

Simulation and Analysis of a Quadrotor UAV while Landing.

P.V.Sawalakhe, J.A. Shaaikh



Abstract— Unmanned aerial vehicles are widely used in military and civilian fields in recent years. Quadrotor Unmanned Aerial Vehicles (UAV) have high advantage among other UAV's, in different categories, due to their ability to hover, and Vertical Take-Off and Landing (VTOL) capability. The mathematical simulation method can be adopted for analysis of UAV. The simulation method can reduce the flight period, cost and risk and improve its performance while Vertical take-off and landing (VTOL). While landing of UAV, the kinetic energy of vehicle is absorbed by UAV frame resulting in high stress concentration. The stresses are also produced in other parts of the UAV. The effect of the landing loads and stresses on the airframe of the quadrotor unmanned air vehicle must be completely understood and the UAV must be designed accordingly in order not to damage during landing. These stresses can be analyzed by simulation method to ensure the sustainability of UAV structure. This work includes structural and frequency analysis for Quadrotor UAV chassis.

Index Terms—UAV, Quadcopters, VTOL, mathematical simulation flight dynamics, dynamic analysis, frequency analysis,

I. INTRODUCTION

An unmanned aerial vehicle (UAV), which is also known as a drone is an aircraft without a human pilot on board. The flight of UAVs may be controlled either autonomously by onboard computers or by the remote control on the ground or in another vehicle of pilot. Advanced development in the field has resulted in autonomous UAVs which eliminated need of pilot. Such UAVs have an on-board controller that takes care of the stability and the trajectory motion of the UAV. There are several names in use for unmanned aerial vehicles, which generally refer to the same concept like, unmanned aircraft system (UAS). [1] The concept of UAV was first used during World War II in a secret mission called Operation Aphrodite. This mission met with little success. [2]

A. Quadrotor UAV

The quadrotor UAV is a small to medium sized UAV having multi rotor that is lifted and propelled by four rotors. Rotors are situated at the ends of a cross which are symmetric about the centre of gravity. Quadcopters generally use two pairs of identical fixed pitched or variable

pitched, two clockwise and two counter-clockwise, propellers. The control can be achieved by varying the speed of each rotor. These rotors provide the aerodynamic forces acting on the rotorcraft, and are modelled using momentum theory and blade element theory. From this, expected payload capacity and lift performance of the rotorcraft can be determined. The six degree of freedom system can be defined by equations using the Euler-Lagrange method. [3] By changing the speed of each rotor it is possible to specifically generate a desired total thrust, to locate for the center of thrust both laterally and longitudinally; and to create a desired total torque, or turning force [4]. A typical quadrotor has a frame, 4 motors, 4 propellers, microcontroller and battery. Also there are some electronic parts like ESCs, transmitter, receiver etc. The structure should be rigid and symmetric and light in weight. [3]

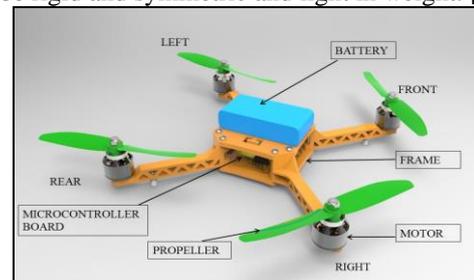


Figure 1 Various parts of quadrotor drone

II. FLIGHT DYNAMICS

A. Frame of reference

There are mainly two co-ordinate reference frames considered while studying flight dynamics. The first is the earth fixed frame. The other is the body reference frame is a rotating coordinate frame with the origin, situated at the centre of gravity (CG) of the rotorcraft. [4]

B. Effect of rotor movements

Movement about the longitudinal axis is called roll. Movement about the lateral axis is called pitch. The movement about vertical axis is called yaw. [5]

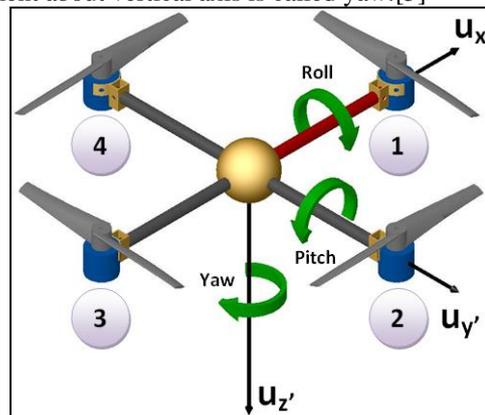


Figure 2 Pitch, Roll and yaw movements of an UAV

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* Correspondence Author

Dr. Pranil V. Sawalakhe, Assistant Professor, Mechanical Engineering, Shri Ramdeobaba College of Engineering and Management (RCOEM), Nagpur, India.

Jahier Abbas Shaaikh, Lecturer, Mechanical Engineering, Debre Tabor University, Ethiopia.

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C. Aerodynamics of UAV

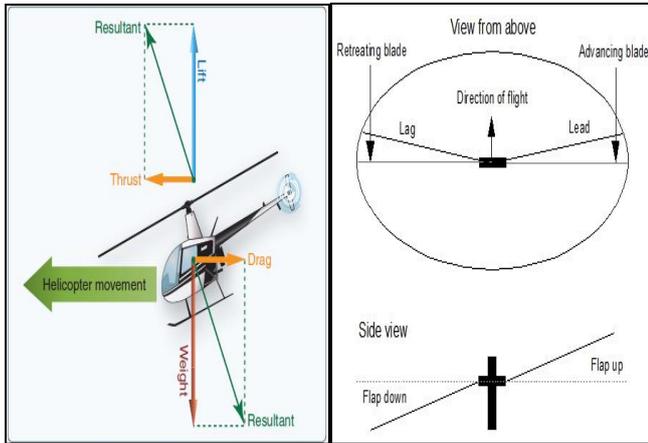


Figure 3 Forces acting on aircraft and blade flapping phenomenon [8]

