Journal of Applied Science and Engineering, Vol. 21, No. 2, pp. 253–260 (2018) *DOI: 10.6180/jase.201806_21(2).0013*

Development of Foldable Wing Structures for Micro Air Vehicles

Vijayakumar Kolandapaiyan[1]*, L. V. Muralikrishna Reddy[2] and M. Sakthivel[3]

[1]*National Design and Research Forum, The Institution of Engineers, India*
[2]*Foundation for Educational Excellence (FEE)*
[3]*Anna University*

Abstract

The enabling technologies for the development of micro air vehicles (MAV) are matured and realistic in the application arena. The foldable MAV is a family of MAV, which are gaining interest due to its unique storing capability in field of operation. The recent developments in foldable wing MAV are enhancing wing design with foldability characteristics including wing profile, material selection and canister capability. The overall objective of this work is to design and develop a mission based foldable wing MAV, which can be packed in minimal volume, unpacked in minimum time and deployed in time-critical situations. In this paper, the main objective is to show the foldable wing capability with the help of canister design. It also discusses the foldable wing profiles, identification of suitable composite materials, orientation, 3D printing and component selection. To consider the suitable wing shape, rectangular and taper wing has been taken. The structural stress analysis of these wing configurations for CFRP and GFRP materials have been analyzed and compared. Analysis of these wing has variation in deformation, strain and factor of safety. Besides, foldable wings and canister design are fabricated. The development and widespread use of MAV in the real life environment have constraint and limitations with respect to handling the vehicle because of its size of the wing and sensitive components attached to it. Foldable wing structures and storage capability in canister is one of the alternatives and has created lots of interest among the MAV development activity.

Key Words: Wing Profile, Stress Analysis, Composite Materials, Canister Design, 3D Printing

1. Introduction

The foldable wing gets folded downwards by applying a force to the tip of the wing similar to umbrella folding and the wingspan gets reduced its size and easy for storing the MAV inside the canister. This is an innovative idea because MAV can change the configuration of its wings because many of the MAV are difficult to carry into the field of operation due to its size. It can be remote – controlled or flown autonomously, not only in civilian roles such as search and rescue operations during natural disasters, but also in military operations for reconnaissance, suspect monitoring, and planning the strategy for attack. It has many applications like urban areas, surveillance and sensing of biological agents etc. MAV is tough to carry, especially in the hill areas, forest regions and higher altitude of military applications [1–24] during natural disasters. Some MAV has roll-able wings like rubber tubing; these kinds of wings have required more joints and assembly [2]. These MAV requires a series of assembly steps to transform the MAV from a deployable condition to a storage condition. The development of these kinds of MAV is really a challenge due to their wing folding, and suitable composite materials [3] for construction, etc. Systematic research needs to be undertaken in several areas in order to meet the various design chal-

*Corresponding author. E-mail: nk.aero@gmail.com

lenges [4,5] to develop highly mission capable MAV that has an airframe, optimised power and propulsion, high fidelity controls and robust airframes. In order to arrive at a highly optimised design, materials etc. are required to carry out systematic studies. Figure 1 shows the foldable wing MAV.

2. Wing Design and Profile

The preliminary design for foldable wing consists of a selection of airfoils, aspect ratio, aerodynamic aspects, etc. For foldable wing, two types of wing design have been considered. Initially, the existing flying fixed wing MAV model with rectangular wing configuration of 300 mm wing span has been considered [5−7] because most of the work depends on to identify the suitable composite materials. The second approach is to identify the suitable wing profile with various platforms. In general, an airfoil defined as the cross section of a body that is placed in an airstream in order to produce a useful aerodynamic force. It is known that the airfoils [8,9] and aerodynamic shaped objects are extensively used in all types of air vehicles, for example, space shuttle, helicopters, aircrafts, and even various types of missiles. Besides, when it comes to fluid machineries such as the shape of the impeller, propeller pump, turbine, windmill, is very important. All the parameters are vital to express the characteristics of airfoils. Figure 2 shows the typical airfoil nomenclature.

