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Low-Cost, Low-Weight Test Rig Design for a Laboratory-Scale Twin Rotor Wind Turbine

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ABSTRACT

Multi-Rotor Wind Turbine (MRWT) has been proven in literature to be advantageous over Single-Rotor Wind Turbine (SRWT) in many aspects. In order to study the performance of MRWT over SRWT, this work presents a novel design for a low-cost and low-weight design for a test rig for laboratory-scale wind turbine SRWT and MRWT configurations. The configurations under study are a single-rotor, and a twin-rotor of the same size with a diameter of 30 cm. Aerodynamic loads have been calculated using the Blade Element Momentum (BEM) method, then the loads were used for stress analysis over the test rig proposed. The test rig is designed on Solidworks and the aerodynamic and inertial loads were applied for static structural analysis. The analysis showed that both configurations are safe against failure and the deflections were reasonable to ensure low vibrations which may affect the turbine performance. The single-rotor configuration test-rig is about 16 gm in mass, with a 1.67 factor of safety, while the twin-rotor configuration weighs 360 gm with a factor of safety of 3.7.

1. Introduction

Nowadays the world is moving towards increasing the use of renewable sources of energy over conventional sources and fossil fuels to maintain a sustainable and environmentally friendly energy output. One of the most significant renewable energy sources is wind energy. The global wind sector had its second-best year in 2021, installing nearly 94 GW of capacity worldwide, trailing the record rise of 2020 by just 1.8%, according to the Global Wind Energy Report 2022. With more than 88 GW of wind power granted globally in 2021, wind installations grew by 153% (Lee and Zhao 2020). So, there are positive trends shown in the research to harvest maximum power from the wind.

Researchers compete to increase wind turbine performance to gather as much wind energy as possible and transform it into usable electrical energy. Although larger wind turbines are thought to be more advantageous from an installation and investment standpoint, the cost of energy is mostly determined by the number of wind turbines, not their size, However, the advantages of larger turbines are outweighed by their higher failure rates and longer maintenance times and heavyweight (M.Hofmann and I.B.Sperstad 2014). Furthermore, if a single-rotor wind turbine breaks, the capacity of that turbine in a wind farm is completely lost.

The capacity of wind turbines can be increased while avoiding the drawbacks of large-scale wind turbines by mounting multiple rotors on a single tower which is called a Multi-Rotor System (MRS). Hoffman first presented the MRS concept in 1930 (P.Jamieson and G.Hassan 2011), and William Heronemus proposed an 18-rotor multi-rotor array arrangement in the 1970s (W.E 2004). Henk Lagerweij created three different MRS WTs configurations in 1980; twin, quadro, and six masters. but at that time, building a multi-rotor was not feasibly possible (Verma 2013). Since advances in materials science

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and analytical techniques have made it simpler to estimate and build a support structure for the MRS wind turbine, MRS has repurposed the interest of researchers in the last ten years.

Many researchers have investigated the performance of MRS wind turbines in terms of aerodynamics, power output, and support structure analyses. Goltenbott et al. conducted an experimental examination of the power produced by MRS in various configurations and found that a 2-rotor configuration produces 5% more power than a single-rotor configuration of the same size, and a 3-rotor configuration produces 9% more power (U.Göltenbott, et al. 2017). Other researchers, such as Chasapogiannis et al., supported those findings by applying Computational Fluid Dynamics (CFD) to analyze a seven-rotor design and discovered a 3% improvement in power per rotor (Chasapogiannis, et al. 2014). Likewise, researchers from the Technical University of Denmark (DTU) investigated the benefits of MRS on a four-rotor configuration, and the result coincided with calculations of an increase of 2% in power output per rotor (Laan, et al. 2019). Also, researchers of The University of The West Indies have studies showed that a the rotor separation distance of 0.25 meters gave an additional power increase of 3.6% over a single rotor wind turbine (O.Mohammed and Adeyanju 2020).

