GRID BASED CONSTRUCTION OF A COMPOSITE MICRO AIR VEHICLE AIRFRAME

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Abstract

The development of a light-weight composite Micro Air Vehicle (MAV) airframe incorporating a novel foam grid based design into Glass prepreg composites is presented. Various combinations of advanced materials are judiciously utilized in different structural configurations to realize diverse requirements in the airframe. Advanced manufacturing techniques such as rapid prototyping, water jet cutting and autoclave curing ensure accurate conformance to the complex contour as well as precise tailored distribution of structural mass. The foam grid based design approach using Glass composites ensures low mass, provides stiffness in multiple directions, imparts crashworthy features and eliminates the problem of electrical leakages. Good correlation between analysis and static test measurement of wing deformation is found. Various issues in the development of a lightweight MAV airframe pertaining to design, tooling, fabrication, testing and analysis are discussed.

Introduction

Micro Air Vehicles (MAVs) are a class of small and light-weight aircrafts designed to operate in situations that are practically unsuitable for larger aircrafts. Rapid advances in sensor technology, electronics and communication devices, in recent years, have opened a plethora of new applications for MAVs. A single MAV or a swarm of MAVs can be used effectively to measure or gather data in hostile environments, for surveillance in urban and confined spaces, and even provide situational awareness in a battlefield scenario. In many situations, MAVs can provide reliable solutions whilst also being extremely cost-effective. The fixed wing MAV program at National Aerospace Laboratories (NAL) has a target to develop a low-cost MAV with a maximum dimension of 300mm, 30 minute endurance and weighing below 300 grams. The mass fraction of various components in a typical MAV of this size is shown in Fig.1. The airframe weight budget for this class of MAV is about 50 grams which can be achieved only by a design incorporating a combination of light-weight advanced materials (like special foams and prepreg composites) and advanced manufacturing processes. Most MAVs do not have a landing gear and hence it is advantageous to design the airframe such that onboard instruments are protected during hard landings. It is extremely useful to have an airframe design that possesses crashworthy features. Also, it is equally important that the airframe, in particular the housing, which contains the electronic components, is devoid of electrical leakage from the electronic components. The electrical leakage associated problems are referred to as ‘glitching’. These requirements present an additional challenge in the design of the MAV airframe. In addition, an MAV airframe provides an ideal platform to demonstrate the aerodynamic benefits of wing morphing because the actuation power required is quite small, and the benefits can be quite appreciable. The current research in the area of MAV with focus on the airframe design and construction is discussed next.

Numerous MAV development programs have been launched worldwide, the most well-known being the MAV initiative by the US Defense Advanced Research Projects Agency (DARPA) [1]. This initiative funded the development of MAVs with a maximum dimension of 152.4 mm (6 in.) and weighing 200 grams or less. A common approach to MAV design is based on the rigid-wing concept [2]. In this approach, the airframe consists of conventional rib/spar elements to support the external aerodynamic loads. The rib and spar elements are usually constructed from different light-weight materials like balsa wood, foam, and glass fiber composites. Galinski [3] constructed a gust-resistant MAV with nose torsion box and ribs made of Carbon fiber composite covered by thin flexible membrane material. Light-weight composite materials have also been tried on flapping wing MAV airframes. Yang et al. [4] fabricated and wind-tunnel tested a

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smart wing with Polyvinylidene fluoride (PVDF)-parylene composite skin. The PVDF film sensor was used to monitor the aerodynamic loads acting on the flapping wing during wind-tunnel testing. Kim et al. [5] are currently developing a flexible flapping wing aircraft using macro-fiber composite actuators.

The research group at University of Florida has been in the forefront of MAV development for more than a decade [6-8]. Ifju et al. have developed several successful fixed-wing composite MAV airframes with maximum dimension ranging from 5 to 12 inches [6]. The airframes were mostly made of unidirectional Carbon fiber prepreg, Kevlar thread, and tough mono-film materials. They reported excellent flight characteristics and crash resistance. Their approach to airframe construction involved the integration of all materials and one-time vacuum bag curing. The most salient feature of their MAV airframe was the deliberate flexible construction of the wing structure to enhance the flying qualities in gusty conditions [8, 9]. The flexibility of the wing structure was achieved by bonding a light-weight, flexible, thin-membrane material like latex rubber, polyester fabric etc. to a cured carbon fiber skeleton. It has to be mentioned here though, that the mechanical properties of latex membranes are known to degrade significantly when exposed to light and heat.

