Structural Optimization of Frame of the Multi-Rotor Unmanned Aerial Vehicle through Computational Structural Analysis

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Abstract. Because of the flexible working nature, the Multi-Rotor Unmanned Aerial Vehicle (MR-UAV) has been implemented in all kinds of real-time complicated problems. Due to this huge implementation, flawless UAVs have been required and used everywhere. Even though flawless UAVs have emerged, some of the domains in UAVs need to be analysed thoroughly to evolve UAVs without life affecting factors. This work deals with such kind of domain, which is a multi-objective investigation on MR-UAV's airframe. In which, five different prime MR-UAV's airframes are constructed, modelled, and computationally solved for three major composite materials and one conventional material. The important selection factors involved in this multi-objective optimization are low-stress induction, less deformation, and high lifetime. The short-listed five platforms of this structural optimization are the "X" frame, "I" frame, “K” frame, “Z” frame, and “+” frame. All these frames are computationally investigated with incorporate the following materials and their relevant mechanical properties: GFRP (Glass Fiber Reinforced Polymer), CFRP (Carbon Fiber Reinforced Polymer), KFRP (Kevlar Fiber Reinforced Polymer), and Aluminium Alloy. Apart from these fundamentals, the involvement of tools and their justifications are played a predominant role in this work. The major tools contributed are CATIA for modelling, ANSYS Workbench for Structural computations. The grid convergence test has been organized in a good manner to validate involved computational procedures. Finally, the suitable MR-UAV’s airframe and it opts material are obtained based on the multi-objective selection factors.

1. Introduction

The Multirotor UAVs like quadrotors have found application in our day to day life although being invented before many decades. UAVs have evolved due to the technological advancements over the years and the invention of MEMS components. Transformations from mechanical only to electromechanical components have paved the way for steadfast development. Quadrotors have been used for both civilian and military purposes like aerial photography, filming, surveillance, delivery of food and medicines, mapping, etc. Quadrotors offer better manoeuvrability, stable VTOL, and better control. They are usually the most preferred type of Multicopter because of their reliability and ease to make flying. Quadrotors are easy to build and are mostly used by DIY community people in the world as they come in various types of configurations which make them more attractive. Usually, UAVs are built to carry different payloads to accomplish their missions. Sometimes the payload may be heavier such that it may cause damage to the structure of the UAV. The vibrations caused by the pair of diagonally placed counter-rotating rotors also have structural effects on the UAV which may lead to breakdown during missions. The heavyweight landing also causes severe stresses on the quadrotor arm...
which makes this case a necessity for providing a solution. As the application of UAVs is expanding in all fields of engineering, it is necessary to provide people with the best in class airframe configuration. To avoid such misadventures, we should have a structurally strong and stable airframe. This paper deals with the structural and vibrational stability, the strength of the different quad airframes to give out the best design for any application, and any kind of payload.

2. Literature Survey

This paper used the Characteristic Mode Analysis (CMA) for analysis purposes. In which the effect of the frame on the electromagnetic coupling to the UAV’s wires was investigated and also it predicted the maximum and minimum coupling spots on the UAV, and then it was optimized to the appropriate position to reduce the vulnerability to unintended signals. The framework was initially developed and optimization was performed for better placement of PCBs and sensitive wires on the frame mitigate interference from undesired electromagnetic sources. By changing the material for the UAV frame change in Maxima/Minima spots of the coupled current was observed. In this case, the modes maxima were located at the arms of the frame. The material effect of UAV frames was studied by analysing the PEC frame and Dielectric Frames. In the PEC frame, wire-1 is above the hot spot of nozzle 1 of the PEC frame, wire-2 is above the modal current minima/maxima of model-1 and wire-3 is above the arm which has the maxima of model 1. The three wires are 135mm long and have a 0.25mm radius. All three were placed 0.1 mm apart from the frame. Results showed wire 1 had a higher induced current and wire 2 was induced the lowest current. In dielectric frame analysis, a dielectric frame with relative permittivity of 3.3 was studied. Here they are tilted to be parallel to the current distribution of model 1. At 0.9GHz wire 2 has the highest coupled current compared to PEC. This paper further showed the study on the effect of the dielectric UAV frame on the modes of the wire by varying the height of the wire above the frame. For heights larger than 5 mm above the dielectric frame, wire 2 acts as if it is in free-space exhibiting a resonance in the coupled current around 1.1 GHz. As the height decreases below 5 mm, the maximum in the coupled current shifts to just below 0.9 GHz and the less significant peak is still 1.1 GHz [1].