Cost-wise, L. Fingersh et. al. studies showed that significant price variations for essential materials like structural steel and copper in 2004 and 2005 affect individual material costs on wind turbine components. Based on the Product Price Index (PPI) of the U.S. Department of Labor, a component cost response model was created (Fingersh, Hand and Laxson 2006). Narayanan et. al. Studied that the major goal of the MRWT is to lower the machine's overall cost. To establish a thorough, safe design, additional IEC design conditions such as extreme operational gusts, extreme turbulence models, extreme direction changes, and extreme wind shear should be taken into consideration (EWS). There will be differential loads, shear, yawing, etc. on the frame. It is important to study other environmental factors as well, such as temperature, wetness, rain, snow, ice, waves, and rain (Narayanan, et al. 2020). Navjot Singh et. al. studies have shown that the cost of a multi-rotor wind turbine comes out to be 83.47% of a single rotor turbine (Sandhu and Chanana 2018). Sandip A Kale studied that, the idea of multi-rotor wind turbines is difficult, but the difficulty idea has become less popular. Researchers and manufacturers will soon turn their attention to small rotors because of this understanding. For chosen size rotors, manufacturing standards can be useful (Kale 2013).

Farahani et. al. studied that the standard concept design is used by the large majority of wind turbines that are currently in use. Dual-rotor wind turbines (DRWT) have just recently been released on the market. In both constant speed and constant pitch angle modes, DRWT adds more damping torque to the network (Farahani, Hosseinzadeh and Ektesabi 2012). Mishra and Paliwal utilized an airflow twin-rotor to increase the wind turbine's torque and power. The results showed that at 16 m/s of wind speed, the maximum torque for a dual airflow wind turbine is 36.9% higher than for a single rotor (Paliwal 2021). Bastankhah and Abkar's studies showed that the short downwind lengths are discovered to cause a multi-rotor wind turbine's wake to recover faster. Different geometrical arrangements affect wake characteristics in various ways. The wake recovery for multirotor turbine wakes is not significantly influenced by the number of rotors or their direction of rotation (Bastankhah and Abkar 2019). K. Hisham et.al. study showed that the twin-rotor configuration's rotor thrust load is as little as 50% of that of the single-rotor configuration. The greatest torque displayed by torque loads was 20% of the torque of a single rotor, while the power output was around 50% of that of a single rotor (Hisham, et al. 2021).

Considering the advantages of MRS wind turbines, Ismaiel and Yoshida conducted an aeroelastic analysis on a T-shaped tower for a twin-rotor wind turbine (Ismaiel and Yoshida 2019). A study at the University of Massachusetts Amherst showed that scaling models have been shown to reduce the weight and price of the RNA components by 25 and 37 percent, respectively, Due to the triangular truss support arrangement, the MRWT's tower top weight is 5.13 percent higher than that of the single-rotor machine, The gearbox and generator in the nacelle will weigh far less than those in single rotor turbines (Verma 2013) (Mate 2014).

According to research by J. Jonkman et. al., NREL created the requirements for a representative utility-scale multimegawatt turbine. The "NREL offshore 5-MW baseline wind turbine" is its current name. This wind turbine is a typical three-bladed upwind turbine with changeable speeds, blade pitches, and feather counts (J. Jonkman 2009). Giger and Kleinhansl's research demonstrates the presentation included presented a multi-rotor wind turbine with several generator drive trains. The loads on the tower structure are reduced by a control structure that was suggested. Using information processing, electronics, mechanical/aerodynamic modeling, and numerical calculation, this method is founded on the mechatronic principle (Giger, Kleinhansl and Schulte 2021). Prajapati and Shukla studied that MR configuration with 0.5D tip distance results in a 9% improvement in power generation when compared to SR configuration with the same frontal area and tower height (Prajapati and Shukla 2022).

Acar et. al. studies involved a three-blade rotor device with parametric stiffness resembling a horizontal-axis wind turbine. Gravitational parametric and direct excitation terms are present in the blade equations, which are related via the hub equation. The system displays superharmonic and subharmonic resonances because of the gravitational influences (Acar, Acar and Feeny 2020). Jiang et. al. studied that, Cities and distant semi-urban locations are thought to benefit more from vertical-axis wind turbines. It was suggested to build a wind turbine with four quadrotors and an active yaw system. The system was willing to adapt the turbine plane parallel to the wind direction under survival conditions (Jiang, et al. 2022). Ghaisas et. al. showed that the LES results can be predicted with reasonable accuracy if the right decisions are made. Beyond about 2D downstream of a single one-rotor or four-rotor turbine, predictions are very accurate. The trend of a steady decline in relative power of each turbine row cannot be replicated by the model (Ghaisas, Ghate and Lele 2020).

