Simulating mechanical stress on a micro Unmanned Aerial Vehicle (UAV) body frame for selecting maintenance actions

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Abstract

The Unmanned Aerial Vehicles (UAVs) are part of our society. According to recent reports from retail research, sales of drones have been tripled over the last few years to about $200 million. The aim of the paper is to highlight the most relevant maintenance actions to take in order to properly maintain commercial UAVs. Describing the main components and characteristics of a UAV, the research wants to provide quick guidelines and suggestions for effectively maintaining micro UAVs. Based on a structure analysis and on the most common flying modes, firstly the paper simulates mechanical stresses on the UAV quadcopter body frames using Finite Element Methods (FEM). Secondly, it analyses the results highlighting the weak aspects of the structure in order to predict possible failure mechanisms and to create effective maintenance approach for guaranteeing high level of product reliability and availability. Finally, it discusses the results for ensuring constant mechanical properties and performance for the entire lifetime of the product.

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Keywords: UAV, Quadcopter, Finite Element Methods (FEM), Mechanical Stress, Maintenance

1. Introduction

Nowadays along with development of modern technologies the design and development of Unmanned Aerial Vehicles (UAV) is getting more and more popular, generating technical and operational issues and safety concerns related to their application in non-segregated airspace [1]. Many companies are being involved in the design of UAVs. One of the most common UAV structures is the quad-rotor layout. The reason is that quad-rotor aerial
vehicles are versatile, easy to construct, and they have vertical take-off and landing feature. Several studies [2-11] were carried out to determine mechanical stresses on different components of quadcopters. However, there are only few studies that establish a relation between mechanical stresses and necessary maintenance actions for UAVs. Figure 1 summarized the steps performed during the research.

In essence, the classic structure of quadcopter is a frame with four arms and brush-less electric motors positioned at the end of each arm. The main parts of a copter are the frame, motors, propellers, electronic speed controller (ESC) and batteries. The angle between the four arms may vary, but the most common configurations adopt angular diameter of 90 and 120 degrees. Propellers on each rotor are creating vertical thrust. The propellers positioned on the same diagonal have same direction of rotation to prevent the spin of the copter in the air. Regulating the round per minute (RPM) of each motor is possible to change the moving direction, to hoover the copter in the air, etc.

The quadcopter movement can be divided in four different states (Fig.2):

- by creating an equal rotational speed of the propellers on each motor the quadcopter generates enough lift force to move upward/downward (a);
- by increasing the rotational speed of the propellers on motors on the same diagonal, the quadcopter produces yaw motion (b);
- by increasing the rotational speed of the propellers on motors on the same side –front motors or rear motors- the quadcopter achieves pitch (c) and roll motion (d);

![Fig. 1. Flow diagram of the methodology used](image)

![Fig. 2. (a) Upward/Downward Motion (Z direction); (b) Yaw Motion; (c) Pitch Motion; (d) Roll Motion.](image)
As mentioned, to investigate the possible maintenance actions suitable to maintain UAV systems it is necessary to analyse the mechanical stresses acting during the flight using FEM methods in order to create reliable maintenance approaches for guaranteeing a safe and available machine.

1.1. Quadcopter frame: dimensions and materials

The frame is an essential component of a quadcopter (and in general of an UAV), and perhaps the most affected by mechanical stresses generated during taking off, flying and landing [3, 5, 7-10]. The torque generated by the motor system, landing impacts and other external forces make the frame vital in terms of design and maintenance. Moreover, the frame must be at the same time as light (to increase the possible payload) and robust (to be able to face shocks) as possible for facing high vibrations [2, 4].

To analyse stresses and evaluate its performance, the authors chose for one of the most common and used frame designs according to the retrieved sources. After a short literature investigation [2-16] in order to find possible states that generate the most mechanical stresses on the quadcopter, as discussed, the analysis has been performed on a micro UAV; the UAV frame is 183 mm wide and it is symmetric about axis Z (Fig. 3).

![Geometrical shape (a) and 3D rendering (b) of the UAV.](image)

Fig. 3. Geometrical shape (a) and 3D rendering (b) of the UAV.

Two main materials have been used during the mechanical simulations: carbon fiber and Acrylonitrile Butadiene Styrene (ABS) plus plastic. The mechanical properties of those materials are summarised in Table 1.

<table>
<thead>
<tr>
<th>Table 1. Mechanical properties of carbon fiber and ABS plus plastic.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Property</strong></td>
</tr>
<tr>
<td>Young's modulus (GPa)</td>
</tr>
<tr>
<td>Ult. Tensile Strength 90° (MPa)</td>
</tr>
<tr>
<td>Density (g/cm³)</td>
</tr>
<tr>
<td>Poisson ratio</td>
</tr>
</tbody>
</table>

According to [7], the authors decided to choose carbon fiber and ABS plus plastic as materials to use in the simulation due to their extensive usage in the micro and small UAV market. Indeed, this choice is affected by their interesting mechanical properties in terms of strength and lightness that make them suitable for being used as body frame.