This research paper deals with 3D printing a Quadcopter that has an 'X' configuration. SOLIDWORKS was used to CAD model the frame. Finite structural analyses such as Static structural, Impact analysis and Modal analysis was performed. The drone frame was built in the PRUSA I3 Mk3 3D printer by using ABS-PC and carbon fibreglass materials as the filament. The drone frame was simulated for lift, drag, and thrust for optimization of the design. The frame was designed to accommodate 5040 propellers and Emax - RS2205 2300kv brushless DC motors on its arm. This fuselage was designed in a way that it could accommodate DYS FC omnibus pro, Matek XT-60 PDB on-board. Housing was designed on the fuse large to minimize the damage to the electronic components during the crash. Dimensions of fuselage are 175.14 mm (Length) X 171.42mm (Breadth) X 48.75mm (Height) X 226mm (Diagonal length). To perform finite element analysis force acting on the frame was analysed and they are lift, drag, weight, and thrust. Static structural analysis was carried out by considering non-linear analysis based on the rate of deformation, material, etc... Theoretical lift forces were calculated and applied across each arm of the frame by deciding fixture position and adding gravitational force acting on the frame. The impact analysis was performed by using the real-time simulation in SOLIDWORK by making the drone free fall from flying twenty-five feet above the ground. Hence net work done by all forces is calculated as $W = 33.6 \text{ kg m}^2 / s^2 = 33.6 \text{ N-m}$. Modal analysis was performed to measure dynamic excitation on the frame. Now considering the average rpm that the motor can generate during the throttle and convert that into the frequency, we can measure the vibrational excitation. It is observed some deformation after 416 Hz. The factor of safety for the 3-D printed frame is 2.5 [2]. This research paper analysed the Modelling and vibration analysis of the Quadcopter body frame to check the failure frequency range by changing the boundary condition. 3-D modelling of the frame was done in CREO 2.0 and the analysis part was carried out on ANSYS 16.2. Carbon fiber reinforced polymer (CFRP) is used. The material has 1600 kg/m3 of density, 0.3 Poisson’s ratio, and 70000 MPa of young modulus of elasticity. The region more prone to failure were determined by using fixed propeller and fixed body analysis. Simulation results show that the Natural frequency of a fixed propeller arm varies from 1084.5 Hz to 4412.9Hz and 1197.8Hz to
1299.8 Hz for a fixed body Base. Furthermore, the frequency of failure varies from 1084.5 Hz to 4412.9 Hz for a fixed propeller arm and 1197.8 Hz to 1299.8 Hz for a fixed body base. The test results show that fixed propeller arms have a lower frequency of failure than the fixed body base. Hence 1084.5 Hz is the minimum fundamental frequency of failure for the considered Quadcopter body frame [3].

This research paper investigated the static and dynamic characteristics of the structure of Quadcopter by determining and analysing the dynamics of the Quadcopter. This paper describes the overall design of the Quadcopter frame model is done in CATIA, and then the frame is analysed with ANSYS 18.0 commercial Finite element code. The selection of Frame, Motor, and Propeller were done. The mechanical modelling of the frame of the Quadcopter is done in CATIA and Static analysis and dynamic analysis were made in ANSYS. During dynamic analysis, the velocity at the different instant is inserted to get the results and a downward force equals the weight of the Quadcopter was applied in the opposite direction. The frame dimensions used in this paper are 495 mm X 363 mm. in this case E-glass fiber was used for the base frame and Polyamide nylon 6 was used for the arms of the Quadcopter. The Quadcopter frame was analysed to test the feasibility, rigidity, and compatibility of the frame. The thrust of each motor was equal to 15.47 N and was calculated by using standard formulas. Static analysis was performed by fixing the frame of the Quadcopter. A boundary condition was created and force equals to the thrust generated by the motor propeller set is applied at the four corners. The maximum deformation of 5.8439 mm was observed across the edges of the Quadcopter arms, the maximum stress of 6.2705 MPa was obtained at the inner edge of the arms of the Quadcopter. As the base plate was grounded, the stress on this is 1.3488*e10 MPa were the results of the static analysis made in ANSYS. And for dynamic analysis, the total deformation of 0.0011674 mm was obtained at the centre of the base plate. And maximum deformation of 0.00064853 mm is obtained at the four corners of the frame. The maximum stress of 0.22924 MPa during dynamic analysis was obtained at the outer edge of the arms. The frame material, motor KVA, and the propeller size all three factors give different contour plots. The stress and deformation on the frame are proportional to the thrust generated by the motors and the geometry of the frame. These contours help us designing the different frame of specific material which can withstand the different variable conditions and specific usage [4].

