Comparative Structural Analysis of Various Composite Materials based Unmanned Aerial Vehicle’s Propeller by using Advanced Methodologies

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Abstract. In the recent technology over the Unmanned Aerial Vehicle (UAV), the implication of propeller contributes a principal part in the production of thrust by pushing the air with the rotating blades. Especially, propeller's incomparably works perfect in the advanced UAVs, because of its huge contribution to UAV's construction. Analyzing the structural behavior of propeller and its rotodynamic effects with the help of advanced engineering approaches can provide better performance and lifetime in advanced operating conditions. The composites of CFRP (Carbon Fiber Reinforced Polymer) and GFRP (Glass Fiber Reinforced Polymer) are widely used for the propellers, due to the advantage of load resisting capacity, lightweight, higher production. This work deals with the comparative studies of the propeller with the different composites such as CFRP and GFRP to inculcate the structural characteristics of deformation with respect to the applied load, maximum stress, and normal stress by coupled cum advanced simulations for different rotational velocities. The primary outcome of these comparative studies is providing the optimized performance as well as its ultimate lifetime of the rotor component for an advanced UAV. Finally, material optimizations are executed for UAV's propeller by using two advanced numerical methodologies that are FSI (Fluid-Structure Interaction) for the evaluation of structural parameters and coupling of CFD (Computational Fluid Dynamics) - MRF (Moving Reference Frame) for the representation of rotating nature of propeller. Through these approaches and grid convergence test, the best composite material is finalized, which is GFRP. Especially, Epoxy-E-Glass UD and Epoxy-S-Glass-UD are performed better than other composite materials, wherein the Epoxy-E-Glass-UD is reacted low deformed value of 3.7829μm and Epoxy-S-Glass-UD is induced low stress value of 55556Pa than other composites at average loading conditions.

1. UAV’s Propeller and its Materials

Generally, the propulsive system of a multi-rotor UAV is focally depended upon its propeller. The endurance is comparatively low in the electric propulsive system based multi-rotor UAVs [1]. Hence, the useful research on propeller can able to increase the performance of a multi-rotor UAVs. Nowadays, the important ongoing research on propellers are, material optimizations for high-speed applications, noise reduction in UAV's propeller, lift enhancement techniques in the propeller and drag reduction techniques in UAVs, etc [2]. The fundamental aims of all these researches are to provide high lifetime and endurance in UAVs. In this work, analyze the structural performance of UAV's propeller in various dynamic environments using advanced and integrated numerical simulation techniques [3]. Currently, the glass and carbon fibers based propellers are drastically used in the UAVs because of its advanced properties. In general, the stiffness to weight ratio is quite high in the
Polymer matrix composite, which can provide better performance at critical phases such as high forward and vertical speed conditions, high gust load environments, and large endurance applications [4]. Also, rotodynamic nature-based propellers have severely occurred structural failure, and thereby the performance may chance to collapse, this complicated condition is perfectly tackled by Polymer matrix composite based propellers [5]. In polymer matrix composite, various varieties are available which are, uni-directional fiber, bi-directional fiber, prepreg production, wet conditionla product, etc [6]. All these variations of glass and carbon fibers are implemented in propellers and analyzed by using ANSYS Workbench to find suitable material to withstand effectively at high loading conditions. Finally, the suitable material with its unique property is to be found for all the loading conditions [7].

2. Problem identification and Solution Techniques

The fundamental platform of this work is the propeller, which has 6 inches in diameter and 4.5 inches in pitch. The conceptual design of the used propeller is shown in Figure 1, in which CATIA is used as a modeling tool. The fundamental platform of this research is to select suitable composite materials for UAV’s propeller under rotodynamic loading conditions. Because of the critical working nature of the propeller, the attainment process of the desired output and its reliability is quite complicated. To attain reliable output for this critical and complicated problem, the advanced numerical simulation approach is used here because it has a flexible facility at any stage and it is an easier adaptation with the advanced techniques [8]. Therefore, in this work, ANSYS Workbench based numerical analyses are conducted on the UAV’s propeller for different composite materials. In this simulation, two different environments are used separately and then coupled with the help of one way coupling FSI to solve complicated rotodynamic and thereby its structural effects [9]. The fluid environmental conditions are analyzed on propeller with various RPMs by using the CFD tool, i.e., ANSYS Fluent. To represent the RPM of the propeller, the MRF (Moving Reference Frame) approach is implemented in the CFD tool. With these advanced implementations, the CFD analyses are executed on the UAV’s propeller and thereby the fluid pressures are estimated. The estimated total pressures are transferred into the structural environmental analysis as an external load category on the UAV’s propeller with the help of a one-way coupling FSI methodology. The one-way coupling FSI is one of the advanced numerical techniques, this is used for load sharing between two different environments to provide reliable output. In this work, the fluid load generation on the propeller to be captured perfectly because of the unpredictable nature of the fluid behavior and that can be transferred to structural analysis without any adjustments. Hence, the advanced numerical tool like one-way coupling FSI is mandatory to work as a coupling tool in-between dynamic fluid analysis and structural analysis [10]. The FEA tool, ANSYS Structural, is used for the estimation of structural parameters such as strain energy, various stresses, and total deformation. Finally, the FSI analyses are executed on the UAV’s propeller for eight different materials, which are Epoxy Carbon Woven – 230 GPa – Wet, Epoxy Carbon Woven–230 GPa–Prepreg, Epoxy Carbon UD–230 GPa–Prepreg, Epoxy Carbon UD–230GPa–wet, Epoxy S–Glass UD, Epoxy E-Glass Wet, Epoxy E-Glass UD, and Aluminium alloy. In which, the Aluminium alloy is used as a reference element, thus the structural outputs are compared with Aluminium alloy, and then optimization is finalized.