The cambered profile shape like NACA2412, NACA 4412, S5010 is identified for rectangular wing and tapered wing platform with wingspan 200 mm and chord 70 mm because camber profile will give a smooth concave surface. It will resist flexing upwards and transferred uplift forces, and also it will regain its original shape better when compared to asymmetric profile while folding the wing downwards. Using CAD software the wing has been designed with minimum thickness. Based on the aerodynamic aspects [5,8] of existing model from different angles of attack, the rectangular wing profile NACA4412 is considered for the first step of foldable wing. Figure 3 shows the various 3D wing shapes and profiles.

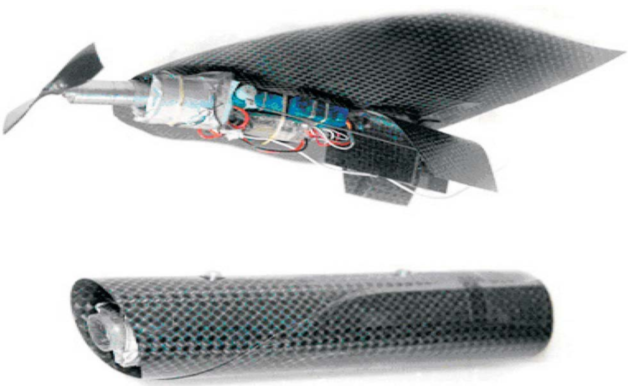


Figure 1. Foldable wing MAV [4].

3. Wing Structural Analysis

3.1 Structural Analysis for Rectangular Wing

For meshing, the patch conforming method was used. The patch conforming tetra mesh method is a tetra mesher with an advancing-front point insertion technique used for mesh refinement. Figure 4 shows mesh with nodes of 85949 and elements of 26062. The patch conforming tetra mesh method provides:

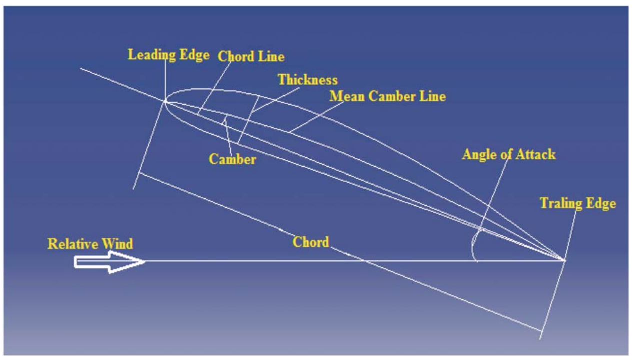


Figure 2. Typical airfoil nomenclature [8].

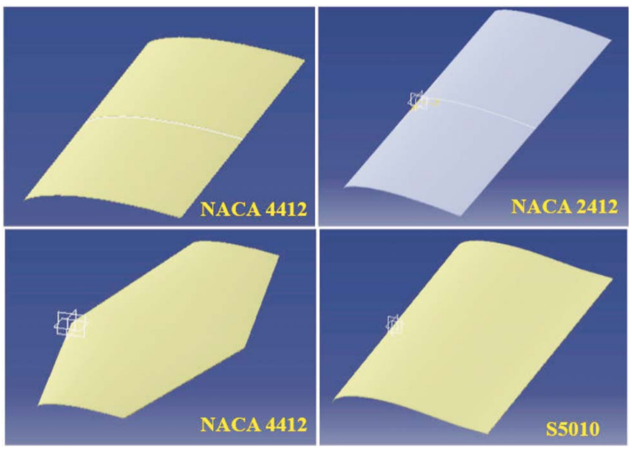


Figure 3. Various 3D wing shapes and profiles.

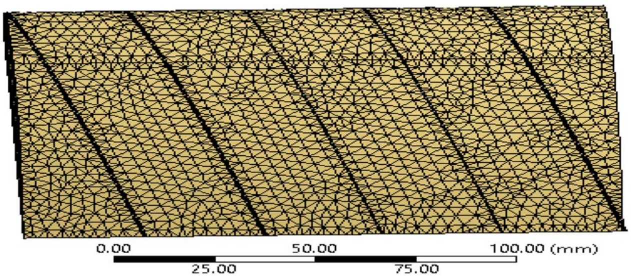


Figure 4. Mesh model.

- Built-in pyramid layer for conformal quadrilateral-tetrahedral transition
- Built-in growth and smoothness control
- Support for 3D inflation
- The mesher will try to create a smooth size variation based on the specified growth factor

In this structural analysis [10–12] the chord area is fixed as a cantilever beam and pressure load is applied. The analysis is done for rectangular wing [carbon fiber reinforced polymer (CFRP) stiffener, glass fiber reinforced polymer (GFRP) skin] having the properties in Table 1.