With logistical benefits like cheaper transportation costs, simpler installation, and easier maintenance, a multi-rotor wind turbine introduces lighter rotors at a lower cost. In order to test the performance of MRWT compared to SRWT, wind tunnel experiments are required to compare the output power for each configuration. Wind tunnel experiments can be performed on a small-scale, or a large-scale turbine (He, et al. 2022). The main goal for wind tunnel experiments is to provide a controllable and adjustable conditions for experiments (Dou, et al. 2020). Wind tunnel tests can be performed to study wind farm layout (Sun, H.Yang and Gao 2019), farm terrain (Nanos, et al. 2020), control effect on performance (Zong and Porté-Agel 2021) (Dou, Qu, et al. 2020), or structural dynamics (Bastankhah and Porté-Agel 2017).

In this context, this work aims to present a design for a low-cost, low-weight test rig for wind tunnel experiments for a small-scale twin-rotor model. The test-rig is specifically adjusted to the size of the rotor model, and the available wind tunnel in Future University in Egypt (FUE). The rotor model is a continuation of a previous work made partially by the authors, where a scale-down of the NREL 5 MW turbine has been made on a laboratory scale. In order to conduct wind tunnel experiments, a test rig is needed, which satisfies both low vibrations, and low cost and weight. The predicted loads on the rotor were calculated using the Blade Element Momentum (BEM) method, then a static structural analysis for the proposed test rig was made using Solidworks.

2. Methodology

In this section, the approach to designing the test rig is introduced. As mentioned earlier, the test rig is designed to support a laboratory-scale wind turbine of 30 cm diameter to fit in the available wind tunnel in Future University in Egypt. The way to achieve that is by first doing a scale-down of the NREL 5 MW wind turbine, calculate the loads of the rotor using BEM. Finally, the aerodynamic and inertial loads were used to simulate the static stresses and deflections on the test-rig to ensure its safety. This section introduces all the steps one by one.

2.1. NREL 5 MW Scale-Down

Wind turbines can be scaled down in a variety of ways, including geometric scaling, dynamic scaling, and empirical scaling. Depending on the required complexity of the problem, each category applies in specific situations. The size limitation of the rotor necessitates the simplest sort of scaling, geometrical scaling, sometimes referred to as zero-order scaling, for the purposes of this work. The scaling factor is simply multiplied by the rotor's dimensions. The rotor diameter D serves as the parametric length in the scaling process, and as a result, dimensions are proportional with the diameter while mass is directly proportional to the cube of the rotor diameter ($m \alpha D^3$). Table 1 displays a comparison between the initial dimensions and structural characteristics of the NREL 5MW rotor and properties of the scaled-down rotor.

Table 1. Comparison Between NREL 5 MW and Scaled-Down Rotor Properties

Property	Original NREL 5 MW Rotor	Scaled-Down Rotor
Blade Length (m)	63	0.15
Rotor Diameter (m)	128	0.305
Tower Height (m)	87	0.207
Rotor Mass (kg)	110,000	$1.4847*10^{-3}$
Nacelle Mass (kg)	240,000	$3.2393*10^{-3}$
Cut-in Wind Speed (m/s)	3	3
Rated Wind Speed (m/s)	11.4	11.4

2.2. Aerodynamic Loads

The aerodynamic loads were calculated using an inhouse BEM code developed in Future University in Egypt. In this theory, the rotor is divided into annular elements with the assumption that there is no interaction between the elements. The code has been verified by the authors (Hisham, et al. 2021). Aerodynamic loads and estimated power have been calculated for a 30 cm diameter rotor. The loads were calculated for different wind speed starting with the cut-in wind speed of 3 m/s at which the rotor starts generating power, until the rated wind speed of 11.4 m/s at which the rated power produced by rotor is achieved, after which, pitch control should be applied to limit the generated power. Figures 1, 2, and 3 show the rotor thrust, torque, and power respectively.

