Design, simulation and optimisation of lattice structures for remote control aeroplane

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Abstract

Purpose – Thus, in this work the goal is to design, simulate and optimise a holder of a brushless motor in lattice structure to get the best performance in terms of mechanical strength, vibration absorption and lightness.

Design/methodology/approach – Nowadays, most manufacturers and designers’ goal are to sell efficient products in mass to keep up or outrun competition. Medical, aeronautical, automobile and civil engineering sectors produce complex parts and products that encompass multiple properties such as lightweight, energy absorbance, vibration reduction and stress resistant. Studies found that lattice structures are more and more useful in these fields since their characteristics satisfy complex behaviour.

Findings – The study’s outcome suggests that the use of lattice structure reduces 60% of the actual motor holder mass while keeping the strength of the material, meeting initial specifications.

Research limitations/implications – The Ram capacity of the PC.

Practical implications – Light materials for aerospace engineering elongate the range of the unmanned aerial vehicle (UAV) to an extra range of flight.

Social implications – Situation awareness of the country border using surveillance drone and minimising the consumption of fuel.

Originality/value – The research allowed reducing 60% the actual holder mass.

Keywords Lattice structures, Unit cell, Design, Simulation, Optimisation, Vibrations, Static and frequency analysis

Paper type Research paper

1. Introduction

Nowadays, vibrations are present in almost all mechanical systems specifically if these systems have parts that translate and rotate with each other. For example, in aviation, the vibrations produced by aeroplane’s engines or rotors in propeller plane can sometimes cause problems for the avionics systems (electronic system), the loss of thrust or be uncomfortable for passengers. Not only they can cause a bumpy and loud flight but also increase part fatigue in the aircraft, which can cause excess in maintenance and accidents as shown in the following article (Laurent, 2019).

This study consists of designing a holder allowing to fix the brushless motor to the fuselage of an aeroplane. The study’s main goal is to reduce the mass of the holder while maintaining its capability to resist to mechanical forces as well as vibrations caused by the motor which have revolutions per minute (RPM) of 10,000. This mass reduction will allow the plane to have more flight autonomy.

Lattice structures (Fast Radius, 2018) are effective solutions for reducing noise and absorbing vibrations within a system. They are widely used in the medical world, for
example, they allow to replace bone tissue for patients who have diseases or some of them who had an accident, the following study (Tse-Hsiang Chen, 2018) shows the use of layer additive manufacturing to three-dimensional (3D) print bone tissue. This study explores the design of a holder based on optimisation of lattice structure that is used in aerospace engineering.

To conduct this study, the first step was to design a unit cell having a reduction in mass and optimisation in geometry. Next step is to design the holder that consist from a scaffold of unit cells. Static and frequency finite element analysis (FEA) have been adopted and then a comparison of performance of each designed model was analysed.

2. Unit cell design

One of the first steps was to design a unit cell, there are different types of unit cell such as body-centered cubic (BCC), face-centered cubic (FCC), auxetic inspired (AUX), organic inspired (ORG). By studying the course “Design, Simulation and Mechanical Testing of 3D-Printed Titanium Lattice Structures” which has been done by (Bari, 2020), it is possible to make some assumptions to get an idea of the most interesting unit cell to be use in this study. The outcome of this shows that ORG design is promising for its energy absorption and predictability, AUX lattice is not stiff enough and its fragile making is easy to break. BCC and FCC are inadequate by every comparison, too stiff, too erratic and has little energy absorption.

The study is based on the analysis of different parts composed of ORG type unit cells, in fact ORG lattice showed a good correlation between simulation and mechanical testing results. Moreover, the main objective of the study is to reduce the weight of an aeroplane, therefore, ORG lattice is the best response to the problem since its structure is hollow, so it would reduce the overall mass of the plane.

Different kinds of unit cells composed of ORG lattices were designed by Catia software and then simulated using Fusion 360 Autodesk software. The goal is to see their mechanical behaviour, therefore, static and frequency analysis were carried out in order to assess their performances. Figure 1a shows the cell unit which had the best compromise between stiffness and weight. This is a $5 \times 5 \times 5$ mm size ORG-type unit cell, its 6 sides have identical geometry. Each side is made from 1.5 mm diameter centre hole, 4 right triangles at its ends and 4 other holes. The unit cell is hollow, the thickness of the walls is 0.5 mm as shown in Figure 1b.

Table 1 summarises the major outcome properties of the unit cell such as its volume, porosity and the Maxwell’s stability criterion, these data are useful for the analysis of the behaviour of the part when it is subjected to a mechanical stress.

![Figure 1.](image-url)
3. Holder design

After designing the unit cell, the new aim is to design a part that absorbs vibrations from the rotation of the brushless motor. Figure 2 shows the sequence of assembling a unit cell into a complete lattice structure that fits the holes of fixing brushless motor.