3. Material Optimization based on FSI

3.1. FSI

FSI is a kind of integrating and advanced methodology, which is used to couple data between two different working environments. The fundamental objective of this work is to select the best composite material based on rotodynamic com structural effects [10 - 11]. Thus, the representation of the rotodynamic effect and thereby the structural effects on UAV’s propellers are unavoidable ones, which provided the path to use one-way coupling FSI [12]. Based on the nature of load sharing, the FSI is
primarily classified into two types, which are one-way coupling FSI and two-way coupling FSI. In one-way coupling, the loads are shared through direct coupling whereas, in two-way coupling FSI, the loads and data are shared with the help of a system coupling system [13 - 14].

3.2. CFD
The first and foremost data of this work is aerodynamic pressure acting on the propeller due to its rotational, which is executed with help of the CFD tool, i.e., ANSYS Fluent. The average speed of the civilian UAVs is flying at the speed of 10 m/s so the same one is used as velocity inlet for this fluid analysis [15]. Thus, the aerodynamic fluid density does not vary and thereby the pressure plays a vital role in the fluid analysis so the pressure-based solver is implemented. Because of the critical work nature of the propeller, the turbulent flow is used at an acceptable rate [16]. A separate comparative analysis is completed with respect to RPM versus thrust generation on the UAV's propeller, in which 2300 RPM can have the capability to provide the thrust of 500 grams. Apart from these primary conditions, the fixed rectangular control volume is used, which has the dimensions of 20x5 inches in the 'X' direction, 10x5 inches in both 'Y' and 'Z' directions. The rotating control volume is also implemented to represents MRF regions with respect to Propeller, in which the dimensions are used as 6X5 inches in diameter. The fine tetrahedral 3-D elements are used in which the finely tuned conditions are used at no-slip regions [17]. Figure 2 is revealed the finite volume model of the propeller, which can able to predict the fluid properties in and around the propeller, and then further needful results are executed. The pressure and velocity variations on the propeller are revealed in Figures 4 and 5. The grid convergence study is organized in this CFD simulation to enhance the reliability of its outcomes. The comprehensive report is generated and revealed in Figure 3.
In this grid convergence study, five mesh cases are implemented, in which Case-2 is short-listed as an optimized case based on the induced velocity outcome. All the five cases are constructed based on fine mesh setup as primary facility and secondary facilities such as inflation, face mesh, refinement, etc.

3.3. Computational Structural Results
The structural parameters such as deformation and stresses are estimated with the help of the FEA numerical tool, in which the roller supports are provided at the hub section of the propeller. The external fluid loads are transferred and applied at the FSI region on the propeller through a one-way coupling FSI facility [16].

3.3.1. Results – Aluminium Alloy – Reference Components

![Figure 6. Deformed structure of Aluminium Alloy’s Propeller](image)

![Figure 7. Equivalent Stress variations of Aluminium Alloy’s Propeller](image)
3.3.2. Numerical Results – Epoxy Carbon UD – 230 GPa – Prepreg

Figure 8. Variations of deformation of Epoxy Carbon UD – 230 GPa – Prepreg’s Propeller

Figure 9. Variations of equivalent stress of Epoxy Carbon UD – 230 GPa – Prepreg

Primarily, four materials are short-listed and analyzed, in which one material is used for reference. The entire materials' details and the structural results are listed in Table 1. The deformations, normal stress, and equivalent stress variations of Aluminium Alloy [reference material] are shown in Figures 6, 7, and 10, in which the values are considered as maximum output data. Apart from this primary material, the structural results of Epoxy Carbon UD-230 GPa-Prepreg are also revealed in Figures 8, 9, and 11.