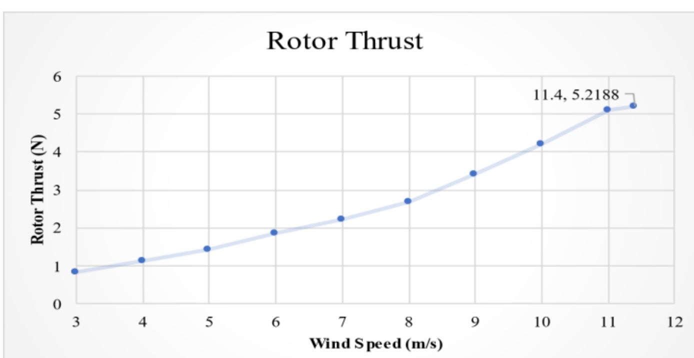


Figure 1. Rotor Thrust

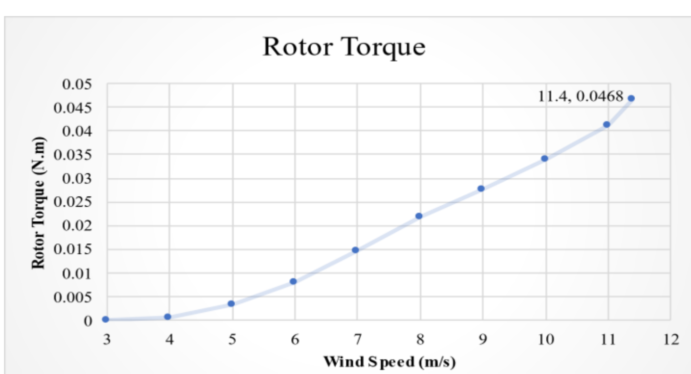


Figure 2. Rotor Torque

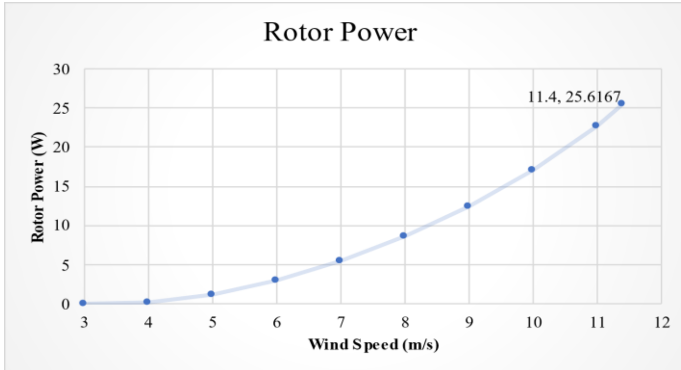


Figure 3. Rotor Power

The estimated power at the rated speed of 11.4 m/s is 25 W per rotor. The aerodynamic loads, namely thrust and torque were calculated for different wind speeds from cut-in to rated wind speed. The maximum loads at the rated speed of 11.4 m/s for both rotors thrust and rotor torque were used for structural analysis to ensure the safety of the test rig.

2.3. Structural Analysis

The structural design and analysis were performed on Solidworks software. The rotor is planned to be printed using a 3D printer with the PLA material. Since the mechanical properties of PLA are not available on Solidworks, the material chosen for design is ABS which is the closest material to PLA. The yield strength for ABS is 31 MPa, and the ultimate strength is 40 MPa. The main criteria for designing the test rig are to accommodate the generator, sustain the loads, and reduce the deflections. Table 2 shows the ABS material properties. Figure 4 shows the design for the single-rotor test rig, while Figure 5 shows the test rig for the twin-rotor configuration.

TABLE 2. ABS Material Properties

Property	Value
Mass Density (kg/m3)	1200
Yield Strength (MPa)	31
Ultimate Strength (MPa)	40
Young’s Modulus (GPa)	2
Max. Service Temperature (°C)	76.9