UAV aerodynamics deals with the drag, lift, thrust, blade flapping etc. [6] Drag, lift, thrust are the forces acting on an aircraft. [7] In translational flight, the advancing blade of a rotor has a higher effective velocity relative to the air, while the retreating blade has a lower effective velocity. This results in a difference in lift between the two rotors, causing the rotor blades to flap up and down once per revolution. This flapping of the blade stilt the rotor plane back away from the direction of motion, which has a variety of effects on the dynamics of the vehicle. [4]

III. PROBLEM DEFINITION

It has been observed that the UAV breaks during rough landing conditions. The structure as well as other parts fails frequently. Hence it is required to design a failproof UAV model. Testing UAV every time is costly affair hence numerical simulation provides the better and cheap way to design. As UAV mostly directly falls on the ground hence drop analysis is essential. Also due to vibrations the frequency analysis of a quadrotor unmanned aerial vehicle (UAV) helped to locate the loaded regions.

IV. LITERATURE REVIEW

Mark Cutler et al. [8] presented the design, analysis and experimental testing of a variable-pitch quadrotor to eliminate the limitations of fixed pitch multirotor. Variable-pitch propeller gives additional degree of freedom for varying the thrust, increase in performance and capability and ability to reverse thrust very quickly.

Yong-Bin Park et al. [9] did structural analysis for the wing and landing gear of a composite target-drone. The analysis predicted the maximum stress at the curved region where supports were attached to the landing gear and found safe. Also normal landing and landing with an angle of 15 degrees were safe whereas the landing with an angle of 30 degrees yielded a stress level in the composite plies close to their strength.

Lakshmi Narashiman Aswin et al. [10] introduced slave and master UAV and did their structural analysis. The displacements in master and slave MAVs are found negligible.

Serhan Yüksel (2009) [11] studied low velocity impact load and stress analysis and explained the effect of impact on the “Güventürk” mini UAV while its belly landing. He observed that short durational impulsive forces are exerted

on the fuselage of the airframe. Contact area also changes in time as deformation and bouncing occurs.

O. Yildirim et al. [12] did analysis of a Skid Type Landing Gear of a Rotary Wing UAV using Implicit type free drop FEA. The deformation in elastic limit is achieved by increasing the size which is calculated by optimizing the radius of the landing skid gear.

Akhilesh Kumar Jha et al. [13] conducted belly landing analysis of a mini UAV using explicit finite element solver HyperWorks. Hertz Contact Law is applied to convert dynamic problem into static problem. The strain observed varies between positive and negative values which then tend to zero with respect to time.

Md. Fazlay Rabbey et al. [14] designed an UAV and conducted drag analysis, stability analysis and weight build-up analysis. It is observed that drag coefficient is 0.0036, the stability margin is 12.2% with payload, the elastic limit can sustain up to 0.02 strain limit with corresponding stresses of 35 psi and structure is safe.

S. Rajiv Rao et al. [15] did fluid flow analysis over the V22 Osprey at different angle of attacks ranging from 0-180 and CL, Cd and Pressure distributions are observed.

V. METHODOLOGY

From the study of literature review, a simple and ideal methodology is adapted to this work.

A. Preprocessing:

- a. Modeling of a quadrotor UAV in CATIA: The parts include frame, arm, motor, propeller, bolts, battery.
- b. Meshing of a CAD model for good mesh quality: The meshing type applied is a tetrahedral meshing with refinements.
- c. Applying initial and boundary conditions to the meshed model: These include fix and moving constraints as well as load conditions.

B. Computation

C. Post processing:

- a. Obtaining alpha-numeric results from computations.
- b. Obtaining graphical results from computations.

VI. CALCULATIONS

After selecting parts for building a drone, the mass can be approximated equal to 1 kg i.e. 1000 gm.

Therefore, weight of a drone is

$$W = m * g = 1 * 9.81 = 9.81 \text{ N.}$$

A. Lift

To overcome the weight of 9.81 N and take off, the lift force should be greater than weight.

As quadcopter has 4 arms, this force can be divided into 4 parts.

Therefore, the lift required for each arm is,

$$L = 9.81 / 4 = 2.4525 \text{ N}$$

At this amount of force, the UAV will hover. To accelerate the drone and increase its altitude, this lift force must be greater than 2.4525 N. so let's consider lift of 3 N for the structural analysis.

B. Motor calculations:

To take off the UAV, the thrust should overcome the weight. when thrust is equal to weight, the UAV just hover and land. When,

$$\text{Thrust} = 2 * \text{mass} = 2 * 1$$

$$= 2 \text{ kg. or } 2000 \text{ g.}$$

The force will twice the hover thrust and can accelerates upwards. Therefore, the motor should be selected which provides the thrust of minimum 2000 g.

VII. MATERIAL SPECIFICATIONS

Table 1
Material Properties

Part	Material	Young's Modulus (Pa)	Poission's Ratio	Density (kg/m ³)
Frame	Glass Fiber	8.5E+10	0.23	2600
Arm	Nylon 6/6 GF	7.6E+09	0.35	1400
Screws	Steel	2.05E+11	0.28	7870
Battery	Battery	7E+10	0.34	2500
Motor	Motor	2.05E+11	0.28	3000
Propeller	ABS			
	Thermoplastic	1.8E+09	0.35	1040

VIII. QUADCOPTOR DESIGN

As quadcopter is symmetrical, so the one forth part of a whole UAV is modeled. The symmetric plane reflection can be applied to the results afterwards. There are three designs of drone arm. Before proceeding to other types of analysis, the basic structural analysis was done to make sure that the design of arm is sustainable to stress. From these analysis results, the best design was chosen. The force of 3 N is applied. The modeling and its structural results for each design is shown below. From the results, the third design is chosen as its displacement is small and it also has minimum weight.