Abdulrahim et al. [10] resorted to wing morphing to improve the roll control of a MAV with flexible membrane wings. This is because conventional control surfaces like ailerons are difficult to mount on membrane wings. The airframe was constructed entirely of carbon fiber composite. Wing leading-edge was made of multiple layers of unidirectional carbon fiber. Battens of same material extended from attachment points on the wing leading-edge towards the trailing-edge. The composite wing skeleton was covered with a flexible membrane skin of thin translucent plastic. The fuselage was made of a two-piece, monocoque structure and the empennage was fixed to the fuselage. Morphing was achieved using a torque rod embedded on the wing. Fuselage mounted servos were used to rotate the torque rods separately and in opposite directions to achieve roll control. The airframe demonstrated excellent roll performance in flight tests achieved through wing morphing.

In a later study, the same researchers used 3 layers of bi-directional plain weave carbon fiber composite to construct the wing center and leading-edge [11]. The outer and inner layers were placed in the ±45° direction and 0°/90° directions, respectively. The thin, batten-strips were made of 2 layers of unidirectional carbon fiber composite with the fiber direction kept parallel to the batten. These battens extend from the attachment points along the membrane/weave boundary to the trailing-edge. Once again, the membrane skin was made of latex rubber. The torque rods are placed in spanwise direction and after a 90° bend, are fastened to a batten with Kevlar© threads. The objective of this work was to optimize the torque rod structure based on a static aeroelastic model of the MAV airframe. A genetic algorithm based optimization approach was followed to obtain an optimal torque rod configuration that improved both the roll rate and lift-to-drag ratio of the airframe.

It is clear from the above discussions that the development of a light weight airframe places an enormous demand not only on the structural concept and approach but also on the efficient incorporation of light weight and advanced materials. These include both filler materials such as special foams to increase the flexural rigidity, as well as proven structural materials like carbon prepreg composites with high specific strength and stiffness which can be tailored in numerous configurational designs. Though carbon composites are undoubtedly superior compared to most other industry grade materials for aircraft structural applications, in this context there are two design requirements which pose a situation inimical to their use. These are the requirements of crashworthiness and glitching (i.e. electrical leakage associated issues). This is because of the limited strain and electrical conductivity property of carbon composites.

In the current work, we present the development of a light-weight composite MAV airframe using a novel foam grid based design incorporating glass prepreg composite construction. Advanced manufacturing techniques such as rapid prototyping and autoclave curing ensure accurate conformance to the complex contour as well as precise tailored distribution of structural mass. The special foam grid based design approach using glass composites ensures required stiffness in multiple directions, imparts crashworthy features and eliminates the problem of glitching. Issues pertaining to the development of lightweight MAV airframe like design, tooling, fabrication and testing are presented.

MAV Description

Table-1 presents the operational parameters of the fixed-wing MAV considered in this study. The airframe configuration is arrived based on airfoil design, weight

Table-1 : Operational Parameters of the MAV

All up weight	< 300 grams
Maximum dimension	< 300 mm
Operating altitude	100 m above ground level
Payload weight	20 grams
Endurance	> 30 minutes
Maximum speed	20 m/s
Operating range	2 km

estimation, geometry and internal layout optimization, and flight mechanics. The airframe consists of wing, housing and vertical fins (Fig.2). The wing is mounted on top of the housing and is responsible for generating aerodynamic lift. The housing holds the payload, battery, autopilot and other electronic instruments. Fins provide lateral stability and the vehicle is controlled using control surfaces called 'elevons'. The main objective of this work is to design and fabricate the MAV wing, housing and fins while fulfilling the requirements mentioned in the introduction section.

Wing Based on Grid Construction

The wing is the most important component of the airframe and is responsible for efficient generation of aerodynamic lift. The wing planform of this MAV has an aspect ratio close to unity (Fig.2). The cruise speed of this MAV is around 12-17 m/s. This speed is of the same range of the gust speeds likely to be encountered by the MAV. Hence, pressure distribution on the wing varies considerably in both chordwise and spanwise directions. To keep wing deformations to a minimum, it is desirable to construct a wing structure with reasonably high stiffness along both spanwise and chordwise directions. A numerical experiment is initially conducted to compare the specific stiffness of various possible wing constructions (Fig.3). The wing skin in each case is identical and is made of 2 layers of GFRP plain weave fabric. A uniformly distributed load of 5 N is applied normal to the plane of the wing. A standard finite element analysis tool (MSC.NASTRAN®) is used to estimate the wing deformations. Fig.4 shows the average tip deflection per unit mass of the wing for different configurations considered in this numerical experiment. Results indicate that for a given wing mass, sandwich construction with foam grid core gives the maximum flexural rigidity to the wing. This is expected as the main contribution for flexural stiffness comes from the sandwich facesheets which is made of GFRP plain weave fabric. The core carries very little load and is therefore made extremely light by using lightweight foam material cut into a grid shaped planform.