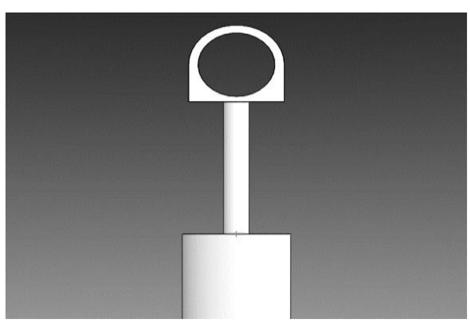


Figure 4. Single-Rotor Test Rig

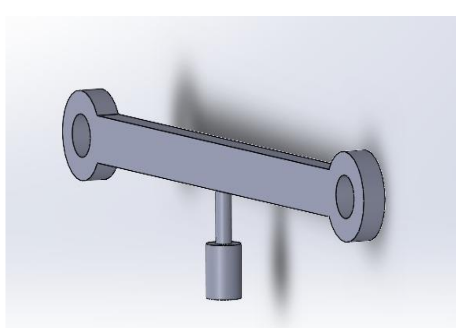


Figure 5. Twin-Rotor Test Rig

The simulation is then performed for both configurations in a static structural analysis to calculate von Mises stress and deflections. The automatic mesh generator on Solidworks was used to generate a fine mesh for accurate calculations. Table 2 shows the simulation conditions for the single-rotor and twin-rotor configurations and Figures 6 and 7 show the mesh on the proposed test rig designs.

Table 3. Simulation Parameters for Single-Rotor and Twin-Rotor Test Rig

Parameter	Single-Rotor Configuration	Twin-Rotor Configuration
Thrust Load (N)	5	5 *2
Torque Load (N.m)	0.045	0.045 *2
Inertial Load (N)	980	980 *2
Mesh Type	Solid Mesh	Solid Mesh
Element Size (mm)	5.26	7.13
Number of Nodes	16,687	16,914
Number of Elements	9,525	9,264

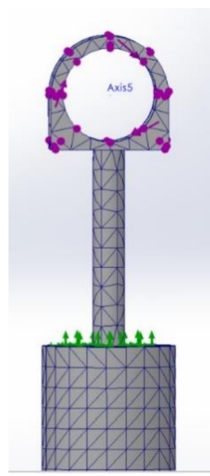


Figure 6. Mesh of the Single-Rotor Test Rig

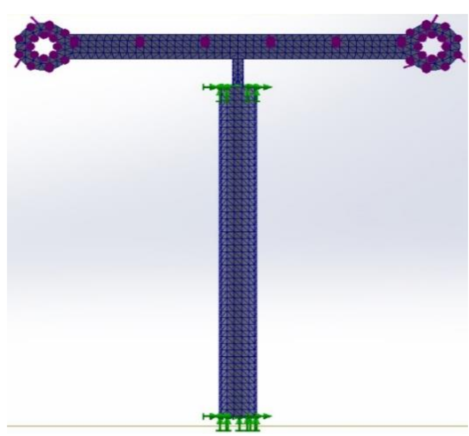


Figure 7. Mesh of the Twin-Rotor Test Rig

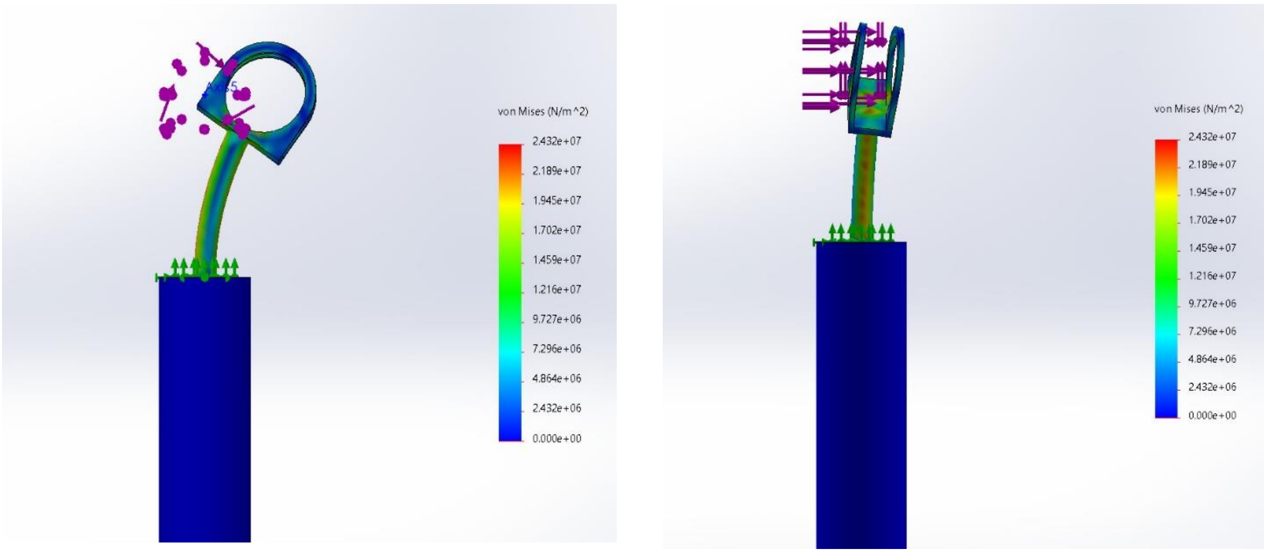
For both configurations, the test rig boundary condition is a fixed support at the lower end of the rig. The loads are placed at the generator casing as concentrated loads with the thrust force pointing perpendicular to the rig plane, and the torque along the circumference of the generator casing.