3. Methodology Used – Computational Structural Analysis

3.1. Conceptual Designs

Based on the mission, the payload weight is estimated as 2.5 kg and thereby the Equation (1) for historical relation supported the estimation of overall weight.

\[ W_{pl} = 0.40 \ W_0 \]

\[ W_0 = \frac{2.5}{0.4} = 6.25 \ kg \] (1)

After the estimation of overall weight, the Thrust requirement at peak loading condition is estimated with the help of Equation (2).

Thrust requirement by the single propeller
\[ \frac{[\text{Thrust to Weight ratio}] * [\text{Overall Weight of the UAV}]}{\text{Number of Propellers}} \] (2)

Thrust requirement by the single propeller = \[ \frac{[1.75] * [6.25]}{4} \] = 2.734375 kg

The estimation of thrust requirement by the single propeller leads to estimate the propeller’s diameter and pitch with the help of Equation (3).
From the literature survey and calculation, it is obtained that the maximum velocity of this proposed MR-UAV is around 50 m/s so the same can be used as exit velocity. Therefore the Propeller Pitch and Diameter are estimated as 5.7 and 6 inches.

Equation (4) and (5) contains the fineness ratio of the arms stick length and fineness ratio of the diameter of the arms stick. Thus, with the help of fineness ratio based equations the values of length of the arms stick length, motor to motor length, and diameter of the arms stick are estimated. Finally, the fineness ratio equation is extended for the length of the landing gear stick.

\[
T = 0.5 \cdot \rho \cdot A \cdot [(v_f)^2 - (v_0)^2] \text{ (N)}
\]  

\[
\text{Arm Stick Length} = 2 \cdot \text{Diameter of the Propeller} = 2 \cdot 6 = 12 \text{ inches}
\]

\[
\text{M2M (Motor to Motor)Length} = 2 \cdot \text{Arm Stick Length} = 2 \cdot 12 = 24 \text{ inches}
\]

Equation (1) to (5) are drastically supported the estimation of all the design parameters of the Quadcopters’ frame. The major focus of this work is a comprehensive structural analysis of Quadcopters’ frame so first and foremost constrain is the same geometrical properties should be maintained for all the frames. Therefore, the length of the arms stick, diameter of the arms stick, length of landing stick, overall outer boundary of the frame, and volume of all the frames are maintained the same for all the frames.

Conceptual designs of the ‘+’ frame, ‘I’ frame, ‘K’ frame, ‘X’ frame, and ‘Z’ frame are modelled with the help of an advanced modelling tool, i.e., CATIA. Figures 1 to 5 revealed the conceptual designs of all the models, in which Figure 1 reveals the ‘+’ frame, Figure 2 reveals the ‘I’ frame, Figure 3 reveals the ‘K’ frame, Figure 4 reveals the ‘X’ frame and Figure 5 reveals the ‘Z’ frame.

**Figure 1.** Conceptual Design of “+” Frame
Figure 2. Conceptual Design of “I” Frame

Figure 3. Conceptual Design of “K” Frame

Figure 4. Conceptual Design of “X” Frame
3.2. Boundary Conditions

Three predominant conditions are used in this comprehensive investigation, which are zero displacements, Weight of a whole UAV, and Lift force of a Propeller. The first and foremost input considered for this computation is Factor of Safety, which is assumed as 1.75. The targeted application of this work is to provide suitable surveillance in complicated working conditions. From the literature survey and mission, the payload weight is estimated as 2.5 kg. The historical relationship between payload weight and the overall weight is obtained for Quadcopter configurations, which is 0.4. Therefore, the overall weight is attained as 6.25 kg from the same aforesaid relationship. The gravity load is obtained as 6.25 * 9.81 = 61.3125 N and the Lift load per propeller is calculated as \((1.75*6.25)/4 = 2.734375 \text{ kg} = 26.82421875 \text{ N}\). Finally, the zero displacements are given at the bottom of the landing sticks in the direction of ‘X’ axis. The pictorial explanations of all the boundary conditions are revealed in Figure 6. Apart from these boundary conditions, the governing equations have been played a vital role. In which, displacement equations, displacement-strain related equations, strain-stress related equations are very important contributors, which are taken from the literature [32]. Additionally, mechanical properties are given input to initiate the computation, in which orthogonal properties such as in-plane and out-plane Young’s Modulus, Poisson ratios, Bulk Modulus, and densities are picked from standard literature survey and computational tools [6 - 32].

