

Design and Static Testing of a Low-cost Inflatable Wing

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I. Abstract

Remote controlled (RC) planes, popularly known as drones or Unmanned Aerial Vehicles (UAV), have gained much attention due to their ability to perform sophisticated tasks, such as environmental monitoring, medical delivery and surveillance. This research was inspired by the demand to explore and develop alternative ways of making UAVs more feasible, less costly and more efficient by utilising the idea of inflatable wings. Previously developed inflatable wings were made from expensive fabricated materials. The use of costly materials is, however, not feasible developing countries, specifically in African countries, which struggle to adopt new technologies due to limited resources. The objective of this study is to create and design a lightweight inflatable wing using low cost and readily available materials that will allow the massive deployment of small aircraft. It also explores different fabrication methods that will enable the low-cost manufacturing of the physical model.

II. Nomenclature

A	=	area of the wing
d	=	vertical deflection of the wing
E	=	Young modulus
F	=	force exerted by the weights on the wing
I	=	second moment of area
c	=	chord of the wing
L	=	length of the wing

III. Introduction

Remote controlled (RC) planes, popularly known as Unmanned Aerial Vehicles (UAVs), have gained attention due to the sophisticated tasks they are performing in our day-to-day lives. As a result, efforts have been made to find different ways of making UAVs more feasible, less costly and more efficient [1]. A deployable UAV is an aircraft that can change its aerofoil/wing size specifically by reducing its size for easy storage. Inventors made early designs out of foldable and flexible wings. From 1486 to 1490, an engineer called Da Vinci tried to develop flapping wings by devising many different flapping mechanisms. Other design mechanisms, such as wing folding, were explored. Research carried out by Moon et al. investigated the 4D printing technology for deployable UAV development [2]. Their design mechanism comprised of hinges, which allows the plane to fold its wings to reduce size for storage. However, these hinges in the design increase the weight of the aeroplane and hence reduce flight endurance and efficiency. The limitations of the above systems led to the re-focus of inflatable wings.

IV. Literature Review

Numerous laboratory and flight tests have been performed to demonstrate the damage tolerance of inflatable wings. The survivability rate has remained at 100% beyond one hundred flight test impacts and has been verified by similar laboratory testing [3]. This paper studies and evaluates the previous literature that mainly focuses on different designs and materials that have been used to build wings for RC planes.



Figure 1: Inflatable wing in a wind tunnel with fiducial markers at the University of Kentucky.

Among relevant research, one study proposed an inflatable wing design that aimed to address the limitations encountered in the existing models by employing an indirect 3D printing [4]. Their design intended to reduce aircraft weight and complexity while improving the aerodynamic characteristics of the aircraft. The inflatable wing was fabricated integrally with a lattice structure as a reinforcement, using a flexible impermeable material silicon rubber. This structure regulated the shape of the inflatable wing and increased the stiffness of the wing by absorbing part of the load exerted on the wing. The lattice structure was fabricated using a silicon rubber, which was injected into the 3D printed mold with a syringe for casting.