The grid shape is chosen based on a scoring system. For the sake of simplicity, the grid shapes were restricted to regular polygons. Four different planform grid shapes were considered along with the full foam construction (Fig.5). The criteria for evaluation were (1) Wing mass, (2) Ease of fabrication, (3) Cell connectivity, and (4) Multi-directional stiffness (Table-2). Wing mass is maximum when a full foam construction is used. The grid shape of the foam core influences the wing mass in two ways. The direct effect is the mass of the core itself. The indirect influence is through the mass of the adhesive used to bond the core to the GFRP skins, which can be a significant fraction of the total wing mass for a MAV. The optimum grid shape minimizes the mass of the core for a given bond area. The mass of the entire core (m_{core}) can be written as:

$$m_{core} = n_{cell} \, m_{cell} \tag{1}$$

where n_{cell} and mc_{ell} are the number of polygon cells and mass of each cell respectively. For a given m_{cell}, m_{core} is least when n_{cell} is least. The problem of minimizing the mass of wing core then reduces to one of maximizing the area of a polygon cell (A_{cell}) for a given m_{cell}, which for a given grid depth and thickness is directly proportional to the perimeter of the grid cell (P_{cell}). The isoperimetric quotient (A_{cell}/P_{cell}^2) of regular polygons is plotted in

Table-2 : Performance of Various Grid Shapes

Criteria	Full Foam	Triangular Grid	Square Grid	Hexagonal Grid	Circular Grid
Wing weight	0	3	6	8	10
Ease of Fabrication	10	8	8	8	8
Cell connectivity	10	8	8	8	3
Multi directional stiffness	10	9	7	9	6
Total	30	28	29	33	27

Fig.5. As expected, the ideal polygon for maximizing the grid cell area for a given perimeter is a circle ($n \rightarrow \infty$). The scoring for the wing mass criteria is chosen based on Fig.5.

Lightweight Rohacell® foam is chosen as the material for the sandwich core grid construction. This foam is cut using the Water-jet facility available at NAL. Obviously, full foam construction scores over all grid-type constructions in the ease of fabrication criterion. Cell connectivity refers to the connected area between two cells of the grid construction. This connectivity is directly related to the ability to carry and transfer loads. In the triangular, square and hexagonal grid shapes, each cell is connected to its neighbor along an edge. However, in a circular grid shape each cell is connected to its neighbor only at a point, which is not desirable from a load transfer point of view. Of course, the full foam construction does not have this drawback. Multi-directional stiffness criterion refers to the ability of the grid pattern to offer resistance to flexural deformation along multiple directions in the plane of the wing. The triangular and hexagonal grids have stiffeners running along 3 directions in the plane of the wing, while the square grid has stiffeners only along 2 directions. Table-2 indicates that hexagonal grid is the likely best candidate for the construction of MAV wing. This is not entirely surprising since hexagonal construction is found in numerous natural and man-made structures such as honeycombs, Geodesic domes, Carbon nanotubes etc.

Tool Design and Fabrication

Fabrication of MAV components involves development of master models and molds. The wing, housing, fins and control surfaces are fabricated using carbon fiber composite molds. Fin mold is a plane surface reflected from surface plate with 50 micron accuracy. The same mold is used for fabricating both fins and control surfaces (elevons).

Wing Mold

The MAV wing is a thin cambered plate with Selig 4083 mean camber line profile. The master model required for fabrication of mold is developed from Rapid Prototyping Technology (RPT). The wing master model is modeled using 3D modeler. The conventional method of master model fabrication contains design of contour templates, check templates, etc. The dimension of wing master model is 410 x 336 x 15 mm. The shape of the master model is derived using Plaster of Paris or wood or conventional metals with skilled man power, it is a time consuming process. The design criteria for wing master model are:

- Withstand atmospheric pressure while vacuum bag curing at room temperature.
- Smooth contour of Selig 4083 camber line.
- Light weight and negligible percentage of shrinkage of contour under atmospheric pressure.