I use the unit cell as shown in Figure 1a, then I build an extruded sheet of 100 unit cells with the option “Rectangular Pattern” as shown in Figure 2b, after that, I design the motor holder that respects measurements indicated in the functional specifications as shown in Figure 2c. Figure 2 shows the projection of the geometry of the motor holder into the sheet of unit cells, I use the “intersection” option to make a boolean operation between the two bodies. Finally, Figure 2e shows the final extrusion part of the lattice structure composed of about 28 unit cells.

In the “Simulations” section, 3 different motor holders will be compared:

1. The “Original holder” currently used as shown in Figure 3a.

2. A structure named “Lattice 202”, has 202 unit cells with dimensions of $2.5 \times 2.5 \times 2.5$ mm each as shown in Figure 3b.

Table 1. Other useful parameters for the unit cell study

| Properties          | Values |
|---------------------|--------|
| Total Volume (mm$^3$) | 125    |
| Volume of void (mm$^3$) | 18.17  |
| Porosity (%)        | 85.5   |

Maxwell’s Stability Criterion

- Joints = 8
- Beams = 12

$M = -6$

⇒ Bending-dominated lattice
A structure named “Lattice 28”, has 28 unit cells with dimensions of $5 \times 5 \times 5$ mm each as shown in Figure 3c.

The Lattice 202 and Lattice 28 have the same general dimensions (length, width and thickness), however, they differ in their unit cell number since they have different unit cell dimensions.

Having holders with the same dimensions and geometry but with different number of unit cell allow making interesting analyses in computational time and mechanical behaviour.

The following figure illustrates the 3 studied holders in the “Simulations” section.

4. Simulations

4.1 Boundary conditions

Once the holders are imported onto the “Fusion 360” simulation software, the first step is to choose the material. Aluminum which has an elastic limit of 275 MPa will be used for all simulations. Then the part is meshed, the size elements used are the ones proposed by Fusion 360, the mesh is not refined, it would take too much time to calculate because the part has a complex geometry.

Boundary conditions are to be set afterwards, the motor holder is attached to a part of the fuselage with four screws at its end. The holder’s own weight is represented, taking into consideration the effect of gravity. A force of 1.96 N is placed concentrically to the axis of the motor at 25 mm of the holder, it represents the weight of the motor under the effect of gravity. The “Static Thrust Calculator” software (Füzési, s.d.) allows to get the thrust motor power applied on the structure by entering the following parameters (Table 2):

In total, a thrust of 11.67 N is applied on the screw-holder contact allowing to fix the brushless motor to the new lattice structured holder. Table 3 recaptures the mechanical forces exercised on the holder.

| Parameters                        | Values         |
|-----------------------------------|----------------|
| Propeller diameter (inch)         | 10             |
| Pitch (inch)                      | 8              |
| Propeller type                    | Standard propeller |
| Number of blades                  | 2              |
| RPM                               | $10,000 = 166.66$ Hz |
| Air temperature (fahrenheit)      | 86             |
| Air density (kg/m$^3$)            | 1.1648         |

Table 2. Useful parameters for deducing motor thrust on aircraft structure.
4.2 Frequency analysis

After entering all useful parameters, a simulation was made for each holder, these simulations took more or less time computing depending on their complexity.

Table 4 has two interesting features to compare: the first mode obtained in Hertz and the total central processing unit (CPU) time in seconds. By analysing the modes, the results seem to be consistent with each other since we can notice that the original holder has a first mode equal to 30 745 Hz, much lower than the modes of the two other structure lattice holders (14 507 Hz and 9 987 Hz).

The original holder is filled with material while having the same geometry, so it is denser, has better mechanical hold and therefore a first mode larger than the two other simulations. The 3 studied holders are valid since their natural frequency is always higher than the motor frequency which is 166.66 Hz with a safety coefficient of 59 for the holder composed of 28 unit cells. The graph below in Figure 4a shows the first 8 modes of the 3 studied holders. Note that the two new holders have similar modal frequencies. Figure 4b on its right is a representation of the simulation obtained for the holder composed of 28 unit cells.

In terms of computational time, the current holder simulates very quickly (2.1 s), the simulation of the holder composed of 28 unit cells lasts about 1 min 30 s because the part is more complex. The computing time of the holder composed of 202 unit cells is much longer (793.5 s), it is about 9 times longer than the 28 unit cells which needs to be took into account.

| Applied forces | Values |
|----------------|--------|
| Fixed support  | /      |
| Gravity (N)    | Automatic |
| Remote force (N) | 1.96    |

| Force (N) | 11.67 |

Figure 4a: Graph of the first 8 modes of the 3 studied holders.

Table 4:

| Data obtained during the frequency analysis of the 3 studied holders | Original holder | New holder: Lattice 202 | New holder: Lattice 28 |
|---------------------------------------------------------------------|-----------------|-------------------------|------------------------|
| 1st mode (Hz)                                                      | 30 745          | 14 507                  | 9 987                  |
| Total CPU time (s)                                                 | 2.1             | 793.5                   | 92.1                   |
4.3 Static analysis

After completing the frequency analysis, it is necessary to do the static analysis in order to study the mechanical behaviour of the 3 holders. This study takes into account the same boundary conditions as the previous analysis such as a gravity, a force, a remote force and 4 fixed support.

