Modal Analysis of a 3D Printed Monocoque Hexacopter

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SUMMARY: This document details the design iteration and model validation of a 3D printed monocoque hexacopter using finite element methods. Our aim is to design and print a hexacopter as a single monocoque body to reduce weight and vibrations that would otherwise occur due to the fasteners and joints used in an ordinary multi-piece frame. We chose to print the hexacopter out of PLA for its stiffness and impact-resistant properties. We begin our design process by drawing the basic monocoque frame shape as a continuous thin surface which allows us to model the frame with shell elements. Next, we experimentally determine the material properties by printing a simple thin cantilever beam with a tip mass and comparing the measured oscillation frequency of this system to an FE shell model and theoretical calculations by hand. Then, we iterate on different shell thicknesses in the FE analysis before designing and printing a solid monocoque frame with a surface thickness that gives us desired vibrational behavior. Finally, we validate the solid model by comparing the experimental stiffness in the direction of the primary vibrational mode with the stiffness derived from a new solid body FE model.

KEYWORDS: 3D Printed, Hexacopter, PLA, Modal analysis, Carbon Fiber

1. INTRODUCTION

Small scale unmanned aerial vehicles, also known as Micro Air Vehicles (MAVs) are an upcoming area of research due to their use in a variety of applications from commercial entertainment to on field military systems. Currently, they are used in the professional film industry to take amazing shots, firefighting from a safe distance, and extended military reconnaissance. A strong and light design is key to durability and flight time, hence we investigated the design of a MAV which takes advantage of surface geometry that can only be created with a 3D printer. Specifically, we analyzed a monocoque 3D printed Hexacopter, a design that utilizes six ducted propellers. From this model, we criticize the potential design by applying a frequency analysis in a finite element environment using Abaqus. We ensure that our chosen motors and propellers operate at frequencies sufficiently different than natural frequencies of our frame. More attention is given to the vibration of the motor support arms as those are the weakest parts of the model. Furthermore, throughout the analysis, we vary the overall thickness of our shelled model to mitigate the instabilities. Our model is then updated and reanalyzed to verify the design.

2. MODEL

Maintaining a low weight for our final printed structure is critical for flight operations and eventually for allowing the carrying of a payload. In order to achieve this low weight, effective modeling and exclusion of non-critical features was completed within Solidworks. All design was completed using surfacing features allowing for a FE mesh to be generated entirely of continuous shell elements.

Figure 1 - Rendering of "BeagleMAV" hexacopter model

The model was created with many design features taken into consideration. The printed circuit boards used for control, telemetry, and data logging are stressed elements. Furthermore, the propeller ducts serve not only to increase the efficiency of the propellers but also to increase safety when flying indoors and add rigidity to the frame. Finally, the motor mounts also serve as the landing gear. These design features all serve to minimize weight, reduce the number of parts, and simplify the assembly process.

3. FINITE ELEMENT MODEL

After creating the Solidworks model as a shell structure initially within Abaqus, we are able to run a basic frequency analysis to identify likely natural frequencies encountered in the physical model once manufactured. Our model was made using only surfaces so that we may define the geometry as a shell with easily adjusted thickness in order to determine a feasible design. Initially, we defined a thickness of 3mm as a likely candidate.

To best replicate in-flight operating conditions, fixed boundary conditions were applied at the four inner radiuses where the flight controller PCBs sit. Point masses are assigned weighing 16gm replicate the motor masses on each of the motor mounts.

Figure 2 – Showing fixed boundary conditions at location of fixation of control board

Figure 3 – Meshing of the MAV Model with 3mm seeding

A mesh sensitivity analysis was performed over several element sizes to confirm that our natural frequencies are feasible in a finite element environment. The study was done using mesh sizes ranging from 10mm to 1mm and we found that a mesh size of 3mm formulates a suitably converged result with a reasonable CPU Time of 12.6 seconds. The S4R shell element was selected for use in this study as the entire structure comprised of Quad dominated shell mesh except the motor mounts were imported as a solid body so to best suit the shell element of the structure, a C3D4 element tetrahedral element was chosen. As we can see from the results, mesh size has little effect on the analysis but an appropriate mesh has to be chosen to guarantee accuracy of the results with minimal CPU time to minimize the cost. Utilizing the stated mesh size of 3mm, we determined the first natural frequency of our structure to be: 78.514Hz.