3. Results and Discussion

Simulations were performed for both configurations in a static structural analysis scheme. Results for both configurations are presented in this section.

3.1. Single-Rotor Test Rig

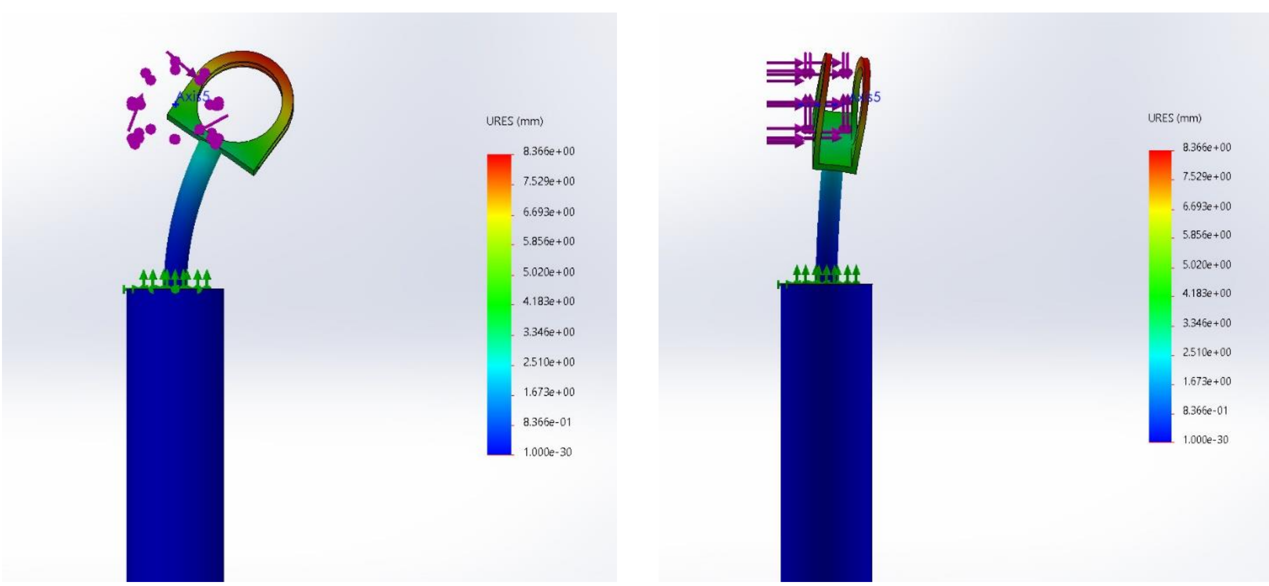
For the single-rotor test rig configuration, von Mises stress and deflections were calculated. Figure 8 shows the von Mises stresses while Figure 9 shows the deflections.



(a) (b)

Figure 8. von Mises Stresses for the Single-Rotor Test Rig: (a) Elevation View, (b) Side View

Recall that the ultimate strength for ABS material is 40 MPa, the maximum stress for the single-rotor test rig configuration is about 24 MPa. This means that the design is safe against failure with a factor of safety of 1.67 according to the maximum normal stress failure criterion. The maximum stress occurs at the lower end of the test rig which was expected since it is the furthest point from the point load, and hence the maximum bending moment exists.