Table 5 has four main characteristics to compare: MPa stress, mm displacement, % Strain and Total CPU Time in seconds. Notice that in the table, all original holder's characteristics values are significantly less than the two others. This is due to the fact that the actual holder has a geometry filled with aluminum. So, it is denser and has a better mechanical hold.

By analysing stress results, notice that the original holder has 1.352 MPa of stress force in Figure 5a, much less than the two other holders in lattice structure (154.9 MPa and 23.89 MPa). Observe that the stress of the 202 unit cells structure in Figure 5b is quite significant for a small part (154.9 MPa), it is well below the elastic limit of the material (275 MPa) but the safety coefficient in traction is 1.77 which remains low for a part intended to go in an aeroplane. The 28 unit cells holder in Figure 5c has a stress of 23.89 MPa which gives a safety coefficient of 11.51, so the maximum stress is well below the elastic limit of the material (275 MPa).

Looking at the level of displacement, the original holder at maximum displacement (1.23e-4 mm) in Figure 6a is lower than the two other holders in lattice structure (9.717e-3 mm and 2.619e-3 mm). The displacement recorded for the two structure in lattice, (for example in Figure 6b: 9.717e-3 mm) has a very small value each, which makes them totally negligible and without consequences when it comes to the part’s resistance.

Pointing at the strain values now, the original holder has a maximum strain of 2.839e-3% in Figure 7a which is less than the two other structures (0.306% and 0.0572%). To have a valid part, the maximum strain must not exceed 1%. Looking at the holder composed of 202 unit cells in Figure 7b, we can note that the strain is 0.3% which is smaller, however, the margin is not very large for a part intended to go on an airplane. The 28 unit cells holder in

|                  | Original holder | New holder: Lattice 202 | New holder: Lattice 28 |
|------------------|-----------------|-------------------------|------------------------|
| Stress (MPa)     | 1.352           | 154.9                   | 23.89                  |
| Safety stress factor | 203.4         | 1.77                    | 11.51                  |
| Displacement (mm)| 0.000123        | 0.009717                | 0.002619               |
| Strain (%)       | 0.00284         | 0.306                   | 0.0572                 |
| Safety strain factor | 352.11       | 3.27                    | 17.48                  |
| Total CPU time (s)| 1.3            | 429                     | 27.6                   |

Table 5. Data obtained during static analysis of the 3 studied holders
Figure 7c has a lower strain value, the maximum strain observed during the simulation is well below 1%: 0.0572%, which is 5.2 times less than for the 202 unit cells holder.

In terms of computational time, the original holder simulates very quickly (1.3 s), the simulation of the holder composed of 28 unit cells lasts 27.6 s because the part is more complex. The calculation time of the holder composed of 202 unit cells is even much longer (429 s), it is about 15.5 times longer than with 28 unit cells which is considerable.

Theoretically, the two new holders (28 and 202 unit cells) will resist since all parameters meet the standards (modes, stress, displacement, strain). However, the static analysis shows precisely that the holder composed of 28 unit cells has better mechanical performance than the one composed of 202 unit cells. To make the final choice, it is necessary to look at the weight of the holder, this parameter is the most important one because, as it is mention in the specification sheet, the goal is to lighten the motor holder to increase the flight range of the aircraft.
Table 6 summarises the main characteristics of the 3 holders studied in the “Simulations” section.

Observations: It can be noted that the mass of the original holder is 5 grams, the one with 202 unit cells has a mass of 2.2 grams meaning that it is 56% less compared to the actual one. The 28 unit cells holder has a mass of 2 grams, a 60% reduction in mass compared to original one.

Therefore, the holder composed of 28 unit cells shows better performance for every characteristics responding to the goals. Thus, this study made it possible to achieve a structure holder that saves 60% of its mass while still being resistant to mechanical stress.

| Material | Original holder | New holder: Lattice 202 | New holder: Lattice 28 |
|----------|----------------|------------------------|-----------------------|
| Volume (mm³) | 2011.65 | 771.25 | 683.94 |
| Mass (g) | 5 | 2.2 | 2 |
| Porosity (%) | 12.56 | 66.48 | 70.27 |

Table 6. Parameters comparison of all 3 holders
5. Conclusion
Reducing the number of unit cells has caused a reduction in structure’s mass, but we managed to find the optimum weight reduction, clicking into the consideration that higher stress were obtained as well. It is also possible to see that the highest level of stress is located where the screws are fixed to the fuselage in Figures 5a–c. The problem with the Lattice 202 in Figure 5b is that the maximal stress is located around the holes that allow to fix the screws to the fuselage; however, Lattice 28’s (in Figure 5c) stress is distributed all along the structure which is vital for a better mechanical structure.

The future work of this study would be to focus on strengthening the area where the screws go into the motor and the holder and removing material in areas where the structure has low stress levels while, certainly, preserving its mechanical properties. Thus, it is important to optimise the overall lattice structure.

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