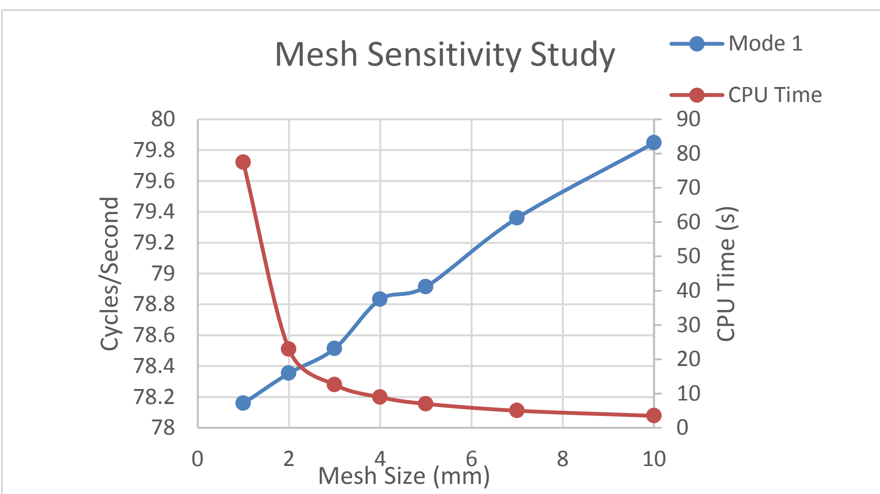

Figure 4 – Mesh Sensitivity Analyses

Table 1 – Mesh Sensitivity Analyses Results

Mesh Size (mm)	Mode 1 (Hz)	Mode 2 (Hz)	Mode 3 (Hz)	Mode 4 (Hz)	CPU Time (s)
10	79.847	95.825	107.35	116.47	3.5
7	79.36	95.245	106.86	116.49	5
5	78.915	94.673	106.53	116.32	7
4	78.833	94.711	106.19	116.08	8.9
3	78.514	94.389	106.02	115.89	12.6
2	78.354	94.137	105.85	115.83	22.9
1	78.158	93.893	105.72	115.7	77.4

4. VALIDATION

Our first-stage validation was completed on a 3D printed cantilever beam of the same material as our Hexacopter (Off-the-shelf "EasyFil" brand PLA-equivalent) with a specified density of 1240 kg/m^3 and Young's Modulus of 3310 MPa and an attached mass of 16gms at the free end. For the cantilever beam Finite Element Model, we performed frequency analysis both experimentally and within Abaqus to determine the likeliness of accurate results between the two environments. After obtaining similar results for the cantilever beam, we can imply that our methods are accurate for our more complex Hexacopter model as well. For validating our Abaqus cantilever beam model, the theoretical natural frequency of an identical geometry beam was determined from Equation 1 [1] where E = Modulus of Elasticity, L = Beam Length, I = Moment of Inertia, m = lumped mass at end of beam + 24% of beam weight:

$$f = \frac{1}{2\pi}\sqrt{\frac{3EI}{mL^3}} \quad = 6.74 \text{ Hz} \tag{1}$$

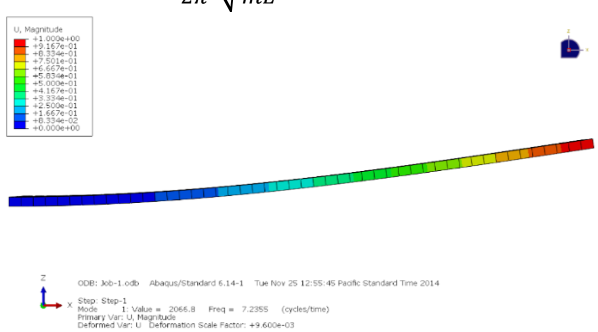

Figure 5 - Abaqus Beam Modal Analysis

The Abaqus model produced a natural frequency of 7.2 Hz which closely correlated with our supporting hand calculations. Our cantilever beam was printed by FDM (Fused Deposition Modeling) on a 3DP 1000 with geometry of 100mm long x 1.5mm thick x 10mm width. This beam was clamped to a table and subsequently an impulse was applied with a flick. In order to measure the frequency we utilize a 30fps video camera to count the number of frames required to complete 8 natural oscillations.