The structural analysis of the wing has variation in the deformation, strain and factor of safety (FOS). Stress value for all the materials remains same as stress is a function of load and area. In this case, pressure load applied and area of the wing is constant in all the calculations. The maximum equivalent (von-Mises) stress value and deformations are obtained for the applied pressure load are 5.149 MPa and 0.20507 mm. Similarly, maximum equivalent elastic strain is obtained for the applied pressure load is 0.00027803. Figure 5 shows the structural analysis outputs for the CFRP stiffener and GFRP skin (rectangular wing).

As the minimum FOS value is greater than 1, the wing can withstand the maximum pressure load which it encounters during the flight. The mesh with nodes of 21828 and elements of 11409 were considered. Here also, the patch conforming method was used. The patch conforming tetra mesh method is a tetra mesher with an advancing-front point insertion technique used for mesh refinement. Similarly, the structural analysis [13,14] for taper wing (CFRP and GFRP) was also analysed. Figure 6 shows the mesh model for taper wing.

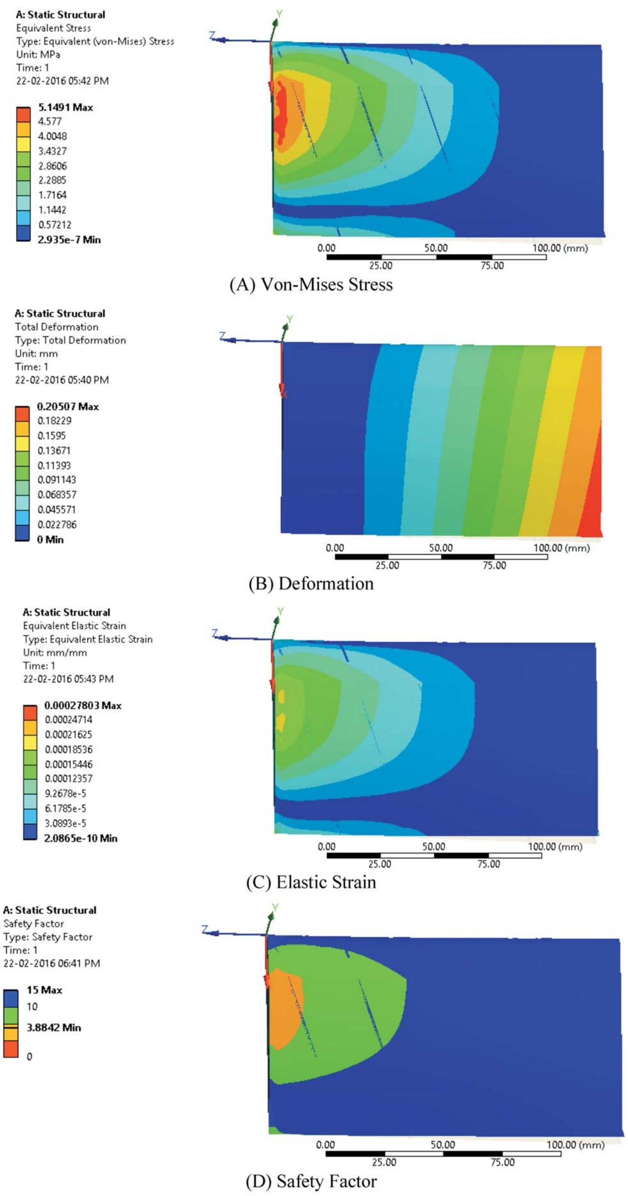


Figure 5. Structural analysis outputs for the CFRP stiffener and GFRP skin (rectangular wing).

Table 1. Material properties [3]

Material	Young's modulus E (GPa)	Poisson's ratio (μ)	Tensile ultimate strength (MPa)	Tensile yield strength (MPa)	Density (Kg/m^3)
CFRP stiffner	1.5	0.28	550	200	1500
GFRP skin	26	0.28	530	125	1800

Correspondingly Figure 7 and Figure 8 show the structural analysis of taper wing for CFRP and GFRP. The comparison results of both CFRP and GFRP for rectangular and taper wing are shown in Table 2.