(a) (b)

Figure 9. Deflections of the Single-Rotor Test Rig: (a) Elevation View, (b) Side View

The maximum deflection occurring in the single-rotor test rig configuration is 8.3 mm which is acceptable on the expense of low-weight and low-cost design of the test rig. However, some modifications can be still made to reduce the maximum deflection in order to prevent affecting the aerodynamic loads.

3.2. Twin-Rotor Test Rig

Similarly, the simulations were made for the twin-rotor configuration. To ensure the safety of the test-rig structural design, the maximum stresses and deflections were calculated in a Finite Element approach. The maximum aerodynamic loads at the rotor's rated wind speed were used, in addition to the rotor and generator masses. von Mises stress for the twin-rotor test-rig configuration is shown in Figure 10. The deflections are shown in Figures 11 and 12.

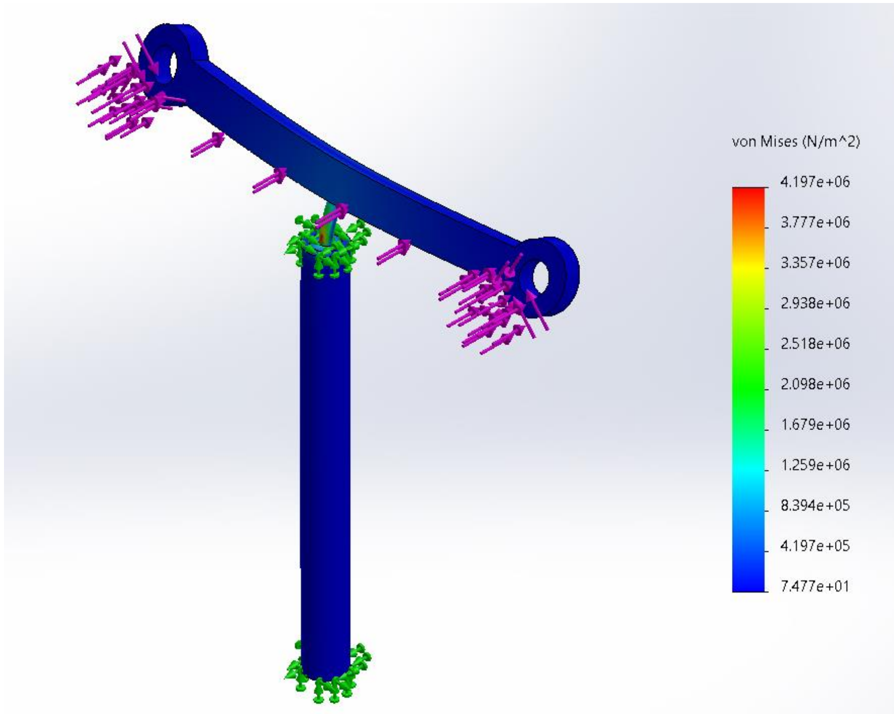


Figure 10. von Mises Stresses for Twin-Rotor Test Rig: Isometric View

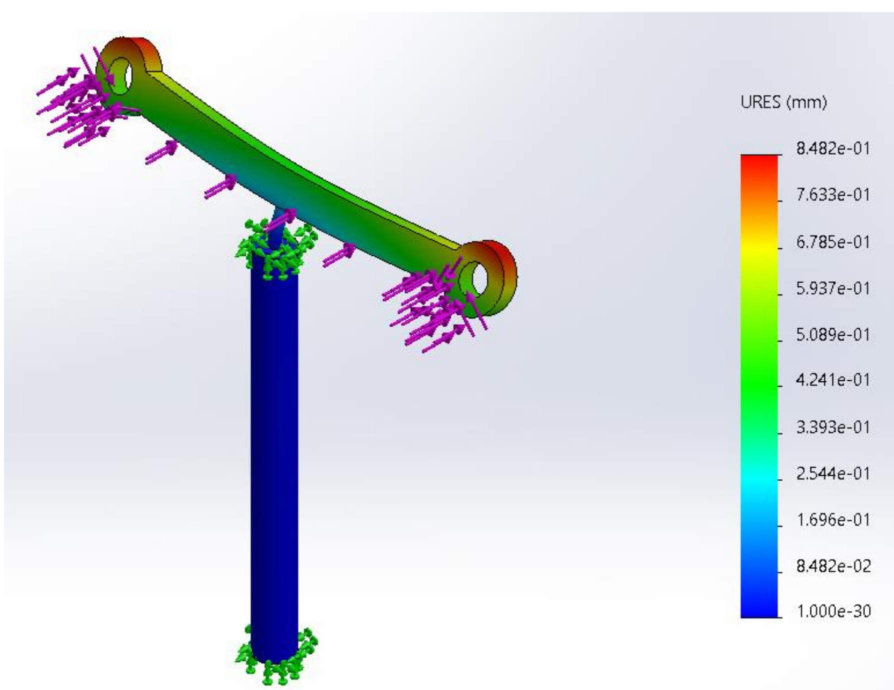


Figure 11. Deflections of the Twin-Rotor Test Rig: Isometric View

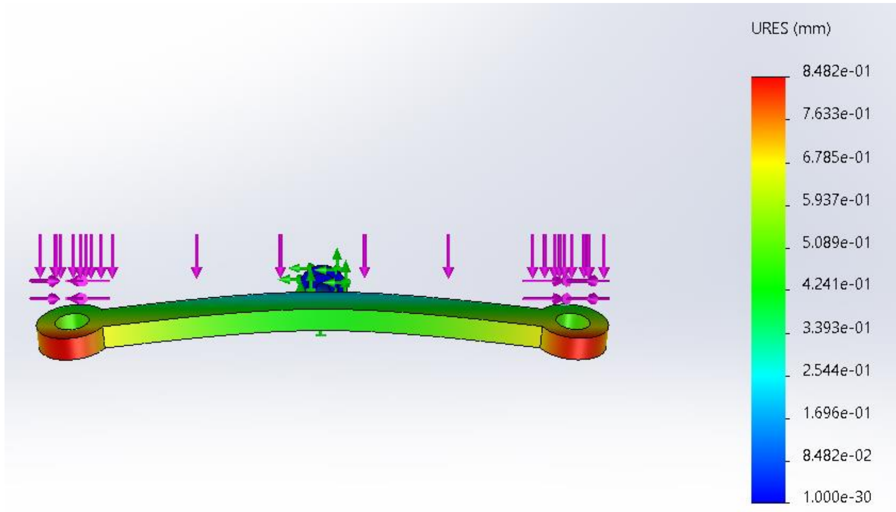


Figure 12. Deflections of the Twin-Rotor Test Rig: Top View

For the twin-rotor test rig, the maximum von Mises stress is 4.19 MPa, which makes it safe for both maximum normal stress and maximum shear stress criteria. For maximum normal stress criterion, the factor of safety is 9.5, while for maximum shear stress criterion the factor of safety is 3.7. The design can be considered over safe, which is the reason why the maximum deflection is 0.84 mm. In fact, due to the dynamic behavior of the aerodynamic loads, it is better to make an over-safe design