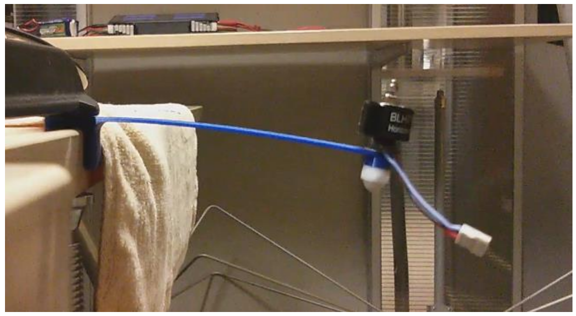

Figure 6 - 3D Printed Cantilever Beam with 16gm motor mass attached at the free end

This produced very similar results to both the Abaqus and theoretical models that were based on other experimentally determined properties of PLA. Over 43 frames taken by video, 8 oscillations were observed through the 30 fps camera resulting in a natural frequency of 5.58 Hz; very close to both prior estimations. Using the theoretical beam theory calculation as a baseline, both Abaqus and experimental results were confirmed to be relatively accurate. Comparing Abaqus to the theoretical baseline resulted in a difference of 7.2 Hz versus 6.74 Hz (respectively) giving a 6.8% error. Comparing the experimental results to the theoretical baseline resulted in a difference of 5.58 Hz versus 6.74 Hz (respectively) giving a 17.2% error.

We believe that the discrepancy between the theoretical model and experiment are due to the fabrication methods utilized by our 3D printer. Once printed, PLA has different properties than before. Furthermore, the printing process does not result in a homogeneous body. However, this small error still allows for us to confidently believe that our method of approach for evaluating the hexacopter with shell elements is accurate. Furthermore, this experiment allows us to adjust the material properties for a more accurate solid body model of the printed MAV itself.

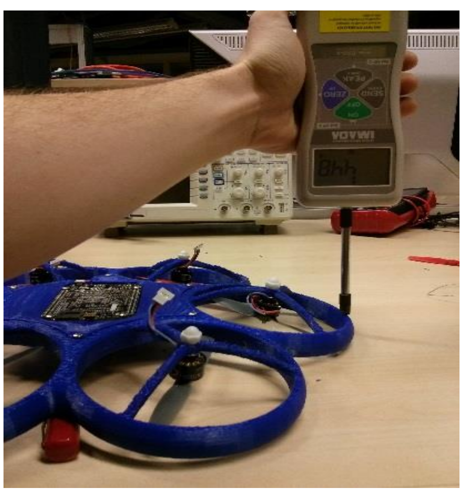

Figure 7 - Force gauge applying an 11.5N force on the outer rim of the printed hexacopter

Our next step in validation was to compare finite element and experimental results for our actual 3D printed Hexacopter after printing. Our first level series of validations highlighted areas of concern that we needed to take into account. As predicted, the real printed part density did not match the prediction based on Solidworks-derived volume. It was, however, very close. We actually measure identical masses of 147g in Solidworks and 147g by scale of the real model. Some disparity still exists between the two as a minor amount of support material is printed inside the frame in order to hold up the structure while printing. We estimate there to be roughly 5g of support material left inside the structure which was not reflected in the Abaqus model. For our particular case, this produced a roughly 3.5% error in measured weights which is considered negligible since we are designing the frame to have a large factor of safety in which frequencies the resonant modes exist.