4. Material Selection

The structural analysis of both rectangular and taper wing results shows that material selection of foldable wings plays a major role. The material design also acts as bio-

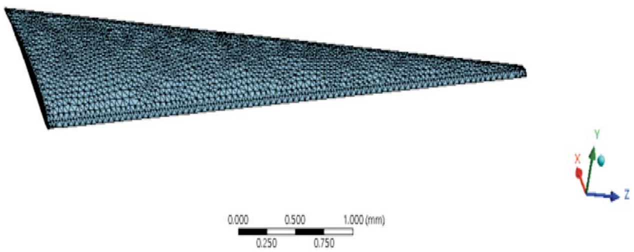
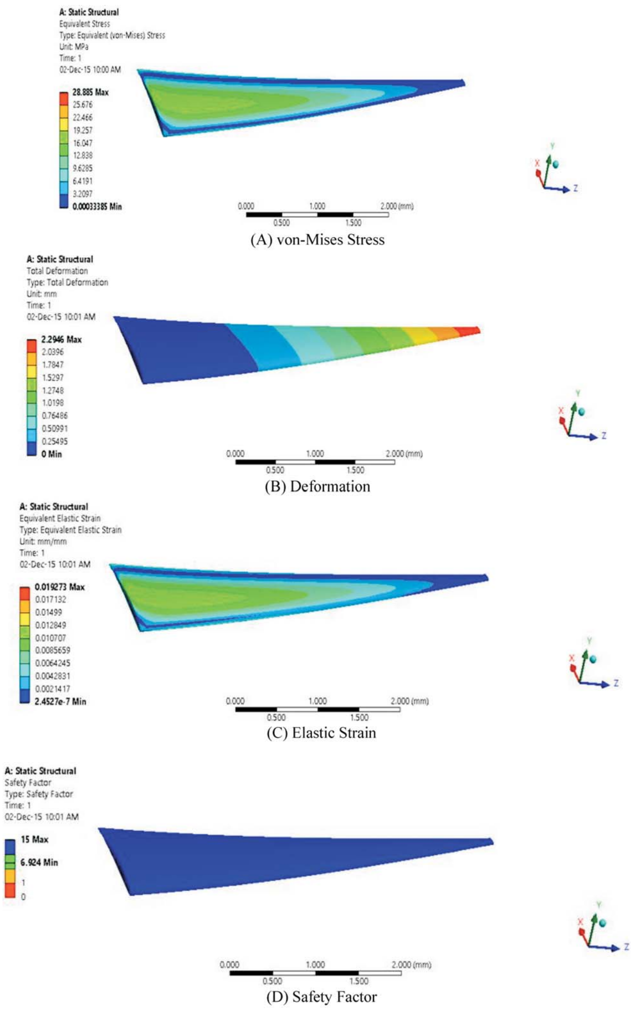
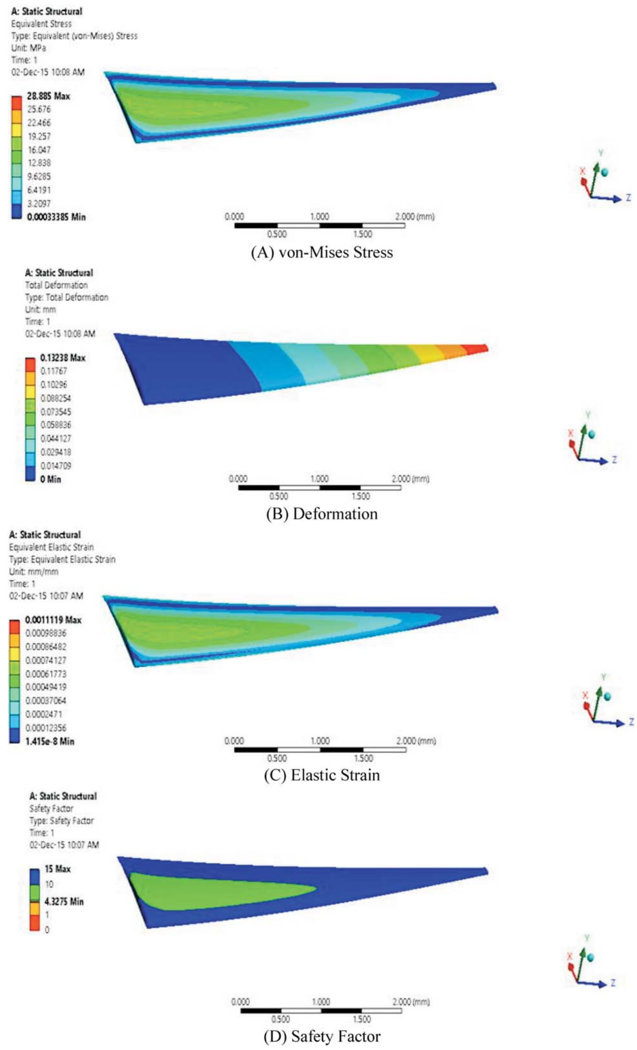