RPT is an automatic construction of physical objects using solid freeform fabrication. The primary advantage of RPT development is its ability to create almost any shape or geometric feature. Simple models can be developed within a few hours. Selective Laser Sintering (SLS) based RPT process provides good strength and durability at relatively low cost. The laser selectively fuses powdered material (NYLON 626-Polyamide) by scanning cross-sections generated from a 3-D digital description of the component on the surface of a powder bed.

Wing mold is designed to withstand high temperature 180°C and 7 bar pressure. Thermal mismatch between component and mold is prevented by using Carbon as base material for the mold. Carbon BD T300-6k from Hexcel Composites, UK is used in a quasi-isotropic layup sequence. Wall thickness of the mold is about 5mm. LY 5210 K24 DY 219 resin system used for mold fabrication sets at room temperature. Post-processing is done to avoid twist and stress relief in autoclave environment. Fig.6 shows the schematic diagram of the mold fabrication setup.

Housing Mold

A female core developed using RPT is used for making the housing master model. The male core is derived by filling the female split core cavity using the LY 5210 K24 DY 219 resin system with Aluminum powder (Fig.7). Later the derived LH and RH solid male cores are placed over the wing mold for fabricating the housing mold. The MAV housing component is closed on three sides and opens on one side. To facilitate easy release of component from mold, the housing mold is fabricated as LH and RH. The LH and RH spilt mold are positioned together using dowel pins for component fabrication. Plain weave Glass fabric is used as the base material for housing mold fabrication to avoid thermal mismatch. Fabrication of LH housing mold is shown schematically in Fig.8.

Component Fabrication and Assembly

Based on preliminary analysis presented in section - Wing based on grid construction, the MAV wing is fabricated using sandwich construction with foam core and GFRP facesheets. The core is made of lightweight Rohacell foam cut into a grid of hexagonal cells (Fig.9). This foam is commercially available in sheet form (10 mm thick) and is trimmed to the required thickness of 2.8 mm by milling. Next, the foam core is cut into the required hexagonal grid shape using a Water jet cutter. The wall thickness of each hexagonal cell is about 3.2 mm. The entire foam grid core weighs about 4 grams. The GFRP woven fabric prepreg (Fibredux 914G-7781-37%) used for wing skin fabrication has an areal weight of about 220 g/m^2. To realize a light-weight wing, some resin is squeezed out of the prepreg while curing through the use of a porous release film and a breather film. The top and bottom skins are each made of a single ply (0°/90° orientation). In order to incorporate wing morphing on this airframe at a later stage by means of drooping the leading-edge, the wing leading-edge is deliberately made less stiff by not using a sandwich construction. Instead, it is simply constructed using 2 layers of ±45° layup. The cured top and bottom skins weigh about 11 grams each. The skins are joined to the foam grid core through secondary bonding.

The control surfaces (elevons) are made using light-weight Balsa wood, each weighing about 1.5 grams. Both elevons are bonded separately to the wing using GFRP adhesive tapes. The top and bottom fins are made of light weight fabric material bonded to a CFRP skeletal structure made of unidirectional reinforcements and weigh 5 and 3 grams, respectively (Fig.10). Both fins are attached to the wing using RPT made clips. The MAV housing is made from GFRP skins and reinforced with ribs and longerons made of Balsa wood (Figure 10). To improve the crash resistance further, a bulkhead made of balsa wood is included near the nose part of the housing. The total weight of the housing is about 27 grams. Onboard electronic instruments and servo actuators are mounted on light-weight foam mounts bonded to the housing (soft-mounting) to prevent damage during landings. Table-3 summarizes the contribution of each component to the total mass of the airframe.

The first prototype airframe (Fig.11) is heavier than the allocated weight budget and we are presently working on reducing this gap. The next prototype will have a housing with Kevlar© skin and stiffeners which is expected to bring the airframe weight down to 58 grams. Also, additional savings in airframe weight is expected through the use of light-weight prepregs, spray adhesives, and an improved housing with a better aerodynamic shape.