To validate the solid model, we perform a static analysis of the stiffness in the direction of deformation when the MAV frame is under its primary (slowest) vibrational mode. To perform the experiment, we support the middle of the MAV off of a table with struts seen in red in Figure 7. We then use a force gauge to bend the entire body a measured amount of 6.3mm deflection of both tips where the force gauge is applied. This required 11.5N of force.

Instead of bending the entire body in the FE model, we performed a half model analysis of the MAV body to save computation time. To do this, we fixed the centerline nodes and applied a static force of 11.5 N on the extreme end. To eliminate singularities caused by point loads, we create a flat surface on the body in Solidworks with surface area of $8mm^2$ over which to distribute the force. We apply the same 11.5N force in the FE model which results in a maximum deflection of 6.36 mm. This half-body model can be seen with exaggerated deflection in Figure 8. This gave a percentage error of roughly 0.95% which is well within the accuracy of our crude test equipment. This result allows us to confidently confirm our modeling technique.

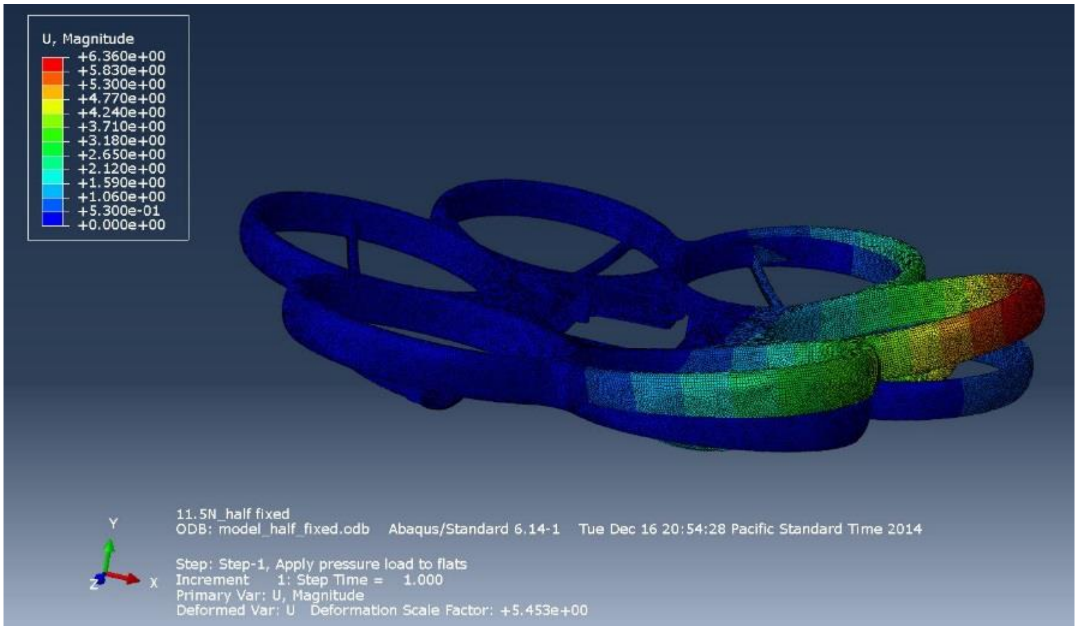

Figure 8 – Deflection of the half-body FEM with respect to the original shape while applying an 11.5N force to the duct tip.

5. RESULTS

With two methods of validation performed, we determine our model to be accurate and capable for further analysis. We derive the following modes of vibration across thicknesses of 2mm to 4mm.

Table 2 – Comparison of different frame thickness with their natural frequencies

Mode	2mm Thickness	3mm Thickness	4mm Thickness
1	66.5Hz	78.6Hz	87.3Hz
2	80.3Hz	94.4Hz	103.7Hz
3	95.3Hz	106.0Hz	110.0Hz
4	108.0Hz	115.7Hz	121Hz
6	165.6Hz	168.3Hz	162.4Hz

This brings to our attention a critical design flaw. We know that the motor and propeller combination has a maximum operating speed of 175Hz. This means that it is likely to excite the 6^{th} mode of vibration which corresponds to the motor mounts themselves deflecting relative to the rest of the body as seen in figure 9.