3.3. Description of Structural analysis

In complicated flight environments, the external loads are been acted on the UAV’s frame in a very critical manner. Because of this critical impact on UAV’s frame, the structural failure may
chance to happen in a high probability manner. Also, the cantilever structure based components are mostly involved in the Quadcopters' frame so these structures may chance to generate high stresses inside the fixed support of connecting arms. Also, the deformation has occurred highly in the place of connecting arms' free support. Due to these two structural effects, structural failure is a major concern, which needs to be analysed perfectly to provide a high lifetime to Quadcopter. Moreover, lightweight is the predominant input for Aerial vehicles therefore stresses and deformations are been analysed on composites and alloys. Thus, this work comprehensively analysed the structural variations over the UAV's frame of lightweight materials under critical loading conditions.

3.4. Grid Convergence Study and its Discussions

Comparatively, a low amount of parts have only contained the design critically in the entire construction of UAVs’ frame. The zigzag connections in the 'Z' frame, both the arm connections of the 'X' frame and 'V' connections in the 'K' frame are quite critical than other parts, which are dealt with utmost care under both design and meshing phases. To reduce the computational time without compromising the efficiency, the structural meshes are employed in all the frames. Especially, perfect brick elements are imposed in all kind of primary regions of frames and tetrahedral elements are imposed in the complicated regions of frames. Grid convergence investigation is executed with the help of six different mesh cases, in which face mesh setup on connecting arms, fine proximity on complicated junctions, fine curvature on the outer circular shape of the connecting arms, and slow apex capture on top of zigzag turns are majorly involved in the construction. The minimum count of elements and nodes are 101254 and 85471, the maximum count of elements and nodes are 1014781 and 811133. The comprehensive grid report is statistically revealed in Figure 7, in which Case-2 is picked-out to use further optimization.

![Grid Convergence Study on 'X' Frame](image)

**Figure 7.** Grid Convergence Test on “X” Frame

4. Results and Discussions

The structural results are computed on all the Quadcopters’ frame for the aforesaid boundary conditions. The foremost structural factors involved in the assortment route are generation of stress induced inside the body at the fixed support and magnitude of deflection at the free support. The structural results are revealed in Figures 8 to 17, in which equivalent stress and deformation are primarily comprised.
4.1. Results of Frame – I ['+' FRAME]

Figure 8. Distribution of Total Deformation of GFRP-E-Glass-Woven

4.2. Results of Frame – II ['I' FRAME]

Figure 9. Equivalent Stress variations of GFRP-E-Glass-Woven

Figure 10. Distribution of Total Deformation of GFRP-E-Glass-Wet
Figure 11. Equivalent Stress variations of GFRP-E-Glass-Wet

4.3. Results of Frame – III ['K' FRAME]

Figure 12. Distribution of Total Deformation of CFRP-UD-Prepreg

Figure 13. Equivalent Stress variations of CFRP-UD-Prepreg
4.4. Results of Frame – IV ['X' FRAME]

Figure 14. Distribution of Total Deformation of GFRP-E-Glass-UD

4.5. Results of Frame – V ['Z' FRAME]

Figure 15. Equivalent Stress variations of GFRP-E-Glass-UD

Figure 16. Distribution of Total Deformation of CFRP-Woven-Wet
From the structural results, the failure locations are identified, which are the regions in and around the hub and arm junctions. Structurally, the reaction force is the main cause for the stress generation at nearby hub regions, whereas the sharp design corner is the main cause for the stress generation at arm junctions. With this input, the optimized frame is picked based on its low structural performance under peak aerodynamic loads.

4.6. Comparative Analysis for Peak Loading Conditions

The all-inclusive structural results for CFRP are listed in Table 1. In which, Epoxy-CFRP-Woven-Wet based composite reacted very low equivalent stress is for ‘+’, ‘I’, and ‘Z’ frames, Epoxy-CFRP-UD-Prepreg based composite reacted low equivalent stress is for ‘K’ and ‘X’ frames.