A. Design I:

This is the simplest design of an arm. Other parts are not yet taken into consideration.

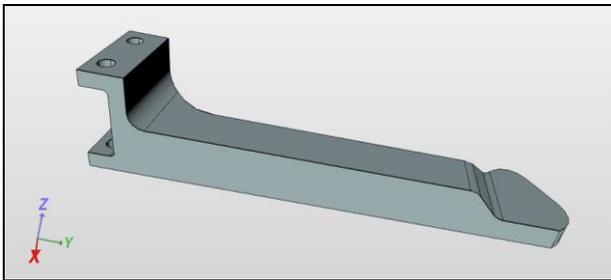


Figure 4 Drone Arm design I

The displacement is observed up to 0.515 mm at the end of an arm.

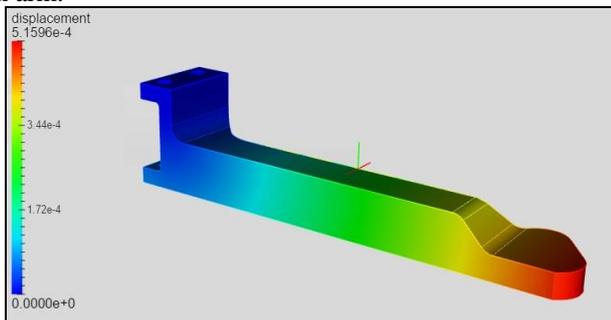


Figure 5 Displacement of Arm for 3 N lift – Design I

B. Design II:

Design 1 arm was sufficiently rigid, but as per requirements, the structure should also as light in weight as possible. To reduce its weight, the design is somewhat modified as shown.

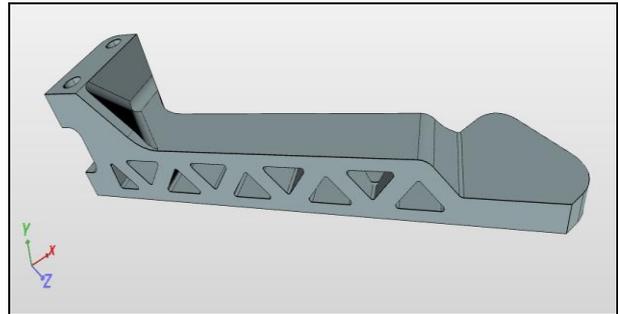


Figure 6 Drone Arm design II

The displacement is observed up to 0.3 mm at the end of an arm where motor is located.

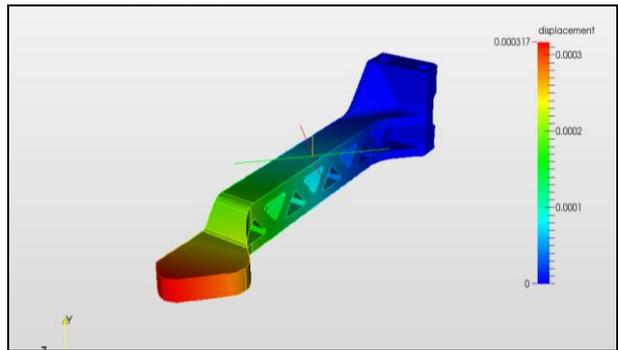


Figure 7 Displacement of Arm for 3 N lift – Design II

C. Design III:

This is very detailed design of arm considering requirements of motor adaption, weight loss as well as strength.

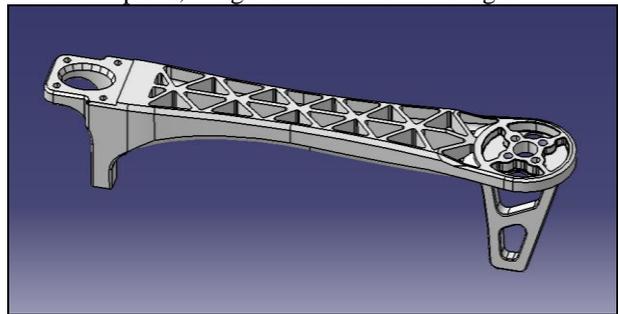


Figure 8 Drone Arm Design III

The displacement is observed up to 0.5 mm at the end of an arm where motor is located.

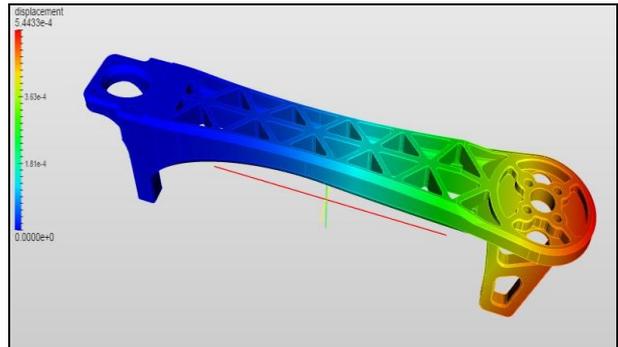


Figure 9 Displacement of Arm for 3 N lift – Design III

D. Assembly:

The assembly has total 20 parts including 5 parts of motor, battery, frame, arm, propeller and 10 screws.