Numerical Modeling and Analysis

To estimate the wing deformation due to aerodynamic loads, a finite element (FE) model of the MAV wing is constructed. The sandwich facesheets made of GFRP fabric are modeled using isoparametric plate elements in MSC.NASTRAN®. The top and bottom facesheets are discretized into 11950 plate elements each. The foam core is discretized into 4450 plate elements. The material properties of the GFRP bi-directional fabric and Rohacell foam core are given in Table-4. This FE model of the MAV wing is validated using simple bench-top static load tests on the wing. The aerodynamic load acting on the MAV wing is simulated in the experiment using rubber pads. These

Table-3 : Airframe Mass Distribution

Sl. No.	Component	Mass (grams)
1	Wing	26
2	Housing	27
3	Top fin	5
4	Bottom fin	3
5	Control surfaces (Eelvons)	3
6	Adhesives, RPT clips, tapes etc	4
	Total	**68**

Table-4 : Mechanical Properties of MAV Airframe Materials

GFRP Bi-directional Fabric	
Longitudinal modulus, E_1 (MPa)	24000
Transverse modulus, E_2 (MPa)	24000
Poisson's ratio, υ_{12}	0.10
Density (kg/m^3)	1900
Foam	
Young's modulus, E (MPa)	75
Poisson's ratio, υ	0.22
Density (kg/m^3)	52

rubber pads are placed over the wing (excluding the leading-edge, elevons and the area directly above the housing) to provide a uniform dead load (Fig.12). The mid-section of the wing directly above the housing is constrained from moving in this bench-top static load experiment. The vertical displacement is measured at the wing tip using dial gauges with a least count of 0.01mm. The load is gradually increased by placing additional rubber pads and the corresponding wing tip deflections are observed. Fig.13 shows the comparison between experiment and FE analysis prediction for various load levels. There is fairly good agreement between analysis and static test measurements. Fig.13 indicates that the wing is reasonably stiff with deformations less than 1 mm up to 750 grams which is 1.5 times the limit load. A realistic estimate of the aerodynamic loads acting on the wing can be obtained through high-fidelity models such as incompressible, low Reynolds number computational fluid dynamics (CFD) analysis. Efforts are currently underway to couple the validated FE model to CFD to study the fluid-structure interaction in MAV wings.

Concluding Remarks

A light-weight composite micro air vehicle airframe has been developed through a systematic approach. A novel foam grid based hexagonal construction was successfully incorporated into Glass prepreg thin wing skins. The merit of hexagonal grid for MAV wing construction based on isoperimetric quotient parameter has been established. Advanced manufacturing techniques such as rapid prototyping, water jet cutting and autoclave curing have proved their utility in realizing a high performance grid based airframe. Static testing of the wing has been carried out using an accurate loading scheme. Detailed structural modeling and analysis of the grid based MAV wing was carried out. Good correlation between measured tip deflection from static test and finite element analysis has been obtained.

The MAV airframe was successfully test flown at NAL. The airframe exhibited good stability in flight due to precise control of mass distribution as per the design. The airframe demonstrated excellent resistance to impact loads during hard landings. Soft mounting approach prevented damage to the onboard instruments and servo actuators. Improvements to this airframe are currently being considered to address the feedback from the NAL flight test team. These modifications will be part of the next prototype of the airframe. Wind tunnel testing of the airframe is currently underway. The flight and wind tunnel test data and their interpretation will be presented in a separate paper. In future, we also plan to incorporate active elements in the wing frame towards realization of a morphing wing MAV.

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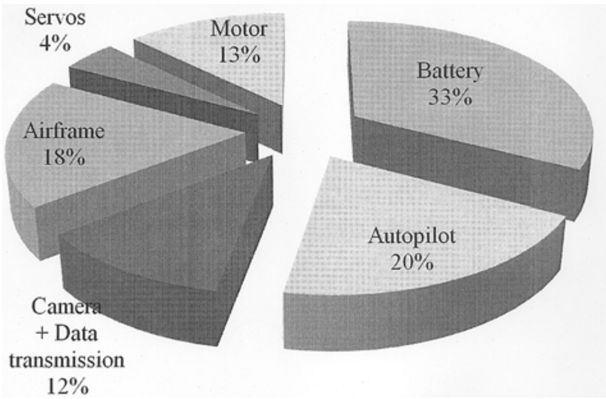