to eliminate the effect of dynamic loading. However, this comes on the cost and weight expense. A compromise should be made to decide the optimum mass/strength ratio for an effective, safe design. As a suggestion, dynamic structural analysis including aeroelastic simulations could be performed for a better understanding of the results. However, within the scope of this work, and for the small scale of turbine loads, the static structural analysis is enough.

4. Conclusions

In this work, two configurations for a test rig for single-rotor and twin-rotor wind tunnel experiments are designed. The rotors are scaled-down from the NREL 5MW rotor. The aerodynamic loads were then calculated for different wind speeds, and the maximum loads were used for a structural analysis. The test rig configurations were designed of ABS material, which is a polymer type with mechanical properties close to PLA material of the 3D printer to be used for manufacturing of the test rig. Both designs were found of low weight and low cost. For the single-rotor test rig configuration, the total mass was found to be 16 gm, with a maximum stress of 24 MPa, and maximum deflection of 8.3 mm. This design can be considered critically safe, with a very low weight, while the factor of safety is 1.67 according to the maximum normal stress failure criterion. The twin-rotor test rig configuration on the other hand was found to be over-safe with a factor of safety of 3.7 according to the maximum shear stress failure criterion. However, the total mass of the test rig is 360 gm. Thus, a compromise between the weight and strength should be followed for an optimum design.

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