Figure 6. Mesh model for taper wing.



(A) von-Mises Stress
(B) Deformation
(C) Elastic Strain
(D) Safety Factor

Figure 7. Structural analysis outputs for the CFRP wing.



(A) von-Mises Stress
(B) Deformation
(C) Elastic Strain
(D) Safety Factor

Figure 8. Structural analysis outputs for the GFRP wing.

Table 2. Comparison between rectangular and taper wing results for both CFRP and GFRP

Material	von-Mises stress (MPa)	Deformation (mm)	Elastic strain (e)	Factor of safety (min value)
Rectangular wing				
CFRP	60.16	3.5031	0.04045	3.3244
GFRP	60.16	0.2021	0.0023336	2.0777
Taper wing				
CFRP	28.885	2.2946	0.01927	6.924
GFRP	28.885	0.13238	0.0011119	4.3275

logical camouflage. MAV construction has consistently implemented composites in airframe structure. The advantages of composites in MAV structures are threefold:

- High strength
- Light weight
- Good resilience

The foldable wing material has required elasticity from which the wing returns to its original, steady state shape. The materials used to form the wing have greater flexibility and elasticity and folds rather than permanently yielding. Each of the wings is formed of a suitable lightweight, flexible and resilient material [15,16] and wings are curved in transverse cross-section with the concave surface facing downwards so as to help develop lift for the MAV while providing sufficient folding stiffness [13,17] to accommodate wing-lift loading. It is concluded that carbon-fiber-reinforced polymer is used because it has a high strength-to-weight ratio and also reduces the weight of the MAV when compared to other composite materials.

5. Rapid Prototyping Fabrication

The results from the structural analysis and wing profile configuration from the design aspects, initially, the fabrication of the foldable wing is considered for rapid prototyping (3D printing). It gave us a rough basic idea to understand the foldable wing structure. Rapid prototyping (RP) enables the quick fabrication of physical models using three-dimensional computer aided design (CAD) data. It can produce highly accurate and detailed parts. Rapid prototyping allows designs from drawing boards into successful end products rapidly and efficiently. Soluble materials create the first layer geometry and it is bonded to model materials according to their respective XYZ planes. Three different layer resolutions are considered for manufacturing the wing model such as 0.007 inch, 0.010 inch and 0.013 inch. In the case of model interior, either, sparse-high density or solid has to be considered as shown in Figure 9.

Multiple iterations are carried out until the model is completed. Typical materials used for fabrication are acrylonitrile butadiene styrene (ABS) and layers of different thicknesses can be opted for deposition. ABS $((C8H8)_x * (C4H6)_y * (C3H3N)*_z)$ is a common thermoplastic [18]. It is a copolymer made by polymerising styrene and acrylonitrile in the presence of polybutadiene.

The 3D foldable wing model is shown in Figure 10. Under various foldable conditions.

6. Canister Design

For making a suitable canister for foldable wing [4, 20–22] is not a big issue because it is mainly depends on the wingspan and fuselage length.