Figure 10. Normal Stress variations of Aluminium Alloy’s Propeller

Figure 11. Variations of normal stress of Epoxy Carbon UD – 230 GPa – Prepreg

| Sl. No | Material Name                   | Equivalent Stress (Pa) | Total Deformation (μm) | Normal Stress (Pa) |
|--------|--------------------------------|------------------------|------------------------|-------------------|
| 1      | Aluminium Alloy                | 55589                  | 0.53514                | 22739             |
| 2      | Epoxy Carbon Woven – 230 GPa – Wet | 55960                  | 5.0932                | 25512             |
| 3      | Epoxy Carbon UD – 230 GPa – Prepreg | 56410                  | 4.3864                | 28658             |
| 4      | Epoxy S – Glass UD             | 55556                  | 4.6575                | 26250             |

From Table 1, it is understood that Epoxy-S-Glass fiber based composite is reacted with low cumulative cum equivalent stress, thus the glass fiber is more suitable to work as a manufacturing material for UAV's propeller.
3.4. Computational Structural Results of various Glass fiber results
Owing to the top role in the primary tests, the structural analyses are extended to all the other good glass fibers such as Epoxy E-Glass UD and Epoxy E-Glass wet [11, 12].

3.4.1. Numerical results of Epoxy S-Glass UD

![Figure 12. Deformed structure of Epoxy S-Glass UD’s Propeller](image)
![Figure 13. Equivalent Stress variations of Epoxy S-Glass UD’s Propeller](image)

The entire structural outputs of glass fibers based composites are analyzed and listed in Table 2. For the sample case, the structural results of the Epoxy S-Glass-UD based propeller are shown in the Figures 12, 13, and 16, wherein Figure 12 is revealed the variations of deformation, Figure 13 is revealed the variations of equivalent stress, and Figure 13 is revealed the variations of normal stress.

| Sl. No | Material Name      | Equivalent Stress (Pa) | Total Deformation (μm) | Normal Stress (Pa) |
|--------|--------------------|------------------------|------------------------|--------------------|
| 1      | Epoxy E-Glass UD   | 55725                  | 3.7829                 | 24279              |
| 2      | Epoxy E-Glass Wet  | 55638                  | 4.1951                 | 23060              |
| 3      | Epoxy S-Glass UD   | 55556                  | 4.6575                 | 26250              |

3.5. Computational Structural Results of various Carbon fiber-based composites results
Comparatively, the deformation of the propeller is also having capable to judge the best material. Thus the low deformed perspective also analyzed, in which carbon UD-Prepreg is reacted with low deformation compared to other materials therefore the FSI analyses are extended for all the Carbon fiber based composite materials. The entire structural results are analyzed and listed in Table 3. The bi-directional carbon fiber-based composite structural results are revealed in Figures 14, 15, and 17, in that the corresponding parameters are deformation, equivalent stress, and normal stress respectively.
3.5.1. Numerical results of Epoxy Carbon Woven – 230 GPa – Prepreg

![Figure 14. Variations of deformation of Epoxy Carbon Woven – 230 GPa – Prepreg’s Propeller](image)

![Figure 15. Variations of equivalent stress of Epoxy-CFRP-Woven-230-GPa-Prepreg](image)

![Figure 16. Normal Stress variations of Epoxy S-Glass UD’s Propeller](image)

![Figure 17. Variations of normal stress of Epoxy Carbon Woven – 230 GPa – Prepreg](image)

Table 3. Comparative structural outputs of CFRP materials

| Sl. No | Material Name                        | Equivalent Stress (Pa) | Total Deformation (μm) | Normal Stress (Pa) |
|-------|-------------------------------------|------------------------|------------------------|--------------------|
| 1     | Epoxy Carbon UD – 230 GPa – Wet    | 56119                  | 4.8002                 | 30515              |
| 2     | Epoxy Carbon UD – 230 GPa – Prepreg| 56410                  | 4.3864                 | 28658              |
| 3     | Epoxy Carbon Woven – 230 GPa – Wet | 55960                  | 5.0932                 | 25512              |
| 4     | Epoxy Carbon Woven – 230 GPa – Prepreg| 55590                 | 5.4908                 | 26458              |

4. Conclusions

The UAV’s propeller is used as a platform for this entire comparative work, in which the diameter is calculated as 6 inches, the pitch is estimated as 4.5 inches and the complete model is designed through CATIA. The shortlisted propeller can able to provide an average thrust of 500 grams, which is the maximum thrust requirement by the real time UAVs. The pressure acting on the propeller surface, velocity variations on the propeller are predicted through the CFD tool, ANSYS Fluent for the given boundary conditions of 1 m/s as fluid input velocity and 2300 RPM is given as rotational velocity. The stresses induced in the composite propellers and its displacement variations are predicted by using FEA numerical tool, ANSYS Structural. Finally, the Glass fiber-based composite is selected as a more suitable material for UAVs, based on its low structural outputs and the results are compared with theoretical outputs for validation purposes. The displacement of the Epoxy E-Glass-UD is 3.8 μm and Epoxy-E-Glass UD is created a low stress of 55556 Pa at peak and average loading conditions, which
means the stiffness to weight ratio is high in this material. Because of this high stiffness to weight ratio, the nature of the propeller's profile does not affect with respect to working time. Therefore the shortlisted material is fit to provide high structural performance at all the critical environments.