Table 1. Comprehensive structural results of CFRP

| Frame  | CFRP-UD-Prepreg | CFRP-UD-Wet | CFRP-Woven-Wet | CFRP-Woven-Prepreg |
|--------|-----------------|-------------|----------------|-------------------|
|        | Deformation (mm) | Equivalent Stress (MPa) | Deformation (mm) | Equivalent Stress (MPa) | Deformation (mm) | Equivalent Stress (MPa) | Deformation (mm) | Equivalent Stress (MPa) |
| ‘+’ Frame | 0.51786 | 5.1104 | 0.56476 | 5.3595 | 0.5981 | 4.3033 | 0.64237 | 4.3975 |
| ‘I’ Frame | 0.61008 | 35.258 | 0.65663 | 33.317 | 0.24989 | 23.357 | 0.25601 | 23.424 |
| ‘K’ Frame | 0.6275 | 15.266 | 0.64566 | 15.914 | 0.68337 | 18.445 | 0.70042 | 19.471 |
| ‘X’ Frame | 0.51643 | 5.964 | 0.56114 | 6.2553 | 0.61638 | 6.0863 | 0.6623 | 6.167 |
| ‘Z’ Frame | 1.3276 | 29.399 | 1.3918 | 30.09 | 1.3931 | 11.882 | 1.4531 | 12.344 |

The all-inclusive structural results for GFRP are listed in Table 2. In which, Epoxy-GFRP-E-Glass-Woven based composite reacted very low equivalent stress is for ‘+’, ‘I’, ‘K’, and ‘Z’ frames, Epoxy-GFRP-E-Glass-Wet based composite reacted low equivalent stress is for ‘X’ frames.

Table 2. Comprehensive structural results of GFRP

| Frame  | GFRP-E-Glass-UD | GFRP-E-Glass-Wet | GFRP-S-Glass-UD | GFRP-E-Glass-Woven |
|--------|-----------------|-----------------|-----------------|-------------------|
|        | Deformation (mm) | Equivalent Stress (MPa) | Deformation (mm) | Equivalent Stress (MPa) | Deformation (mm) | Equivalent Stress (MPa) | Deformation (mm) | Equivalent Stress (MPa) |
| ‘+’ Frame | 0.46092 | 4.156 | 0.55147 | 4.186 | 0.56213 | 4.3324 | 0.42929 | 3.596 |
| ‘I’ Frame | 0.54663 | 23.835 | 0.60773 | 22.565 | 0.65314 | 25.31 | 0.35421 | 20.70 |
| ‘K’ Frame | 0.58533 | 12.066 | 0.65352 | 12.12 | 0.64167 | 12.799 | 0.64827 | 11.239 |
| ‘X’ Frame | 0.47522 | 4.1993 | 0.53393 | 4.0637 | 0.57306 | 4.7903 | 0.4559 | 4.206 |
| ‘Z’ Frame | 1.1897 | 12.328 | 1.3126 | 10.626 | 1.3525 | 14.741 | 1.211 | 8.332 |

The all-inclusive structural results for KFRP and Aluminium alloy are listed in Table 3. In which, as per this selection factor, Aluminium alloy performed better than Epoxy-KFRP-UD-49 based composite.

Table 3. Comprehensive structural results of Aluminium Alloy and KFRP

| Frame  | KFRP-UD-49 | Aluminium Alloy |
|--------|-------------|-----------------|
|        | Deformation (mm) | Equivalent Stress (MPa) | Deformation (mm) | Equivalent Stress (MPa) |
| ‘+’ Frame | 1.3276 | 29.399 | 1.3918 | 30.09 |
| ‘I’ Frame | 1.3931 | 11.882 | 1.4531 | 12.344 |
| ‘K’ Frame | 1.3525 | 14.741 | 1.211 | 8.332 |
| ‘Z’ Frame | 1.1897 | 12.328 | 1.3126 | 10.626 |

Figure 17. Equivalent Stress variations of CFRP-Woven-Wet
### Table 3

| Frame   | Deformation (mm) | Equivalent Stress (MPa) |
|---------|------------------|-------------------------|
| ‘+’ Frame | 0.8254            | 4.8881                   |
| ‘I’ Frame | 0.9926            | 35.647                   |
| ‘K’ Frame | 1.0559            | 16.533                   |
| ‘X’ Frame | 0.8253            | 5.8263                   |
| ‘Z’ Frame | 2.2633            | 32.251                   |