- Wingspan (b_{max}) = 2 π d
- If b_{max} approximately 200 mm, the minimum diameter (theoretical) achievable is approx. 32 to 35 mm
- Figure 11 give the rough estimation of canister design

For storing into a canister, it is essential to provide

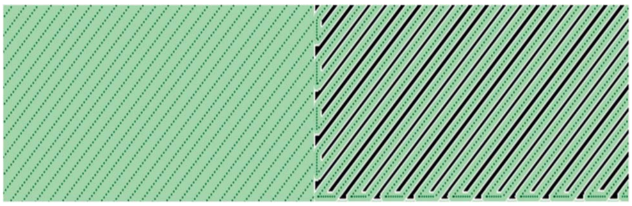
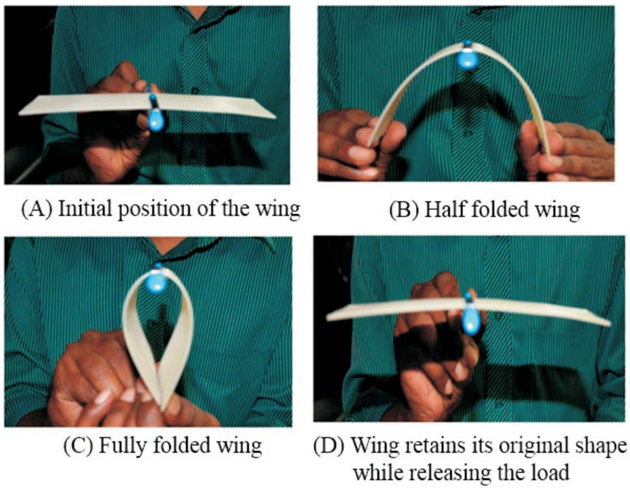


Figure 9. Model interior: solid and sparse.



(A) Initial position of the wing
(B) Half folded wing
(C) Fully folded wing
(D) Wing retains its original shape while releasing the load

Figure 10. 3D wing model: various foldable conditions.

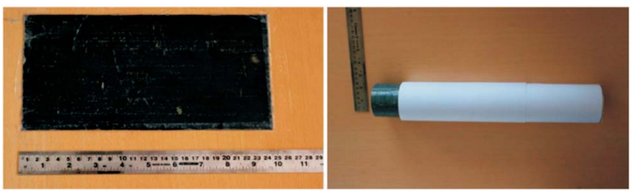


Figure 11. Canister design.

suitable clearance between the canister and wing for a long duration before the vehicle is deployed. The authors are trying to use 3D printing techniques to make a suitable configuration.

In addition to this, a preliminary testing was carried out. Based on the wingspan and fuselage length, the canister is chosen. Figure 12 shows the foldable wing demonstration with canister.

Based on this experiment, the stiffness, flexibility issues and other aspects about the rapid prototyping technology (RPT) wing model has been understandable.

7. Composite Construction

Based on the experiment and structural results the foldable wing should have the capabilities such as large strain compatibility, large displacement and less stress induction through thickness direction. Glass composite is a good candidate to meet the requirement. It has large strain capability. The stiffness can be tailor made to meet the requirement. Glass fabric embedded with carbon unidirectional fabric helps in attaining the required stiffness and thermoset epoxy in a pre-impregnated form, which demonstrated very high strength after cure, has been considered for construction. In addition to this, the wing folds ability would be achieved through processing of composites (CFRP/Kevlar/GFRP) carbon fibre wing is coated with an adhesive and a thin latex rubber is applied to the wing. And also both unidirectional & bidirectional is considered for construction [3,10,11]. Figure 13(A) shows the thin latex rubber; (B) shows the uni-directional rolled and unrolled condition and bi-directional rolled and unrolled condition.

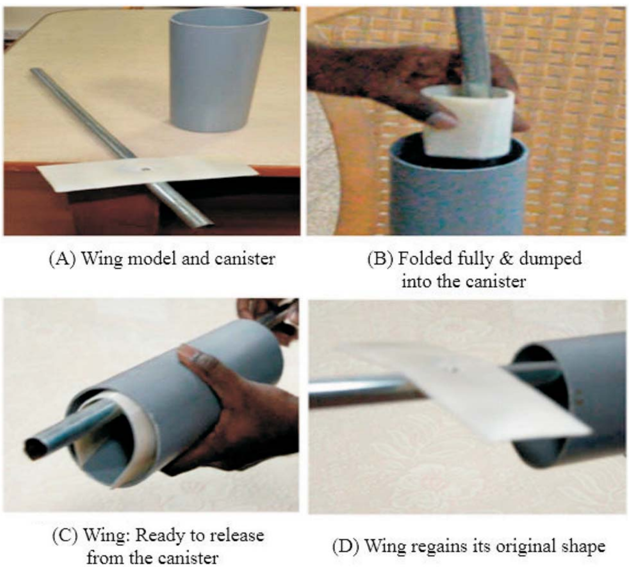


Figure 12. Foldable wing demonstration with canister.