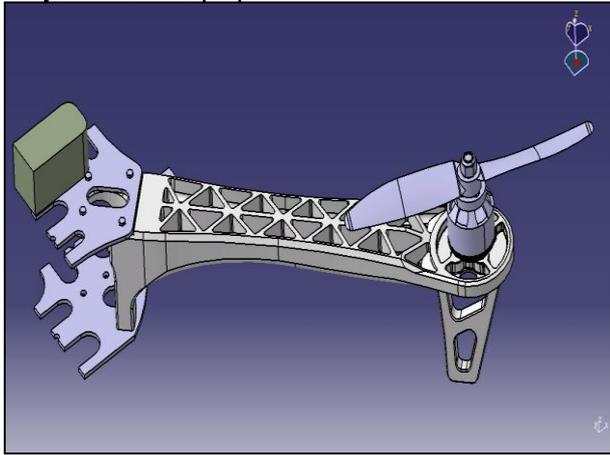


Figure 10 Assembly of a drone

IX. QUADROTOR MESHING AND ANALYSIS

Meshing the model before analysis is very essential for getting more accurate result. For the meshing and analysis purpose, an online open source is used provided by German organization named Simscale.

A. Structural Analysis:

The structural analysis of an arm is done for 3 N lift forces. The lift is applied at the end of the arm where motor is located.

**Table 2
Mesh Details For Structural Analysis**

Mesh Type	Tetrahedral with refinements
Max. edge length (m)	0.001
Min. edge length (m)	0.0006
Max. refinement edge length (m)	0.0003
Min. refinement edge length (m)	0.0001
Number of Nodes	119507
Number of 2D elements (Edges)	23289
Number of 2D element (Faces)	192700
Number of 3D elements (Tetrahedral)	400280

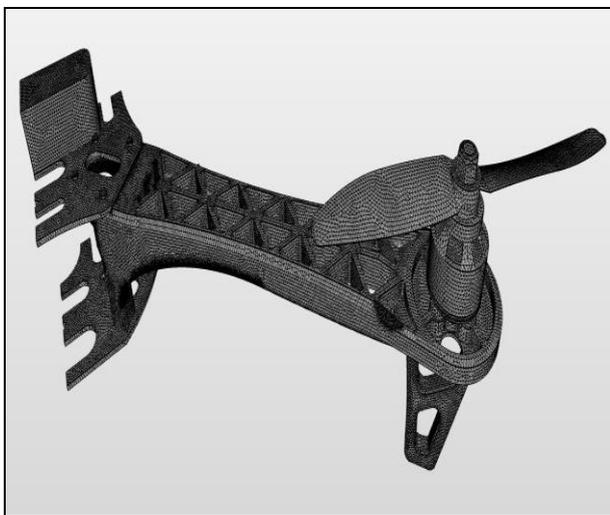


Figure 11 Meshing of drone for structural analysis

The displacement contour is shown below. It can be observed upto $2e^{-5}$ m. i.e. 0.02 mm.

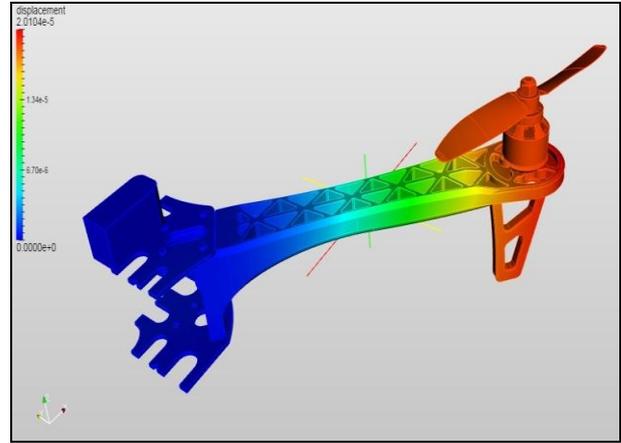


Figure 12 Displacement contour of structural analysis

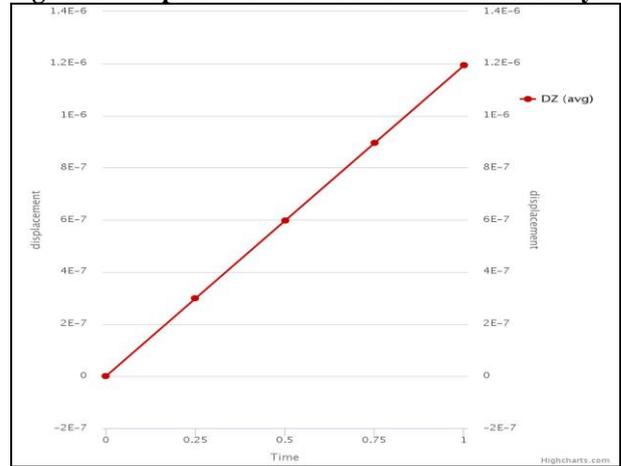


Figure 13 Displacement Vs. Time chart

B. Advanced Dynamic Analysis: Landing Analysis

It allows the time-dependent calculation of displacements as well as stresses and strains in one or multiple solid bodies. The distance between UAV and floor is 450 mm. and the speed of an UAV is considered 5 m/s. We can see the mesh details below.