### 5. Conclusions

The structural simulations are carried out on five different Quadcopter frames, in which equivalent stress and total deformation are primarily considered as important selection factors. The major concern involved in this investigation is executed under the maximum aerodynamic loads, which is achieved through the assumption of FOS as 1.75. Downward and upward forces are majorly acted as the external load on four lightweight material families such as Aluminium Alloy, CFRP, GFRP, and KFRP. From the comprehensive results, the following observations are obtained: GFRP is performed better than other lightweight materials, wherein Epoxy-E-Glass-Woven is structurally reacted in a very positive manner. Apart from GFRP, Epoxy-CFRP-Woven-Wet has secured the second position based on the low generation of equivalent stress. Finally, Epoxy-KFRP-UD-49 based composite is performed well than other CFRP composites. At last, ‘+’ and ‘X’ frames are awarded as best Quadcopter configurations to withstand any kind of external loads. The complete structural variations with respect to peak load for different lightweight materials of five Quadcopter’s frames are comprehensively revealed in Tables 1, 2, and 3 in favour of the future research perspective.

### References

[1] M. Z. M. Hamdalla, A. M. Hassan and A. N. Caruso, Characteristic Mode Analysis of the Effect of the UAV Frame Material on Coupling and Interference, IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting, Atlanta, GA, USA, 2019, pp. 1497-1498, 2019, DOI: 10.1109/APUSNCURSINRSM.2019.8888344.

[2] Sai Mallikarjun Parandha, Zheng Li, Design and Analysis of 3D Printed Quadrotor Frame, International Advanced Research Journal in Science, Engineering and Technology, Vol. 5, Issue 4, pp. 66 - 73, 2018, DOI 10.17148/IARJSET.2018.5411.

[3] Anamika Bhandari, Faraz Ahmad, Pushpendra Kumar, Pravin P. Patil, Design and Vibration Characteristics Analysis of Quadcopter Body Frame, International Journal of Applied Engineering Research, Vol. 14, No. 9, pp. 66 - 70, 2019.

[4] Rahul Singh, Rajeev Kumar, Abhishek Mishra, Anshul Agarwal, Structural Analysis of Quadcopter Frame, Materials Today Proceedings, Vol. 22, Part 4, pp. 3320-3329, 2020, https://doi.org/10.1016/j.matpr.2020.03.295.

[5] Alberto Martinetti Mihran Margaryan, Leo van Dongen, Simulating mechanical stress on a micro Unmanned Aerial Vehicle (UAV) body frame for selecting maintenance actions, Procedia Manufacturing, Vol. 16, pp. 61-66, 2018, https://doi.org/10.1016/j.promfg.2018.10.160.

[6] Vijayanandh R et al., Design and Fabrication of Solar Powered Unmanned Aerial Vehicle for Border Surveillance, Proceedings of International Conference on Remote Sensing for Disaster Management, Issues and Challenges in Disaster Management, Geomechanics and Geoengineering, eBook ISBN Number 978-3-319-77276-9, Edition Number - 1, 2019, pp. 61-71, DOI: 10.1007/978-3-319-77276-9.

[7] Vijayanandh R., M. Senthil Kumar, K. Naveenkumar, G. Raj Kumar, R. Naveen Kumar, Design Optimization of Advanced Multi-rotor Unmanned Aircraft System Using FSI, Innovative Design, Analysis and Development Practices in Aerospace and Automotive Engineering, Lecture Notes in Mechanical Engineering, eBook ISBN - 978-981-3-2718-6, Chapter No. 28, pp. 299-310, DOI 10.1007/978-981-3-2718-6.