8. Component Selection

One of the most important steps in designing the MAV is component selection. Based on literature survey [4–9, 17,19–24], the authors concluded that the choice of components is largely defined by the minimum diameter of the canister. A high-aspect-ratio wing would result in a short overall length, but needs grouping of components. This would result in a larger packed diameter. A low-aspect-ratio wing would allow greater distribution of the components along the chord line, resulting in a smaller packed diameter but it would result in greater overall length.

9. Conclusion

The suitable configuration for the foldable MAV has

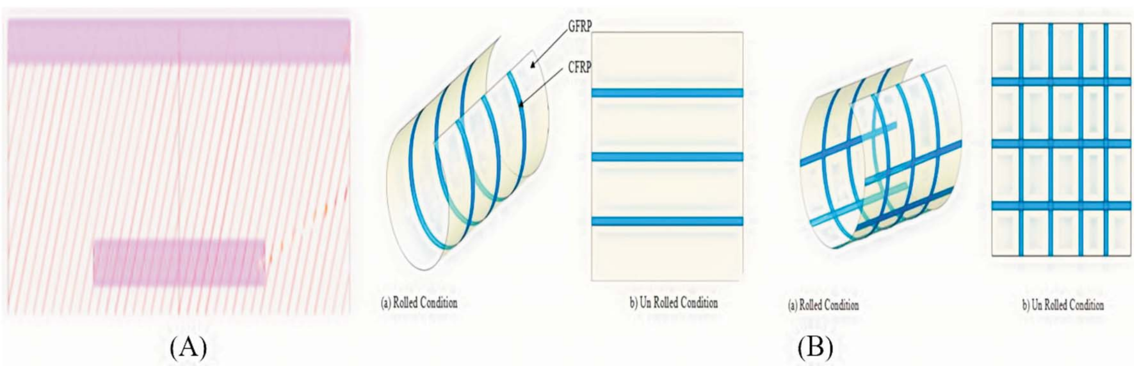


Figure 13. Composite construction: uni and bi-directional.

been arrived by designing the wing and wing profile. The structural analysis of rectangular and taper wing were analysed successfully and well understood for the CFRP and GFRP. Furthermore, the rapid prototyping technique (3D printing) was also studied. Besides, an attempt has been made successfully to show the foldable wing demonstration with the help of canister design. In addition to this, the suitable composite materials for the fabrication of the wing and airframe geometry have been identified. Similarly, for canister design and manufacturing, the authors are planning to use 3D printing techniques to develop the suitable configuration for packing the entire vehicle. Moreover, the component selection for the entire foldable wing MAV is well studied and identified.

Acknowledgments

We acknowledge the support provided by the National Program on Micro Air Vehicle (NP-MICAV). Also, the authors are grateful to the National Design and Research Forum, Anna University, Foundation for Educational Excellence for their valuable support and insights regarding this research work.

References

[1] Valavanis, K., et al., *Handbook of Unmanned Aerial Vehicles*, Springer Netherlands 2015, Print + eBook ISBN 978-90-481-9708-8. doi: 10.1007/978-90-481-9707-1

[2] Umezu, S., et al., "Bio-inspired wing-folding mechanism of micro air vehicle (MAV)," *Artif Life Robotics*, Vol. 22, p. 203 (2017). doi: 10.1007/s10015-016-0339-9

[3] Raul, et al., *Advanced Composite Materials for Aerospace Engineering*, Edition: 1st, Publisher: Woodhead Publishing, Elsevier, ISBN: 9780081009390. doi: 10.1016/B978-0-08-100037-3.00001-8

[4] Mueller, T. J., et al., *Introduction to the Design of Fixed-wing Micro Air Vehicles: Including Three Case Studies*, AIAA 2007, ISBN-13: 978-1563478499, ISBN-10: 1563478498. doi: 10.2514/4.862106

[5] Hicks, G. et al., "Multidisciplinary Design and Prototype Development of a Micro Air Vehicle," *Journal of Aircraft*, Vol. 36, No. 1, pp. 227–234 (1999). doi: 10.2514/2.2429

[6] Truong, Q. T., et al., "Design and Demonstration of Insect Mimicking Foldable Artificial Wing Using Fourbar Linkage Systems," *Journal of Bionic Engineering*, Vol. 11, No. 3, pp. 449–458 (2014). doi: 10.1016/S1672-6529(14)60057-3