References

[1] 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, 2018, 410-422.

[2] 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(E): 2249-8001 Vol. 9, Special Issue 1, 2019, 243-255.

[3] Vijayanandh R., M. Senthil Kumar, K. Naveenkumar, G. Raj Kumar, R. Naveen Kumar, Design Optimization of Advanced Multi-rotor Unmanned Aircraft System Using FSI, Springer Series Title - Lecture Notes in Mechanical Engineering, eBook ISBN - 978-981-13-2718-6, DOI 10.1007/978-981-13-2718-6, pp. 299 – 310, 2019.

[4] Vijayanandh R, Ramesh M, Raj Kumar G, Venkatesan K, Senthil Kumar M, Research of Noise in the Unmanned Aerial Vehicle’s Propeller using CFD, International Journal of Engineering and Advanced Technology, 8, 6S, 2019, pp.145-150, DOI:10.35940/ijeat.F1031.0868S19.

[5] 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, Vol. 8, Spl Issue 7, pp.152-164, 2018.

[6] 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, Vol. 8, Special Issue 7, pp. 423-439, 2018.

[7] K. Naveen Kumar, R. Vijayanandh, G. Raj Kumar, Hariharan B, S. Guru Prasad, Comparative Approaches for Fatigue Life Estimation of Aluminium Alloy for Aerospace Applications, Int. J. Vehicle Structures & Systems, 10(4), 282-286, doi: 10.4273/ijvss.10.4.11.

[8] Arul Prakash. R, Sarath Kumar. R, Vijayanandh. R, Darsi Venkata Praveen Raja Sekar. K & Ananda Krishnan. C, Design Optimization Of Convergent - Divergent Nozzle Using Computational Fluid Dynamics Approach, International Journal of Mechanical and Production Engineering Research and Development, Vol. 9, Spl Issue 1, pp. 220-232, 2019.

[9] R. Vijayanandh, M. Ramesh, K.Venkatesan, G.Raj Kumar, M.Senthil Kumar, and R. Rajkumar, Comparative Acoustic Analysis of Modified Unmanned Aerial Vehicle’s Propeller, Advances in IC Engines and Combustion Technology, Lecture Notes in Mechanical Engineering, 45, pp. 557-571, 2021, https://doi.org/10.1007/978-987-15-5996-9_45.

[10] P. Jagadeeshwaran, Dr. V. Natarajan, Vijayanandh R, Senthil Kumar M, Raj Kumar G, Numerical Estimation Of Ultimate Specification Of Advanced Multi-Rotor Unmanned Aerial Vehicle, International Journal Of Scientific & Technology Research, ISSN 2277-8616, Volume 9, Issue 01, 2020, pp. 3681 – 3687.

[11] Naveen Kumar K, Vijayanandh R, Bruce Ralphine 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, 8, 6S3, pp: 1075 - 1086, 2019, DOI: 10.35940/ijeat.F1178.0986S319.

[12] 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, November 2019.
[13] G. Raj Kumar, Vijayanandh R, Experimental and Numerical Studies on Mechanical characterization of EPDM/S-SBR with Nanoclay Composites, IOP Conference Series: Materials Science and Engineering, 912, 052016, 2020, pp. 1-11, doi:10.1088/1757-899X/912/5/052016

[14] 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

[15] 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, Pages 2673-2687, https://doi.org/10.1016/j.matpr.2019.11.247

[16] Ramesh Murugesan, Vijayanandh Raja, Acoustic Investigation On Unmanned Aerial Vehicle’s Rotor Using CFD-MRF Approach, Vol.-2, Proceedings of the ASME-2019, V002T08A005, 7 pages, ISBN: 978-0-7918-8353-2, https://doi.org/10.1115/GTINDIA2019-2430.

[17] Balaji Sonaimuthu, Prabhagaran Panchalingam, Vijayanandh Raja, Comparative Analysis Of Propulsive System in Multi-Rotor Unmanned Aerial Vehicle, Volume-2, Proceedings of the ASME 2019, V002T08A004; 8 pages, ISBN: 978-0-7918-8353-2, https://doi.org/10.1115/GTINDIA2019-2429.