamic designs.

6.2 Societal Impact and Contribution to Global Sustainability

Wind turbines play an important role in advancing the sustainability goals of contemporary energy production. They transform wind energy into a sustainable and energy source which is environmentally friendly, reducing consumption of fossil fuels and significantly reducing emissions to atmosphere. In addition, great importance will be given to conducting research on the sustainability of the efficiency of wind turbines, developing this technology and increasing the positive effect on the environment.

Partial production of wind turbine blades offers a number of advantages and creates positive impact side of sustainability. Compared to the production of traditional long blades in one piece, the batch production method significantly simplifies the transportation, assembly and maintenance processes. Thus, the installation of turbines in more remote and hard-to-reach areas becomes more effective, and transportation costs also decrease. When this feature of offshore wind turbine projects is considered together with their ability to provide very good adaptation to the different and harsh conditions found in the sea, a provides a significant advantage for sustainable energy production.

Partial production of blades has a positive effect on recycling activities and waste management. Each blade segment is specially designed and can be produced from recycled materials, and in case of any damage during the operation of the turbine, the total amount of waste can be reduced by replacing a specific segment.

However, it is very important to control the additional masses that may occur on the blades of wind turbines. In this way, the possibility that additional masses will affect the aerodynamic performance of the wings and reduce their mechanical strength by creating vibrations can be prevented. Therefore, optimizing wing designs is important to manage additional masses and keep them to a minimum.

Consequently, Studies on wind turbines should include plans to increase sustainability and efficiency in technology. Innovations such as segmented production of blades are encouraging researchers, engineers, and industry experts in this field to find more efficient solutions to future needs of energy and minimize environmental impacts. Developing research on wind energy directs the future towards a more sustainable and environmentally friendly life.

6.3 Future Prospects

Recommendations for the future development of wind turbine technology include continuous innovation and sustainability efforts in the industry. Chief among these suggestions are innovations in the basic design elements of wind turbines. It is predicted that turbine blade profiles that are optimized and aerodynamically improved can increase energy efficiency. In addition, it is possible to increase the durability and life of wind turbines by using new generation materials.

Partial production and modular design concepts are of significant cost importance by optimizing transportation, assembly and maintenance processes. It is possible that costs will be reduced significantly. This approach can offer significant advantages for wind turbines with taller towers and larger diameter rotors. Taller towers and larger diameter rotors could also allow future turbines to produce energy more efficiently; because it is predicted that these features may allow more energy to be obtained from winds at higher altitudes. Additionally, as shown in the study, optimization of mass distribution on the blade should not be ignored. It is very important to examine the longitudinal load distribution and include it in the calculations during the production stages.

These recommendations provide actionable strategies to support the future growth of the wind energy sector, increase energy efficiency and minimize environmental impacts. Future studies may lead to the advancement of wind turbine technology in this direction and provide more effective solutions for sustainable energy production.

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