[8] Balaji S, Prabhagaran P, Vijayanandh R, Senthil Kumar M, Raj Kumar R, Comparative Computational Analysis on High Stable Hexacopter for Long Range Applications,
[9] Vijayanandh R, Senthil Kumar M, Rahul S, Thamizhanbu E and Durai Isaac Jefferson M, Conceptual Design and Comparative CFD Analyses on Unmanned Amphibious Vehicle for Crack Detection, Unmanned Aerial System in Geomatics, Lecture Notes in Civil Engineering, eBook ISBN: 978-3-030-7393-1, Chapter No. 31, pp. 369-391, 2020, https://doi.org/10.1007/978-3-030-37393-1_31

[10] Vijayanandh R, Kiran P, Indira Prasanth S, Raj Kumar G, Balaji S, Conceptual Design and Optimization of Flexible Landing Gear for Tilt-Hexacopter Using CFD, Unmanned Aerial System in Geomatics, Lecture Notes in Civil Engineering, eBook ISBN: 978-3-030-7393-1, Chapter No. 15, pp. 151-174, 2020, https://doi.org/10.1007/978-3-030-7393-1_14

[11] G Raj Kumar et al, Comparative Investigations on the Main Elements of Carbon Fiber Based Composites Using Computational Structural Simulations, Journal of Physics : Conference Series, 1504 012003, pp. 1-11, 2020, https://iopscience.iop.org/article/10.1088/1742-6596/1504/1/012003

[12] R Vijayanandh et al, Theoretical and Numerical Analyses on Propulsive Efficiency of Unmanned Aquatic Vehicle’s Propeller, Journal of Physics: Conference Series 1504 012004, pp. 1-10, 2020, https://doi.org/10.1088/1742-6596/1504/1/012004

[13] Balaji Sonaimuthu, Prabhagaran Panchalingam, Vijayanandh Raja, Comparative Analysis of Propulsive System in Multi-Rotor Unmanned Aerial Vehicle, ASME 2019 Gas Turbine India Conference, GTINDIA 2019, pp 1-8, https://doi.org/10.1115/GTINDIA2019-2429.

[14] K. Venkatesan, K. Ramanathan, R. Vijayanandh et al., Comparative structural analysis of advanced multi-layer composite materials, Materials Today: Proceedings, Volume 27, Part 3, 2020, pp. 2673-2687, https://doi.org/10.1016/j.matpr.2019.11.247

[15] Vijayanandh R, Venkatesan K, Senthil Kumar M, Raj Kumar G, P. Jagadeeshwaran, Raj Kumar R, Comparative fatigue life estimations of Marine Propeller by using FSI, IOP - Journal of Physics: Conference Series. 1473 (2020) 012018, doi:10.1088/1742-6596/1473/1/012018

[16] K. Mohamed Bak, Raj Kumar G, Ramasamy N and Vijayanandh R, Experimental and Numerical Studies on The Mechanical Characterization of Epdm/S-Sbr Nano Clay Composites, IOP Conference Series: Materials Science and Engineering, 912, 052016, pp. 1-11, 2020, doi:10.1088/1757-899X/912/5/052016

[17] Senthil Kumar. M, Vijayanandh. R & Gopi. B, Numerical Investigation on Vibration Reduction in Helicopter Main Rotor Using Air Blown Blades, International Journal of Mechanical and Production Engineering Research and Development, ISSN (E): 2249-8001, Vol. 8, Special Issue 7, pp. 152-164, 2018.

[18] Rajagurunathan. M, Raj Kumar. G, Vijayanandh. R, Vishnu. V, Rakesh Kumar. C & Mohamed Bak. K, The Design Optimization of the Circular Piezoelectric Bimorph Actuators Using FEA, International Journal of Mechanical and Production Engineering Research and Development, ISSN(E): 2249-8001, Vol. 8, Special Issue 7, pp. 410-422, 2018.

[19] Vijayanandh, R Ramesh. M, Senthil Kumar. S, Raj Kumar. G, Senthil Kumar. M & Naveen Kumar. R, The Conceptual Design of the Tilt-Copter Based on the Speech Control (A Theoretical Approach), International Journal of Mechanical and Production Engineering Research and Development, ISSN: 2249-8001, Vol. 8, Special Issue 7, pp. 423-439, 2018.

[20] Raj Kumar. G, Vijayanandh. R, Mohammad Bak. K, Shyam Chander. R & Arawinth. R, Experimental Testing On Mechanical Properties Effect of Aluminum Foam, International Journal of Mechanical and Production Engineering Research and Development, ISSN: 2249-8001, Vol. 8, Special Issue 7, 1047-1059, 2018.

