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Research Article

Structural analysis of the proposed multi-layer dodecarotor UAV

Nihat Çabuk[1*], Şahin Yıldırım[2] and Veli Bakırcıoğlu[1]

[1] *Vocational School of Technical Sciences, Aksaray University, Aksaray, Turkey*
[2] *Department of Mechatronics Engineering, Engineering Faculty, Erciyes University, Kayseri, Turkey*

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* Corresponding author
nihatcabuk@aksaray.edu.tr

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Nihat Çabuk
0000-0002-3668-7591
Şahin Yıldırım
0000-0002-7149-3274
Veli Bakırcıoğlu
0000-0002-1170-5327

ABSTRACT

In this study, structural analysis of a multilayer dodecarotor drone system is presented. In the structural analysis performed with the finite element method, a multi-body analysis was performed for the major components that make up the system in order to see the effect of the contact forces at the joints due to assembly. In this way, the mechanical behavior of the material used for the main parts of the drone under the effect of the predicted forces was examined and its minimum requirements were determined. Among these parts, currently available carbon fiber materials were used for components with standard geometry. However, more specific components with non-standard geometry are produced by additive manufacturing method using Polylactic Acid material. The forces acting on the system was predicted by considering the propeller and motor properties to be used in the system and the stress, strain and displacements occurring in the components under these forces was examined. Finally, system strength has been discussed by presenting the obtained analysis results both graphically and numerically.

Keywords: Drone; Multi-copter; Structural analysis; UAV

1. Introduction

Unmanned aerial vehicles (UAVs) have attracted the attention of researchers as a popular study subject in recent years. UAVs are now used even by individual users due to their common application, various physical sizes and economically accessible. The widespread use of these vehicles has revealed many study issues such as control [1–5], different physical designs [6–9] and analysis [10–14]. In addition, depending on the developments in manufacturing technologies, manufacturing techniques that can be accessed by individual users are also improving. As a result of these developments, additive manufacturing technique has now become applicable by individual users using 3D desktop printers. In addition to various additive manufacturing techniques in the literature, the Fused Filament Fabrication (FFF) method has become the most widely known and widely used method. The main reason for this can be summarized as the simplicity, reliability and affordability of the FFF process. The FFF process is based on the extrusion of fused feedstock thermoplastics from a nozzle tip to deposit layers onto a platform to form parts directly layer by layer from the solid model, unlike the conventional manufacturing techniques based on extracting material from the workpiece. However, as in every manufacturing method, a structural analysis should be performed to verify the strength of the material at the design stage in order to reduce the design feedback in the final product in the additive manufacturing method.

By using physics-based simulations that eliminate the need for hardware testing, unexpected design errors that can occur during hardware testing are naturally reduced. Moreover, simulations can be performed for performance and reliability analysis with the solid model represented in a computer-aided design (CAD) tool. Structural analyzes made in a CAD tool are widely used in determining the strength of mechanical systems. These analyzes, which must be done before the production of mechanical components, make it easier to identify situations that cannot be easily noticed in terms of both efficient amount of materials to be used and mechanical strength.

In this study, performed structural analysis of a proposed non-standard multilayer UAV at the design stage using a CAD tool is presented. Structural analysis was performed with the estimated forces according to the characteristics of the actuator subsystem to be used in the UAV in order to converge to the real system behavior. From the results of the analysis, it was seen that the material and manufacturing method used met the minimum requirements for the simple, reliable and affordable production of the proposed non-standard UAV.

The presentation of this paper is as follows; In the following section, the mechanic components that compose the system, the manufacturing method of these components and the materials used for these components are detailed. Subsequently, the analyzes were presented and the results were given graphically and numerically. Finally, the discussion of the results and the contribution of the analysis results to the design studies are presented.

2. Materials and Methods

In this section, the materials used in the manufacture of the basic components that make up the system are introduced. The solid model of the whole system is given in **Figure 1**. As can be seen from the figure, some of the rotors are placed in the lower plane and some of them in the upper plane. In this study, the proposed of the system was designed according to the following objectives.

- The system consists of up to 12 rotors which can be controlled independently.
- Eight of the rotors are in the upper plane and four in the lower plane.
- The number of rotors can be changed according to the purpose of the system.
- Arm lengths can be changed according to the needs of the system.

Fig 1. Solid model of the proposed UAV

The body of the proposed UAV and its joint parts are mainly produced by additive manufacturing method using PLA. The main body part of the proposed UAV consists of two main parts in two different layers. For the connection of the actuator arms of the UAV to the body, which is made of carbon fiber profile, the connection element was manufactured using PLA. The landing gear required for the UAV to remain stable during take-off and landing and to contact the ground are made of carbon fiber profile. Finally, motor connection parts were created using PLA to be used for the assembly of the actuator subsystem.

PLA is the most extensively researched and utilized biodegradable and renewable aliphatic polyester. PLA has a proven potential either to replace conventional petrochemical-based polymers for industrial applications or as a leading biomaterial for numerous applications in medicine [15]. 3D printers are used to produce solid components of any system using PLA materials. Although PLA materials are easier to process in these printers than ABS and metal-based materials, the parts produced with these materials are not suitable for use in environments with high temperatures. In this study, this material was preferred because the parts produced from PLA materials cannot be used in high temperature parts and because of its easy processing.