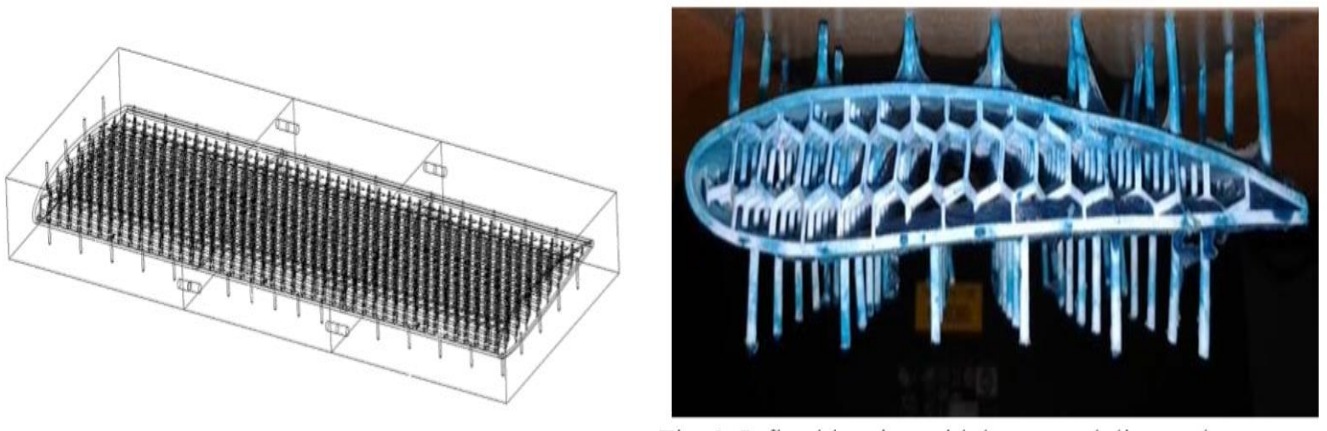


Figure 2. (a) The lattice structure wing. (b) Hexagonal diamond structure of the inflatable wing.

The proposed indirect 3D fabrication may have undesirable characteristics required for the lightweight inflatable wing. The hexagonal lattice structure in the wing interior provides wing stiffness. However, it may result in increased wing

weight that reduces flight endurance. Also, the fabrication methods are quite sophisticated and costly, especially for African companies to adopt.

Looking more into previous designs, other researchers presented work on testing of inflatable wings for UAVs [5]. The discussion focused on the aerodynamic forces generated by the shape and also the correlation between internal pressure and wing stiffness. Two design variants were developed and tested: 3(a) inflatable wings that require constant pressurisation and 3(b) inflatable/rigidizable wings that harden into a persistent shape once inflated. The rigidizable wings are constructed using a composite material that becomes rigid on exposure to UV light. The aerofoil was created by sewing woven material. The rigidizable wing was made using layers of the resin-impregnated woven fabric selected for handling characteristics, and an internal containment layer.

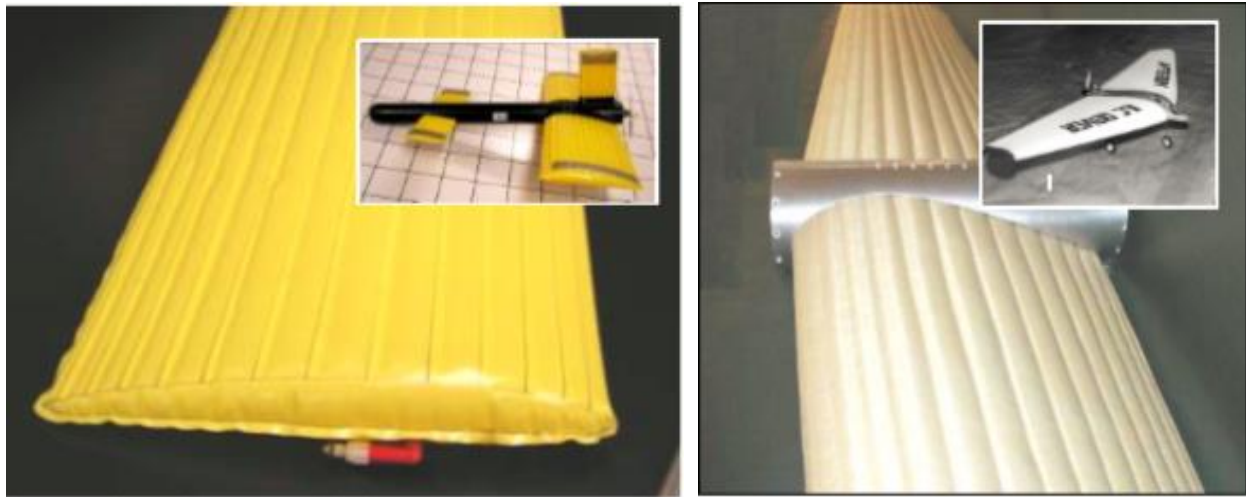
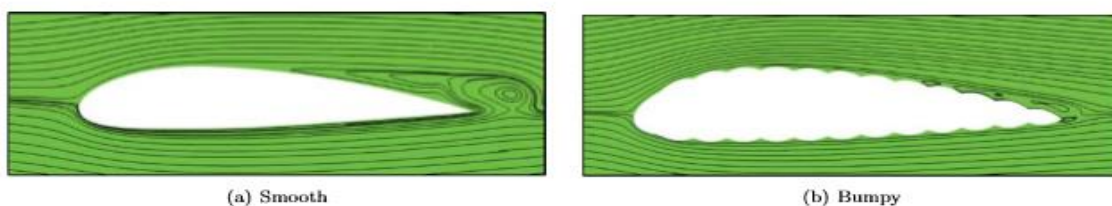