[21] K. Naveen Kumar, R. Vijayanandh, G. Raj Kumar, B. Sanjeev, Hariharan Balachander and S. Guru Prasad, Comparative Approaches for Fatigue Life Estimation of Aluminium Alloy for Aerospace Applications, Int. J. Vehicle Structures & Systems, 10(4), 282-286, 2018, doi: 10.4273/ijvss.10.4.11
[22] Raj Kumar, G, Senthil Kumar, M, Vijayanandh, R, K, Raja Sekar, Mohamed Bak, K & Varun, S, The Mechanical Characterization Of Carbon Fiber Reinforced Epoxy with Carbon Nanotubes, International Journal of Mechanical and Production Engineering Research and Development, ISSN: 2249-8001, Vol. 9, Spl. Iss. 1, pp. 243-255, 2019.

[23] Vijayanandh, R, Venkatesan, K, Ramesh, M, Raj Kumar, G, Senthil Kumar, M, Optimization of Orientation Of Carbon Fiber Reinforced Polymer Based On Structural Analysis, International Journal of Scientific & Technology Research, ISSN 2277-8616, Volume 8, Issue 11, pp. 3020-3029, 2019.

[24] Raj Kumar, G, Balasubramaniyam, S, Senthil Kumar, M, Vijayanandh, R, Raj Kumar, R, Varun, S, Crash Analysis on the Automotive Vehicle Bumper, International Journal of Engineering and Advanced Technology, ISSN:2249-8958, vol.8, 6S3, pp.1602-1607, 2019, DOI:10.35940/ijeat.F1296.0986S319.

[25] Naveen Kumar K, Vijayanandh R, Bruce Ralphin Rose J, Swathi V, Narmatha R, Venkatesan, K, Research on Structural behavior of Composite Materials on different Cantilever Structures using FSI, International Journal of Engineering and Advanced Technology, ISSN: 2249-8958, Volume-8, Issue-6S3, pp: 1075 - 1086, 2019, DOI: 10.35940/ijeat.F1178.0986S319

[26] K. Venkatesan, S. Geetha, R. Vijayanandh, G. Raj Kumar, P. Jagadeeshwaran, and R. Raj Kumar, Advanced structural analysis of various composite materials with carbon nano-tubes for property enhancement, AIP Conference Proceedings 2270, 030005 (2020), pp. 030005-1 to 030005-6, https://doi.org/10.1063/5.0019367

[27] P. Mirrudula, P. Kaviya Priya, M. Malavika, G. Raj Kumar, R. Vijayanandh, and M. Senthil Kumar, Comparative structural analysis of the sandwich composite using advanced numerical simulation, AIP Conference Proceedings, 2270, pp. 040005-1 to 040005-5, 2020, https://doi.org/10.1063/5.0019370

[28] S. Indira Prasanth, K. Kesavan, P. Kiran, M. Sivaguru, R. Sudharsan, and R. Vijayanandh, Advanced structural analysis on E-glass fiber reinforced with polymer for enhancing the mechanical properties by optimizing the orientation of fiber, AIP Conference Proceedings 2270, pp. 040006-1 to 040006-5, 2020, https://doi.org/10.1063/5.0019378

[29] S. Bhagavathyappan, M. Balamurugan, M. Rajamanickam, R. Vijayanandh, G. Raj Kumar, and M. Senthil Kumar, Comparative computational impact analysis of multi-layer composite materials, AIP Conference Proceedings, 2270, pp. 040007-1 to 040007-5, 2020, https://doi.org/10.1063/5.0019380.

[30] Vijayakumar Mathaiyan, R, Vijayanandh and Dong Won Jung, Determination of Strong Factor in Bird Strike Analysis using Taguchi’s method for Aircraft Manufacturing guide, Journal of Physics: Conference Series, 1733 (2021) 012002, 1-6, doi:10.1088/1742-6596/1733/1/012002

[31] Ramesh M, Vijayanandh R, Raj Kumar G, Vijayakumar Mathaiyan, P Jagadeeshwaran, Senthil Kumar M, Comparative Structural Analysis of Various Composite Materials based Unmanned Aerial Vehicle’s Propeller by using Advanced Methodologies, IOP Conf. Series: Materials Science and Engineering, 1017, 012032, 1-10, 2021, doi:10.1088/1757-899X/1017/1/012032

[32] Vijayanandh R, Raj Kumar G, P Jagadeeshwaran, Vijayakumar Mathaiyan, Ramesh M, and Dong Won Jung, Carbon Nanotubes and Their Polymer Nanocomposites, Nanomaterials and Nanocomposites: Characterization, Processing, and Applications, Chapter –9, pp. 139 – 165, ISBN 9780367483890, 2021.

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