[7] Albertani, et al., "Wind Tunnel Testing of Micro Air Vehicles at Low Reynolds Numbers," SAE World Conference, Reno, NV, November (2004). doi: 10.4271/2004-01-3090

[8] Anderson, J., *Fundamental of Aerodynamics*, Fifth Edition, McGraw-Hill (2011), ISBN 978-007-128908-5. doi: 10.1017/S000192400000676X

[9] Secanell, M., et al., "Design of a Morphing Airfoil Using Aerodynamic Shape Optimization," *AIAA Journal*, Vol. 44, No. 7 (2006). doi: 10.2514/1.18109

[10] Hyer, M., *Stress Analysis of Fiber-reinforced Composite Materials*, McGraw-Hill (1998). doi: 10.1017/S0001924000096366

[11] Whitcomb, J. D., et al., "Analysis of Plain Weave Composites Subjected to Flexure," *Mechanics of Composite Materials and Structures*, Vol. 5, No. 1, pp. 41–53 (1998). doi: 10.1080/10759419808945892

[12] Lee, D., et al., "Aeroelastic Studies on a Folding Wing Configuration," 46th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics & Materials Conference, (Austin, Texas), April (2005). doi: 10.2514/6.2005-1996

[13] Tang, D., et al., "Theoretical and Experimental Aeroelastic Study for Folding Wing Structures," *Journal of Aircraft*, Vol. 45, pp. 1136–1147 (2008). doi: 10.2514/1.32754

[14] Wlezien, R., et al., "Aircraft Morphing Program," Proc. SPIE Conference on Smart Structures and Materials, Vol. 3326, (San Diego, California), pp. 176–187 (1998). doi: 10.1117/12.310633

[15] Haftka, R., et al., *Design and Optimization of Laminated Composite Materials*, Wiley, New York (1999). doi: 10.1.1.170.9445

[16] Backman, D., et al., "Composite Materials and Joining Technologies for Composites," Proceedings of the 2012 Annual Conference on Experimental and Applied Mechanics, Vol. 7, eBook ISBN 978-1-4614-4553-1. doi: 10.1007/978-1-4614-4553-1

[17] Stanewsky, E., "Aerodynamic Benefits of Adaptive

Wing Technology," *Aerospace Science and Technology*, Vol. 4, No. 7, pp. 439–452 (2000). doi: 10.1016/S1270-9638(00)01069-5

[18] Chua, C. K., et al., *3D Printing and Additive Manufacturing: Principles and Applications*, Fifth edition, World Scientific Publishing Company Pte Limited (2016). doi: 10.18063/IJB.2016.02.002

[19] Wereley, N. M., et al., "Morphing Wings of a Small Scale UAV Using Inflatable Actuators for Sweep Control," AIAA-2003-1802 (2003). doi: 10.2514/6.2003-1802

[20] Lind, R., et al., "Roll Control for a Micro Air Vehicle Using Active Wing Morphing," AIAA Paper AIAA-2003-5347 (2003). doi: 10.2514/6.2003-5347

[21] Ng, T. and Leng, G., "Application of Genetic Algorithms to Conceptual Design of a Micro Air Vehicle," *Engineering Applications of Artificial Intelligence*, Vol. 15, No. 5, pp. 439–445 (2002). doi: 10.1016/S0952-1976(02)00072-6

[22] Bowman, J., et al., "Development of Next Generation Morphing Aircraft Structures," AIAA Paper 2007-1730, 48th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Honolulu, Hawaii, 23–26 (2007). doi: 10.2514/6.2007-1730

[23] Lau, F., et al., "Aero-structural Optimization and Performance Evaluation of a Morphing Wing with Variable Span and Camber," *Journal of Intelligent Materials, Systems and Structures*, Issue published: July 1 (2011). doi: 10.1177/1045389X11416031

[24] Basri, M. H., et al., "Optimization of Aerodynamic Efficiency for Twist Morphing MAV Wing," *Chinese Journal of Aeronautics*, Vol. 27, No. 3, pp. 475–487 (2014). doi: 10.1016/j.cja.2014.04.017

Manuscript Received: Sep. 12, 2017
Accepted: Jan. 17, 2018