Figure 3 a) Non-rigidizable inflatable wing (b) rigidizable inflatable wing

Following their designs and analysis, the rigidizable wing was preferred for adoption. This choice was because it does not need constant pressurisation to maintain its shape, as required by the non-rigidizable wing. However, the rigidizable wing uses a multi-spar design that does not use foam spacer material and so packs compactly. This arrangement might increase the weight, which is undesirable for RC planes and also increases the cost of production of this composite; hence it is expensive to acquire.

More designs have been explored to improve the aerodynamic characteristics of aerofoils. In the paper, *Flight Testing and Simulation of a Mars Aircraft Design Using Inflatable Wings*, Reasor et al. present two aspects of the current development efforts of inflatable wings for Mars exploration, i.e. low-altitude flight testing of an inflatable wing aircraft and computational fluid dynamics (CFD) simulations of different wing geometries [6]. They performed flight tests that demonstrated flight performance, such as endurance and stall velocity. They also built smooth and bumpy aerofoil samples, which were tested across a range of conditions including weather and payload. CFD and experimental observation suggested less flow separation over the bumpy profile as compared to the smooth counterpart. The results also indicated that the presence of bumps on the leading edge reduces the dynamic pressures



on a wing resulting in a loss of lift.

Figure 4. Flow profiles of bumpy and smooth aerofoils

The numerical simulations have suggested that bumpy aerofoils must be adopted as it helps make control surfaces more effective. However, there is a need for more simulations to determine the optimum configuration for a given specification/application.

V. Design Prototype and Analysis

The insights gained from the literature review helped identify the gap in the need to explore the possibility of using low cost and readily available materials for the design of the inflatable wing. Large wingspan increases flight endurance; however, it is not suitable for deployment. Two main models were explored, which were:

- Foldable wings: result in increased weight which is an undesirable flight characteristic.
- Inflatable wings: have a minimal packed-volume-to-weight ratio, thus they are desirable for substantial endurance.

Ultimately the inflatable wing was chosen as it has optimum flight characteristics than foldable wings.

A. Material Selection

One of the research questions was to design an inflatable wing using low cost and readily available materials. A material selection process was performed on some of the materials that were suggested from the literature review. The Pugh Matrix was used to evaluate and determine the material that fits the criteria. From the table below, it is observed that Hypalon emerged as the best-fit material. However, PVC was used for building prototypes as that was the only available material at the time.

Table 1. Pugh Matrix used for material selection

Evaluation Criteria	Weight	Baseline	Kevlar	Hypalon	PVC	Neoprene	Urethane
Manufacturability	4	0	-4	+4	+4	+4	+4
Cost	3	0	0	+3	+3	-3	-3
Strength	2	0	+2	+2	0	-2	0
Availability	1	0	-1	+1	+1	-1	-1
Total			-3	+10	+8	-2	0

B. Designing Prototype

Two designs of the inflatable wing were sketched. The first design was made up of a traditional singled volume aerofoil structure; a control design which was compared with the proposed design solution for the research. Factors from the literature, as well as biological inspiration, influenced the design solution. The proposed design consists of sperate cylindrical chambers that run parallel to the wingspan. The cylindrical sections are of varying sizes to accommodate the shape of the wing. Unlike the traditional design, which has a single volume chamber, the proposed model has air pumped into the individual chambers that make up the aerofoil.

The following factors were considered when coming up with the design prototype.

- Insights from the literature showed that readily available materials such as PVC are abandoned because they possess poor static characteristics for a wing, which includes stiffness. In the design solution, the proposal of separate cylindrical volumes helps to aid the stiffness, as well as flexural strength of the wing.