**Table 3
Mesh Details For Landing Analysis**

Mesh Type	Tetrahedral	with refinements
Max. edge length (m)	0.001	
Min. edge length (m)	0.0006	
Max. refinement edge length (m)	0.0003	
Min. refinement edge length (m)	0.0001	
Number of Nodes	118431	
Number of 2D elements (Edges)	23256	
Number of 2D element (Faces)	191240	
Number of 3D elements (Tetrahedral)	396260	

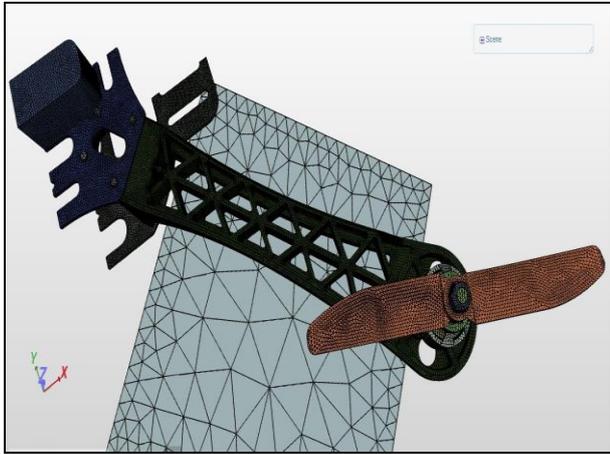


Figure 14 Meshing of drone for drop analysis

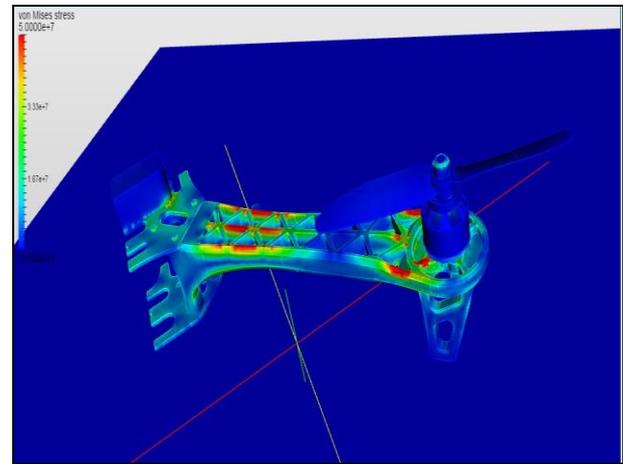


Figure 17 Von Mises stress at 0.094 sec.

The time step count is kept 2 before it touches the floor and it kept 25 after it touches the floor to save the computing time and memory to store the results. By the given velocity and distance, we can say that the drone will touch the floor at 0.09 sec. The von Mises stress plot is given which shows that the stresses are produced when drone touch the ground and it increases for some time.

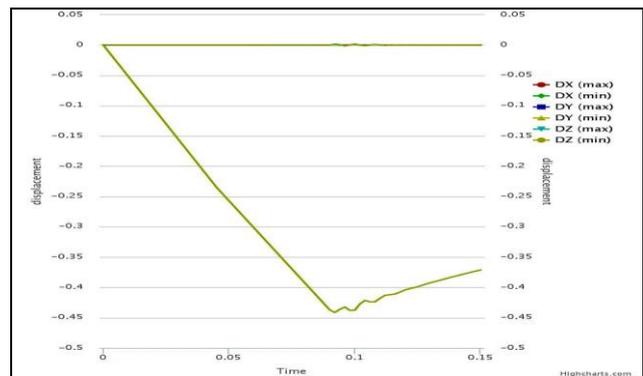


Figure 18 Displacement of propeller tip Vs. Time

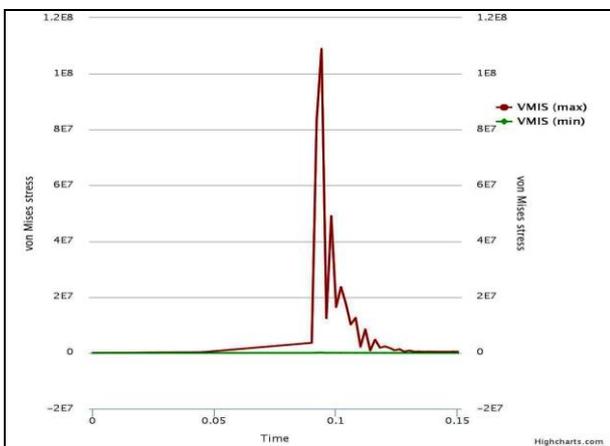


Figure 15 Maximum von Mises stress vs. Time plot

At the moment of strike, the maximum stress produced is up to 1 MPa.

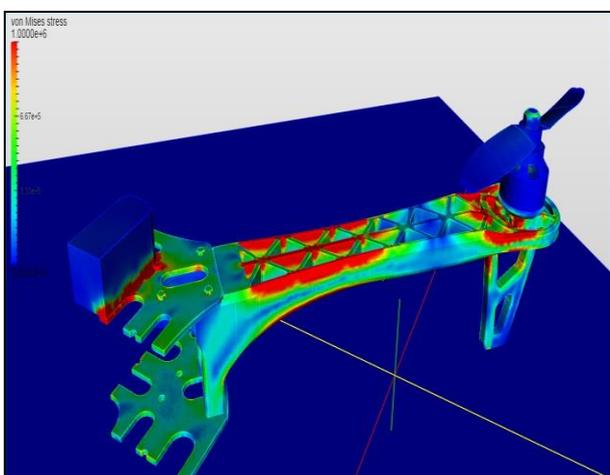


Figure 16 Von Mises stress at 0.09 sec.

After striking on the floor, the drone bounces back and the stresses increases. At 0.094 sec; the maximum stress produced is 50 MPa.

C. Frequency and Harmonic analysis

Frequency analysis enables the computation of the eigenfrequencies and eigenmodes of structure and harmonic analysis simulates the steady state structural response of solids to periodical loads. For frequency analysis, simple gravitational condition is applied and for harmonic analysis, load of 3 N is applied as a lift force.

TABLE 4
MESH DETAILS FOR FREQUENCY AND HARMONIC ANALYSIS

Mesh Type	Tetrahedral	with refinements
Max. edge length (m)	0.001	
Min. edge length (m)	0.0006	
Max. refinement edge length (m)	0.0003	
Min. refinement edge length (m)	0.000	
Number of Nodes	109749	
Number of 2D elements (Edges)	16902	
Number of 2D element (Faces)	159394	
Number of 3D elements (Tetrahedral)	394360	

Simulation and Analysis of a Quadrotor UAV while Landing.