Profiles made of carbon fiber material, which is another component used in the body of the drone, are used in arms to which rotors are connected, which are one of the long parts of the drone, where flexibility is not desired and mechanical strength is important. Because, the parts produced from these materials have both high mechanical strength and light weight. Mechanical properties of these materials are given in **Table 1** [15–17].

Table 1. Mechanical properties of the materials used

Parameters	Materials	
	PLA	Carbon Fiber
Elastic Modulus [GPa]	0.3-3.5	230-245
Poisson ratio	0.36	0.23
Density [g/cm3]	1.20-1.25	1.77
Yield Strength [MPa]	70	3950
Tensile Strength [MPa]	48-53	3750-3900
Shear Modulus [MPa]	1287	5120

It is extremely important in terms of a problem-free application to calculate the reaction of a new designed mechanical system against external loads under operating conditions before manufacturing [18–22]. As the complexity of the system increases, it becomes difficult to produce a theoretical solution. In such cases, approximate solution methods are used. The most common of these methods is the Finite Element Method. In this method, the system, which is referred to as the "mesh" operation in the literature, is divided into uniform geometric small elements and the solution is realized in this finite element network with various assumptions. The larger the size of the finite element mesh, the more difficult the solution, but more realistic results can be obtained. Ansys, Solid Works, Catia and so on, which are based on the Finite Element Theory and bring visuality to the fore. Thanks to the programs, many systems can be analyzed and their working conditions can be calculated and it is not necessary to know much about the details of finite element theory. For this reason, one of these programs, SolidWorks, was used in the creation of the solid model of the drone system designed in this study and performing its static analysis.

3. Static analyses and results

In order to perform static analysis, the components to be analyzed must be divided into finite small pieces – called meshing. Although the more accurate results can be obtained as the size of these parts decreases, the time to perform the analysis significantly increases. In fact, the analysis cannot be concluded since it may cause insufficiency of the computer to be analyzed in terms of both processor and memory. For this reason, the mesh values given in **Table 2** were determined as reasonable values and the analysis was started. The body image formed after the mesh operation performed with the analysis program is shown in **Figure 2**. The static analysis is started by applying a force of the value that will be exposed in the real system to the mechanical system, whose meshing process is completed, to the relevant regions. After the analysis process, many mechanical properties related to the system are obtained both numerically and visually.

Table 2. Mesh properties

Parameters	Value
Maximum Element Size [mm]	28.4395
Minimum Element Size [mm]	5.6879
Total Number of Nodes	362145
Total Number of Elements	194901
Maximum Aspect Ratio	290.71
Ratio of Elements with An Aspect Ratio <3 [%]	56.4
Proportion of Elements with An Aspect Ratio> 10 [%]	10.7

Fig. 2. 3-D view of mesh model

Many outputs can be obtained in the static analysis performed. In this study, the stress, strain, contact pressure and displacement of the mechanical system are focused on. **Figure 3** shows the stresses occurring in the whole body of the vehicle. It is seen that the stresses are mostly in the arms. Carbon fiber, which is a material resistant to high tensions, is used in the arms. Similarly, the stresses in the motor connection parts are seen in **Figure 4**. As can be understood from the figure, the design was updated and reinforcement was made in the parts where the stresses are the most in these parts.

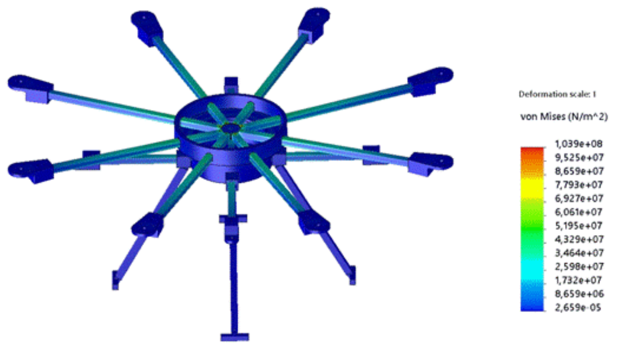

Fig. 3. Stress analysis result of the whole multi-body system

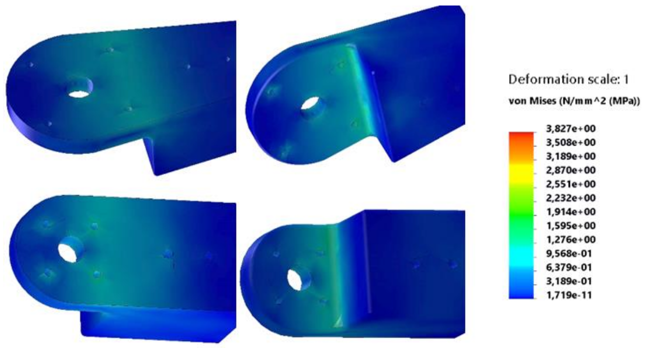

Fig. 4. Stress analysis result in motor fittings

The second variable obtained as a result of the analysis is the contact pressures formed at the joints of the body parts. As seen in **Figure 5**, the moment affecting the body is high due to the distance of the motors generating the force to the main body. Thus, it causes more pressure in the parts where the contact surface area of the arms to the body is less.