- The literature also showed that the main disadvantage of the inflatable wing is its inability to maintain the internal air pressure to keep in-flight configuration. In case of a fault, inflatable winged aircraft usually lose lifts. The use of separate individual cylinders helps to solve this challenge. If one cylinder is faulty, the other cylinders will be able to maintain the shape of the wing at least, hence avoiding accidents and loss of the drone.
- Lastly, the inspiration for the design was gained from the natural biological setup of the honeycomb.

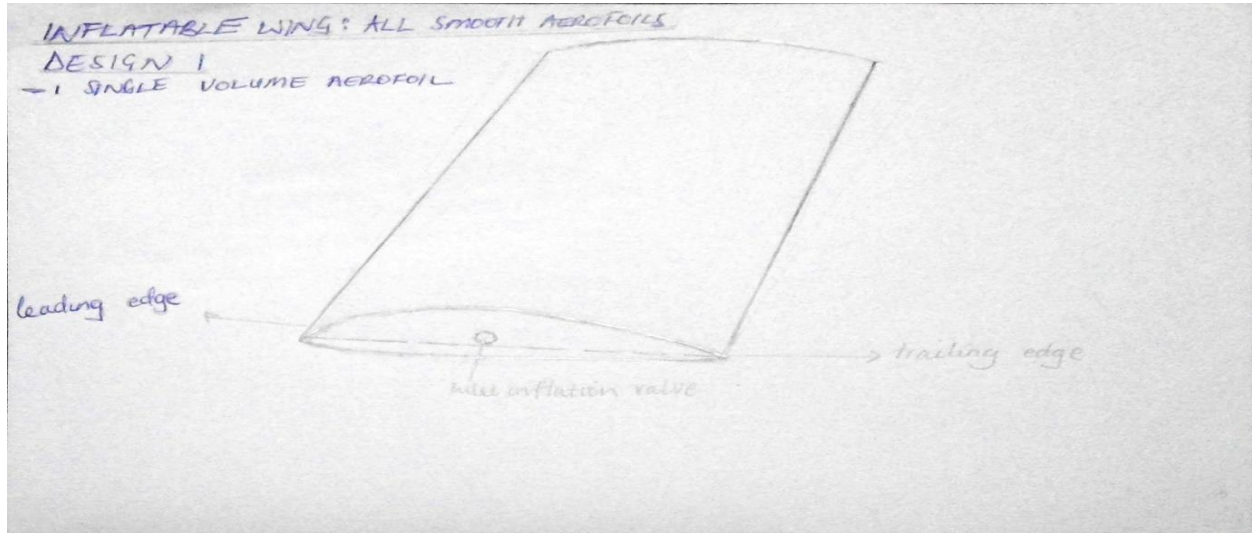


Figure 5(a) Singled volume aerofoil

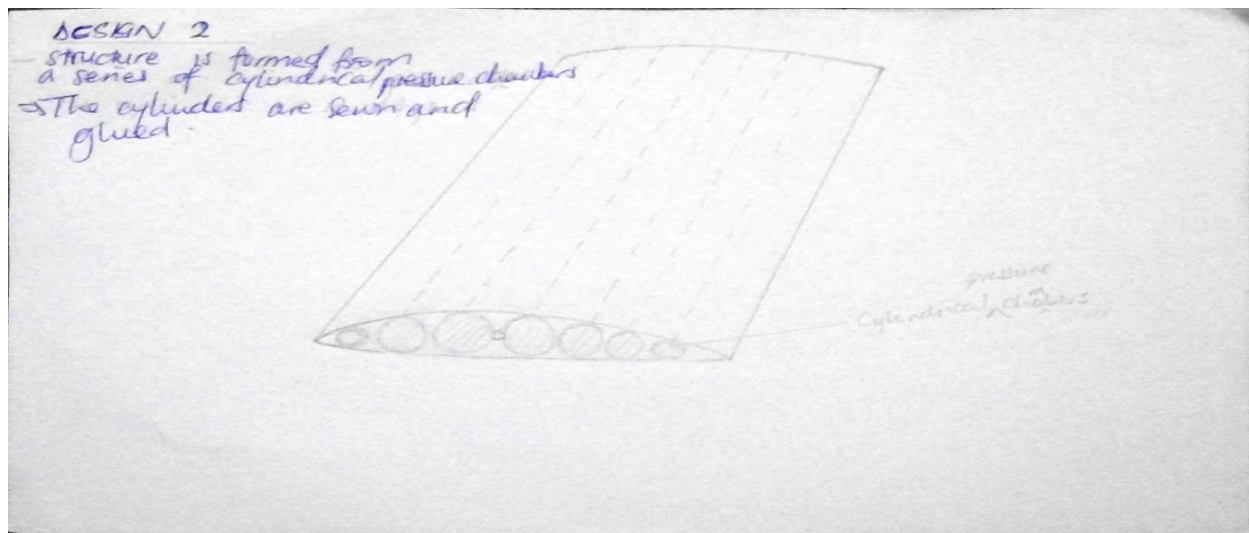


Figure 5(b) Structure formed from a series of cylindrical chambers

The above two figures show pencil sketches of the inflatable wing design. Figure 5(a) shows the traditional single-volume design, and Figure 5(b) is the sketch of the proposed design solution

C. Building the Prototypes

Two prototypes of inflatable wings were made using PVC, epoxy glue and pressure valves. Protractors and pencils were used in the fabrication process. The wing can be rolled when storing energy and then deployed when beginning flight.