Figure 19 Meshing of drone arm for frequency and harmonic analysis

As a result of frequency analysis, the numerical values of the eigenfrequencies as well as the displacement representation of the eigenmodes can be analyzed.

TABLE 5
RESULT- EIGENFREQUENCIES

Eigenmode	Eigenfrequency
1	1.11E+02
2	2.36E+02
3	4.36E+02
4	5.29E+02
5	1.23E+03
6	1.32E+03
7	1.62E+03
8	2.38E+03
9	2.46E+03
10	2.77E+03

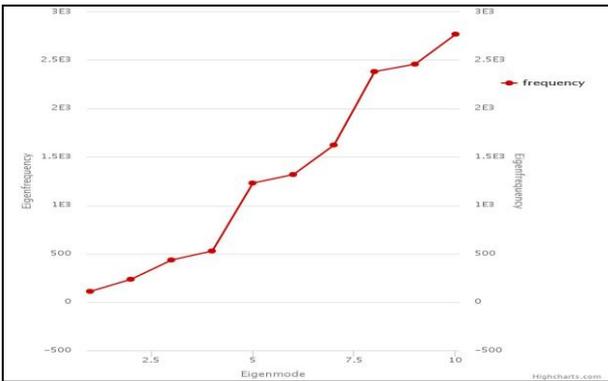


Figure 20 Eigenfrequencies Vs. Eigenmodes

For harmonic analysis, the displacements between frequencies 230 Hz to 240 Hz are observed given the force of 3 N and considering effect of gravitational force.

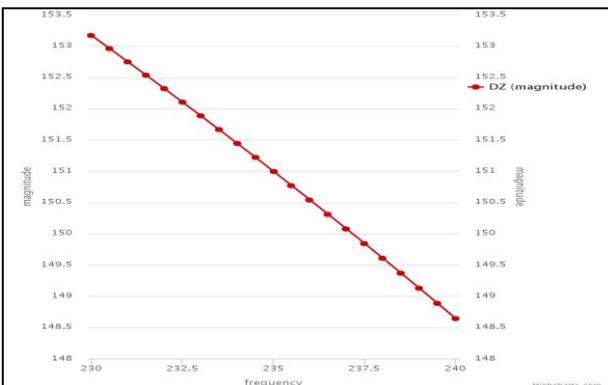


Figure 21 Magnitude of acceleration Vs. frequency

The displacement of an arm is observed between 0.075 mm to 0.065 mm for the frequencies 230 Hz to 240 Hz respectively.

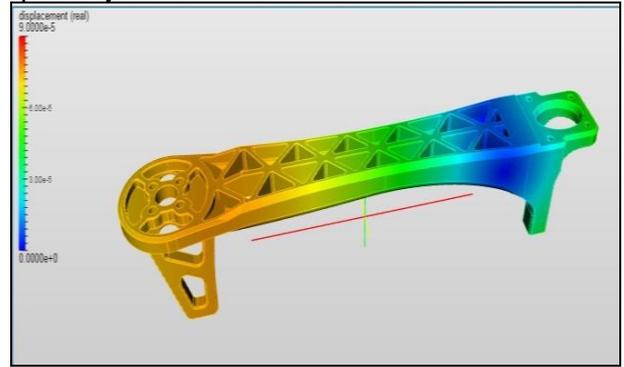


Figure 22 Displacement of drone arm at frequency 230 Hz

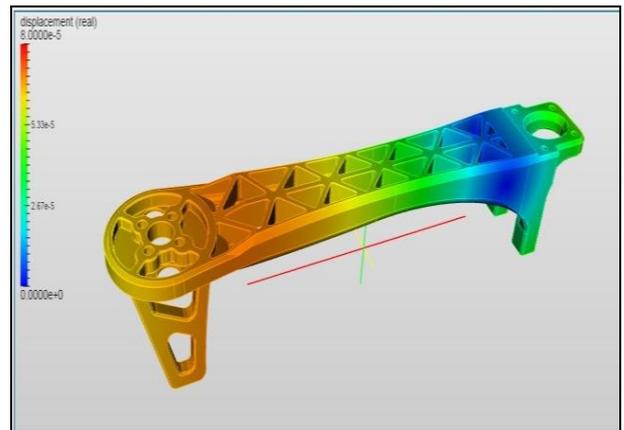


Figure 23 Displacement of drone arm at frequency 240 Hz

D. Fluid Analysis:

While landing the UAV, it faces drag of air present below it. It affects the velocity and pressure difference can be observed. While air passes upwards near the drone surface, the friction occurs leading to very little amount of heat generation. In this type of analysis, these changes can be observed.

TABLE 6
MESH DETAILS FOR FLUID ANALYSIS

Mesh Type	SnappyHex Mesh
Domain Size (m)	0.5*0.5*2
Number of Nodes	2678138
Number of 2D elements (Faces)	6170391
Number of Tetrahedra	7
Number of Hexahedra	1142787
Number of Prisms	156313
Number of Polyhedra	494653

The meshing of model including domain are shown below.