2. FEM Simulations

The FEM simulation was carried on using the SolidWorks Simulation Tool and Abacus.
2.1. Mesh Definition and flying time moments

The main variables introduced in the creation of the mesh for simulating the states of the quadcopter are summarised in Table 2

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Mesh Representation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mesh type</td>
<td>Solid Mesh</td>
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</tr>
<tr>
<td>Jacobian points</td>
<td>4 points</td>
<td></td>
</tr>
<tr>
<td>Max Element Size</td>
<td>0.0112011 m</td>
<td></td>
</tr>
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<td>Min Element Size</td>
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<td></td>
</tr>
<tr>
<td>Total nodes</td>
<td>90553</td>
<td></td>
</tr>
<tr>
<td>Total elements</td>
<td>51865</td>
<td></td>
</tr>
<tr>
<td>Maximum Aspect Ratio</td>
<td>47,189</td>
<td></td>
</tr>
<tr>
<td>with Aspect Ratio &gt; 10</td>
<td>1,26</td>
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</tr>
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Quadcopter flying time has been divided in two main moments characterised by different values of mechanical stress; lifting/hovering and landing on rigid surface. Analysing UAV life cycle, it has been discovered that around 80% of the quadcopter flight time will be in lifting and hovering mode, and around 20% in downward motion for landing from a defined height. However, after a thorough discussion with UAV manufactures and an exhaustive literature analysis, it appeared clear that most of the mechanical stresses arise during the landing moments. Consequently, the focus of the research has been oriented to understand this particular situation.

For both materials (carbon fiber and ABS plus plastic) Von Mises stresses and displacements were tracked during the simulation in order to find under which conditions the body frame of the micro UAV would have been heavily stressed.

2.2. Landing simulations

![Simulation results for landing: (a) Von Mises stresses for ABS plus plastic (Max 35 MPa); (b) Von Mises stresses for carbon fiber (Max 38 MPa).](image-url)
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![Simulation results for landing](image)

After the simulations (run both with SolidWorks Simulation Tool and Abacus), it appears clear that the most vulnerable part of the quadcopter in terms of mechanical forces is the arm, and, specifically, the connection point between the arm and the body frame.

3. Discussion

Based on FEM results, it is possible to highlight that the highest stresses in landing mode occur, as said, on the arms near to frame center.

Fig. 4 shows the landing test results and how stresses are expanding after contact with ground. Simulation test pinpoints that while for ABS plus plastic frame the landing drop from a height of 1 meter (with a velocity value most likely of 4.43 m/s) on a rigid surface cannot cause cracks, for the carbon fiber, the generated stresses of 38 MPa (beyond the tensile strength of 27 MPa [7]) can bring the material to plastic deformations and cracks. Fig. 5 shows that due to different Young’s modulus the calculated stresses generate possible displacements in the surrounding of the connection between the arms and the body frame, respectively of 3,2 and 6,5 mm for ABS plus plastic and carbon fiber.

These considerations lead to agree that there is a consistent difference between usage of carbon fiber and ABS plus plastic during hard landing events in terms of mechanical strength. Due to its mechanical properties, carbon fiber is a stronger material with a high Young modulus, which is generating lower elastic strain and fragile behavior beyond the tensile strength. On the other hand, ABS plus plastic has higher tensile strength, which can reduce probability of sudden cracks in a collision with rigid surfaces during emergency landing.

According to the presented results, continuous maintenance and special monitoring actions should be taken into account by micro UAV users and operators for:

- Checking after every landing on rigid surface bolt and connectors between frame and arms (specifically looking for possible cracks), widely considered as critical to flight functional failure;
- Designing or equipping rubber nozzles or shock absorption devices on the landing gears to reduce stresses and vibrations from the ground.

4. Conclusions

Using SolidWorks Simulation Tools and Abacus for FEM analysis, an estimation of the mechanical stresses generated by impacts on simple quadcopter frame has been studied. The analysis was conducted for two types of materials: carbon fiber and ABS plus plastic. Von Mises stresses on quadcopter arms have been highlighted. Those stresses represent a critical factor (in relation with tensile strength of ABS plus plastic and carbon fiber 3D printing material) creating possible plastic deformations and cracks in case of drop landing on rigid surface. The study finally gave suggestions for correcting checking and maintaining the quadcopter frame.
Further researches have to be conducted to move from a simulation contest to a real condition monitoring system for micro UAVs in order to prove the results obtained with FEM methods. Furthermore, it has to be evaluated the financial feasibility to equip, at least, micro UAVs deployed in urban non-segregated area with specific monitoring sensors to avoid functional collapses during flights.

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References