Figure 6. Finished inflatable wing prototype

VI. Experimental Design and Test

Static Tests

Two tests were carried out to determine the static characteristics of the wing. These are the bending test and wing stiffness test. Favourable static aspects of the wing emerge when it does not deform permanently after a load has been applied to it.

1) Bending test

The test involved the following steps:

- The wing was mounted on a rigid test stand like a cantilever beam
- A load of 0.5N (50g) was added at the wingtips, and vertical deflection was measured
- The preceding step was repeated with the gradual addition of 0.5N weights until 5N

The graph of load against deflection was plotted using excel

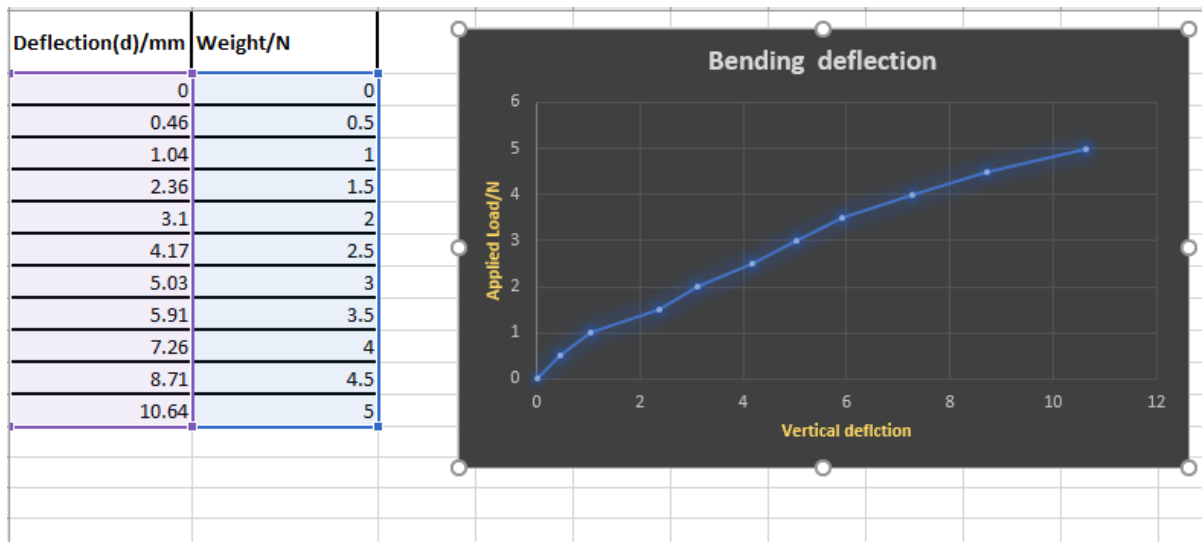


Figure 7. The graph of deflection against applied load

2) Wing stiffness Test

With the data above, the flexural rigidity of the wing was calculated from the formula $EI = \frac{FL^3}{3d}$. The graph of weight against rigidity was plotted.