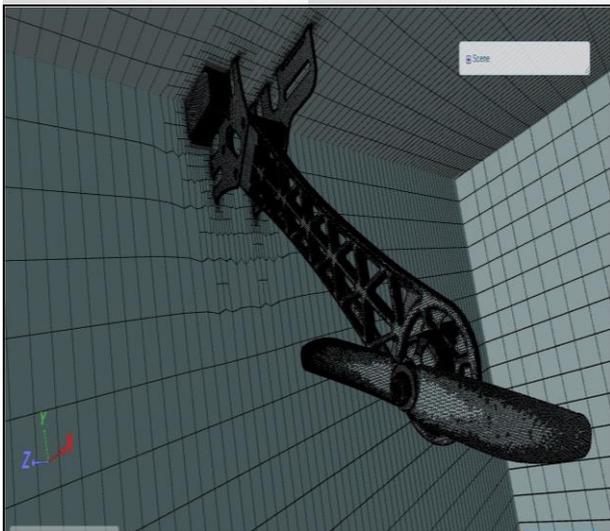
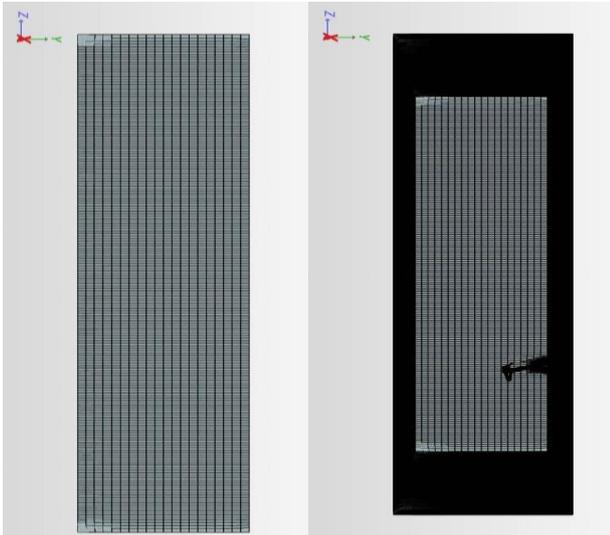


Figure 24 Meshing of drone and its domain for fluid analysis

The variations of different quantities are shown below in graphical format.

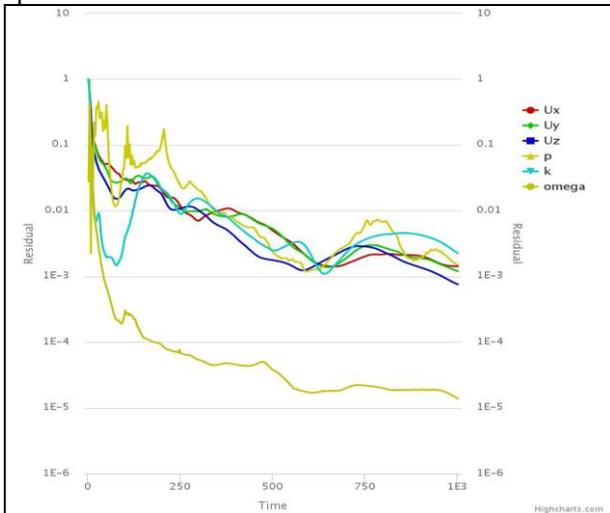


Figure 25 Convergence plot for fluid analysis

The kinetic energy of air around domain is observed up to 60 gigajoules. The omega is specific rate of dissipation of the turbulence kinetic energy k into internal thermal energy which is observed $9e^9 \text{ m}^2/\text{s}^3$. And the pressure is observed up to $10e^{10} \text{ N/m}^2$. These results are shown below.

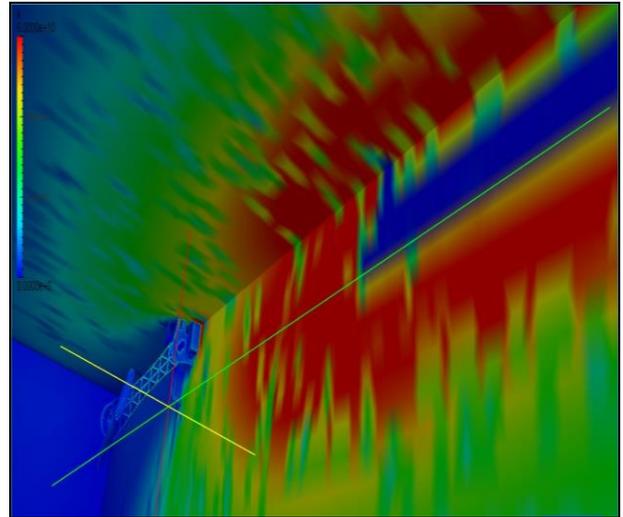


Figure 26 Kinetic energy of air around domain

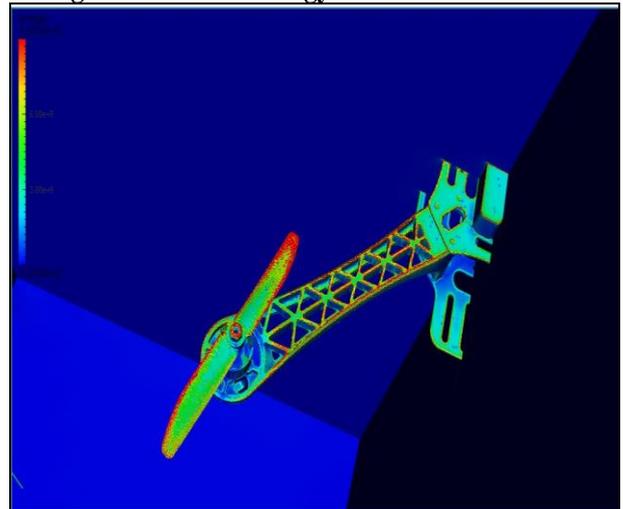


Figure 27 Specific rate of dissipation of the turbulence kinetic energy k into internal thermal energy