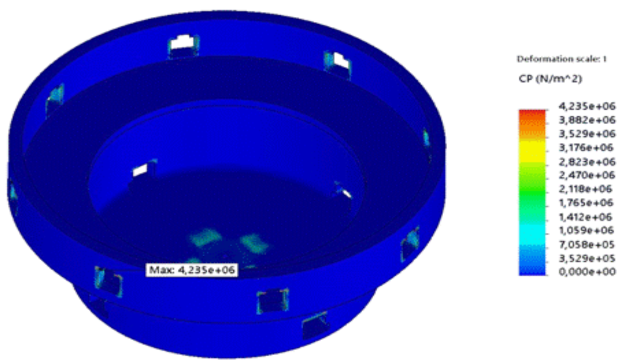

Fig. 5. Contact pressure analysis result affecting the body

Similarly, in **Figure 6**, the contact pressures occurring in the area where the arms come into contact are seen in the part where the upper arms are fixed.

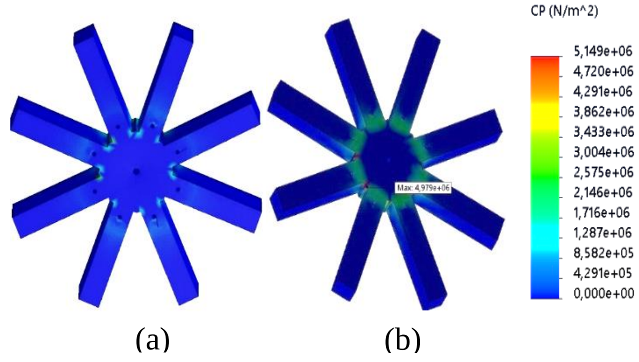

Fig. 6. Contact pressure analysis affecting upper (a) and upper (b) parts of upper arm connection part

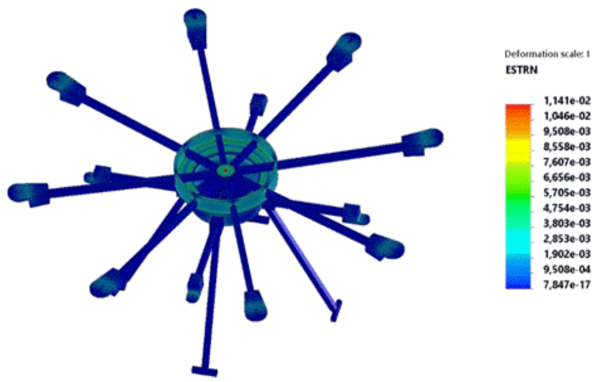

Fig. 7. Top view of the strain analysis result of the whole body

Another one of the static analysis results, the strain expressed as unit elongation is expressed as the ratio of the length change of the part to the previous length. **Figure 7** and **Figure 8** give the top and bottom views of the body of the strains that occur in the body. Since PLA materials are more flexible than carbon fiber materials, it can be seen in these two figures that the strain that occurs in the components where PLA materials are used in the drone system is higher.

Fig. 8. Bottom view of the strain analysis result of the whole body

Another result of analysis is the displacement in the mechanical system. Displacements are a result of the elastic structure of materials. Since the components made of PLA material have a lower elastic modulus, they cause a significant displacement in the mechanical system. If the ambient temperature increases, the material selection should be made according to the operating conditions of the system, since this change in location increases.

It is seen in **Figure 9** that the displacement amounts are greater where the distance of the applied force to the moment point is greatest. The displacement that occurs in the components to which the motors are connected is at most 13 mm and this value does not cause any problems in the operation of the drone system.

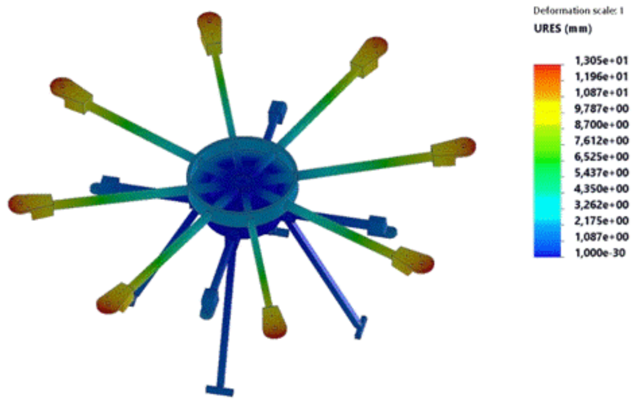

Fig. 9. Displacement analysis result for the whole body

4. Discussion

According to the results obtained from the static analysis, the necessary changes are made in the solid model and the most appropriate physical dimensions obtained as a result of repeated analyzes are determined, and the mechanical components of the drone system are produced. The production and assembly phase were started over the final mechanical design. However, it is possible to produce mechanical components at more appropriate scales with advanced design optimization techniques.

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