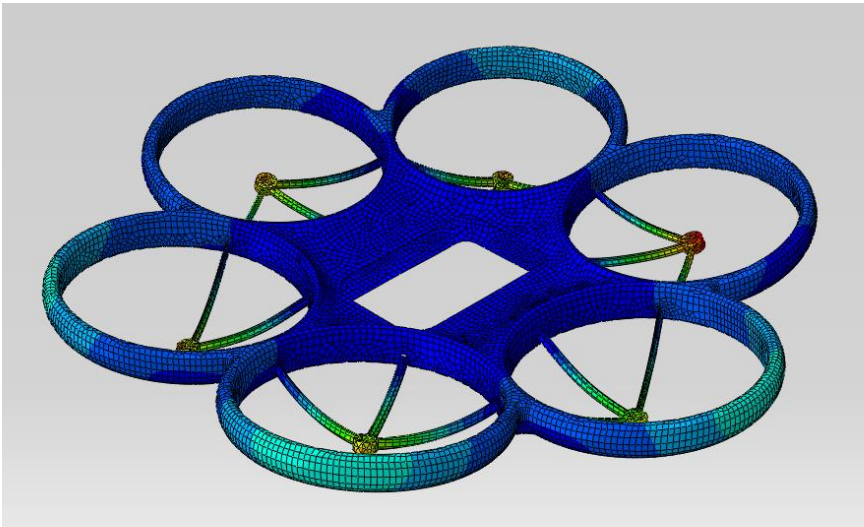

Figure 9 – 6th Mode of vibration

Since changing the thickness of the shell elements does not seem to affect this mode significantly, we elected to redesign the motor mounts to have three evenly spaced arms which are now solid instead of hollow. The new printed model with these changes made demonstrates a motor mount stiffness that is roughly 5 times stiffer by feel. This is a significant enough improvement that we are confident in the factor of safety of this revised component. See Figure 10 for the new motor mount configuration.

The results of rapid iterations of shell thickness allow us to not only choose a surface thickness for the primary body, but also indicate to us that simple thickness alterations are not enough to stiffen parts of the structure. Thus, we are able to revise the design geometry to compensate before a possible failure in flight.

6. CONCLUSIONS

Our Abaqus model was successfully confirmed as accurate via the modeling, analysis, printing and testing of a PLA cantilever beam resulting in minimal error. Afterwards, we fabricated the full hexacopter model and confirmed density by weighing a printed model while comparing it to Solidworks weight; resulting in a minor 3.5% error. We then performed a deflection study that was compared against our Abaqus model. The minimal error of our hexacopter deflection study at 0.95% led us to further confirm our Abaqus modeling technique along with the material properties derived from the cantilever test. This verified model let us feel comfortable enough to explore additional design improvements such as adjusting the monocoque geometry and thickness.

For the above said studies, different mesh seed sizes were explored in order to identify the most efficient mesh size relative to optimal computation time. As shown in Table 1, there was minimal discrepancy on determined natural frequencies as a result of mesh size. However, a 3mm mesh was chosen to ensure optimal accuracy within a reasonable computation time.

We believe we have demonstrated that highly complex surface bodies such as a monocoque frame lend themselves to design revisions based on FEA analysis. We were able to accurately model the elastic stiffness of a porous 3D printed material, perform multiple design thickness revisions with a FE model, and fix potential design flaws without needing to print the MAV itself. The result is a monocoque MAV frame which is both lighter and stiffer than any of us anticipated.

Figure 10. Final design with revised motor mounts

REFERENCES

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APPENDIX

Group Contributions:

As a group we all worked on everything however certain team members took to their strengths and spent more of their time on areas of expertise.

James Strawson: Solidworks expert, 3D printing expert, project concept, Abaqus consultant, Experimental work

Ahmed Ebeido: Abaqus expert, Theoretical Validation, Experimental Assistance, Documentation

Chris Stone: Solidworks, Abaqus, Documentation, Presentation, Experimental Assistance

Sonny Pham: Solidworks, Abaqus, Mesh Refinement Study, Experimental Assistance, Documentation