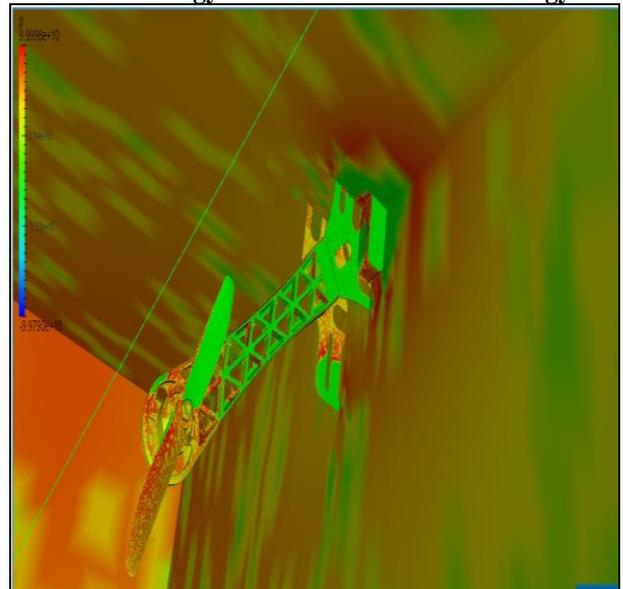


Figure 28 Change in the pressure of air

X. EXPERIMENTAL SETUP

The results obtained from analysis will be validated experimentally on actual setup.

Simulation and Analysis of a Quadrotor UAV while Landing.

The mass of an UAV is around 1 kg. The calculations presented before are considered while choosing the parts. The UAV parts with its specifications are given below.

A. Frame

Width: 450mm
Height: 55mm
Weight: 270g

B. Motor

Type: 1200 KV brushless motors
Weight: 57g each
Max. thrust: 2200 grams

C. Propeller

Diameter: 10 inch
Pitch: 4.5 inch
Weight: 16 g each

D. Electronic Speed Controller:

Amp. : 30A
Weight: 32 g each

E. Flight Controller

Size: 50.5mm x 50.5mm x 12mm
Weight: 21 gram (IncPiezo buzzer)
IC: Atmega644 PA
Gyro/Acc: 6050MPU InvenSense Inc.

F. Battery

Chemistry: Li-Polymer
Voltage: 11.1V
Capacity: 3000mAh
Discharge: 30C
Cell: 3S



(A)



(B)

Figure 29 Actual drone assembly for validation

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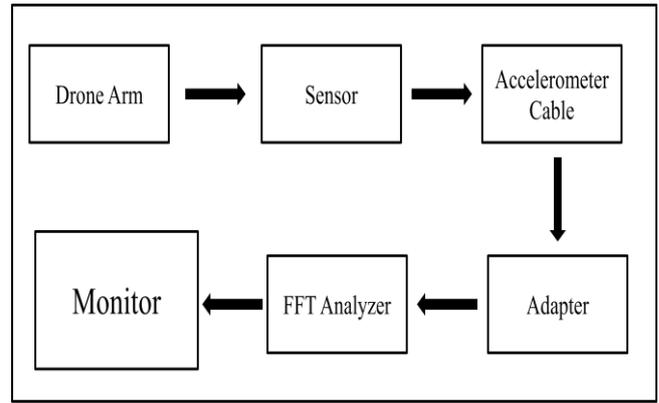


Figure 30 Block diagram for validation process

The conceptual illustration of the validation process is shown above. The sensors are attached to the position where maximum value is observed. The sensor transforms the data to FFT analyzer through accelerometer and results are displayed on monitor.

XI. RESULT AND DISCUSSION

After selecting a design for quadcopter, the maximum displacement of entire assembly is observed 0.02 mm. in structural analysis. In case of frequency analysis, the eigenfrequencies varies from 1.11E2 to 2.77E3Hz. For periodical load of 3 N, the displacement of an arm is observed between 0.075 mm to 0.065 mm for the frequencies 230 Hz to 240 Hz. respectively. Also the acceleration reduces from 153 m/s² to 148 m/s² with respect to frequencies. In case of drop analysis, the time steps are divided in different subdivisions for before and after the UAV touch the floor. The maximum von Mises stress is observed from 0 to 110 Mpa. at different time step after striking the floor. The fluid analysis gives the changes in values of kinetic energy of air around domain is observed up to 60gigajoules. The maximum value for Omega is observed 9e⁹ m²/s³. And the pressure is observed upto 10e¹⁰ N/m².

XII. CONCLUSION

The presented work covered basic quadrotor dynamics. The review of literature for various analyses is also done. It can be said from the literature that, the analysis for landing of an UAV is also very important for smooth landing as special purpose UAV may be mounted by delegate gadgets like camera etc. The structural analysis, drop analysis, fluid analysis as well as vibration analysis is done for calculating stresses, displacements etc. due to forces acting on it. The displacements observed are negligible and within the limit. The maximum stresses produced are 110 MPa. which are within range.

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AUTHOR PROFILE



Dr. Pramil V. Sawalakhe is Assistant Professor, Mechanical Engineering, at Shri Ramdeobaba College of Engineering and Management (RCOEM), Nagpur, India. He holds a Ph.D in Mechanical Engineering, awarded by RTMNU, Nagpur also MSc in Advanced Manufacturing systems awarded by Teesside University UK. He is member of IAENG. He has

published his research many National and International Journals. He is in the field of Research and Teaching from 8 Yrs.



Jahier Abbas Shaaikh M Tech (Production), PhD Scholar (Mechanical), Lecturer in Mechanical Engineering at Debre Tabor University, Ethiopia. Aerospace and defense industry professional and engineering teacher with 22+ years of experience. Expertise in operation and project management systems for mechanical industries. Contributed engineering institutes by setting up of laboratories, imparting project based learning, enhancing students'

employability.