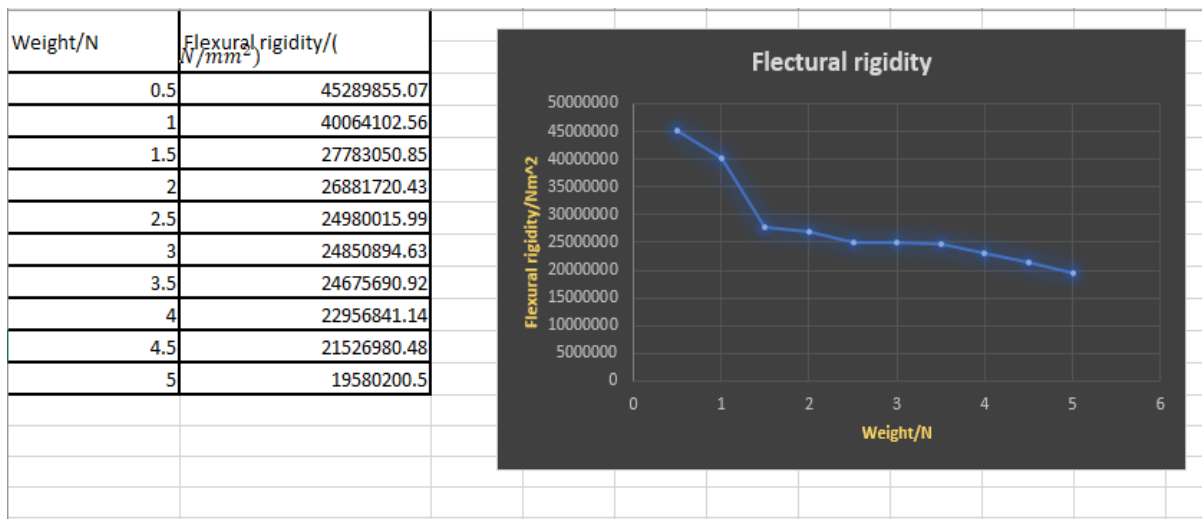


Figure 8. graph of weight against flexural rigidity

The graph shows that the flexural rigidity decreased as the load are increased, hence the aircraft must have a maximum weight limit.

VII. Future Work and Conclusion

This research paper was able to answer the research questions by conducting experiments using cheap and readily available materials. Also, it illustrated how the designing of an inflatable structure to attain the same or improved static characteristics by applying the multiple cylinder design. The primary limitations were related to making the inflatable wing airtight. The single-volume prototype (control design) was not tested to compare the results with the proposed design prototypes. There were shortages of resources such as the lack of a wind tunnel to examine dynamic

characteristics of the wing; hence only static tests were carried out. More future work needs to be done to complete the research project. These include:

- wind tunnel testing to determine drag and lift characteristics of the wing,
- development of an autonomous inflation system to allow easy deployment,
- building the UAV prototype to assess the features of the wing.

Appendix

The primary data for the above tests are shown below.

Table 2. Primary data from the bending test experiment

Mass/g	Weight/N	Deflection(d)/mm
0	0.0	0.00
50	0.5	0.46
100	1.0	1.04
150	1.5	2.36
200	2.0	3.10
250	2.5	4.17
300	3.0	5.03
350	3.5	5.91
400	4.0	7.26
450	4.5	8.71
500	5.0	10.64

Table 3. Flexural rigidity data derived from the bending test results

Weight/N	Flexural rigidity/(N/ mm ²)×10 ⁶
0.0	0.00
0.5	45.29
1.0	40.06
1.5	26.48
2.0	26.88
2.5	24.98
3.0	24.85
3.5	24.68
4.0	22.96
4.5	21.53
5.0	19.58

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