Fig.1 Mass Fraction of MAV Components

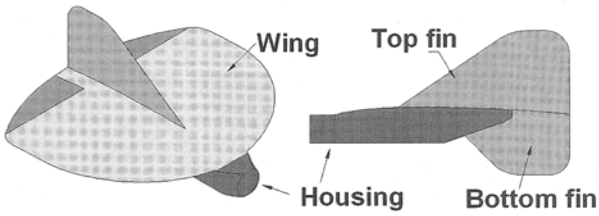

Fig.2 MAV Airframe

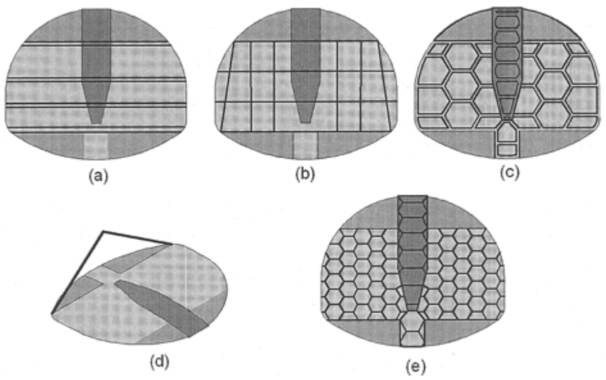

Fig.3 Wing Constructions Considered for Stiffness Comparison, (a) Plannar Wing with Spanwise CFRP Stiffeners, (b) Sandwich Wing with Spanwise and Chordwise Foam Stiffeners, (c) Planar Wing with Hexagonal CFRP Grids, (d) Planar Wing with Guy Wires, and (e) Sandwich Construction with Foam Grid Core

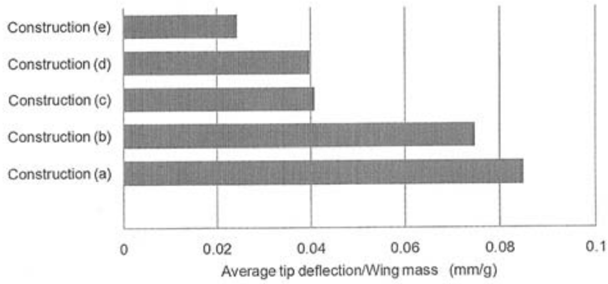

Fig.4 Specific Stiffness of Different Wing Constructions

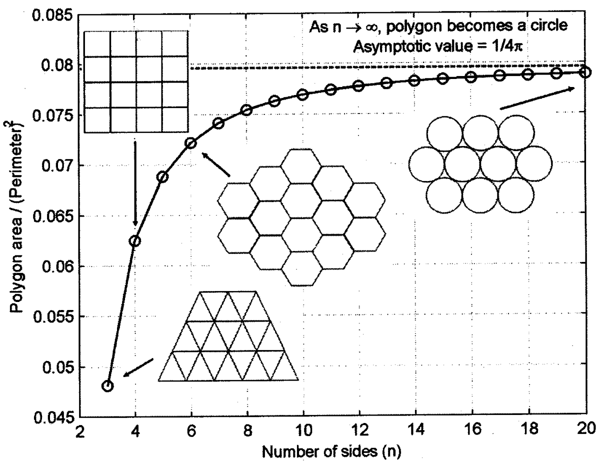

Fig.5 Isoperimetric Quotient of Regular Polygons

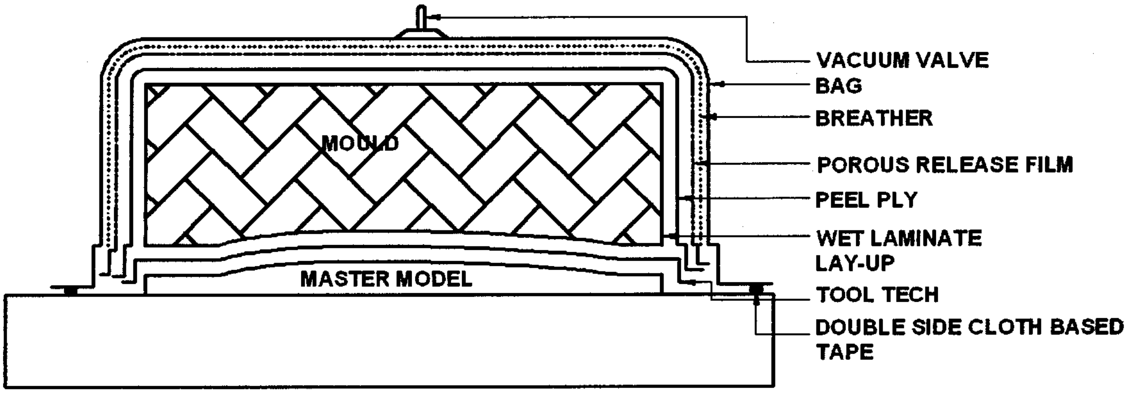

Fig.6 Schematic Diagram of Wing Mold Fabrication

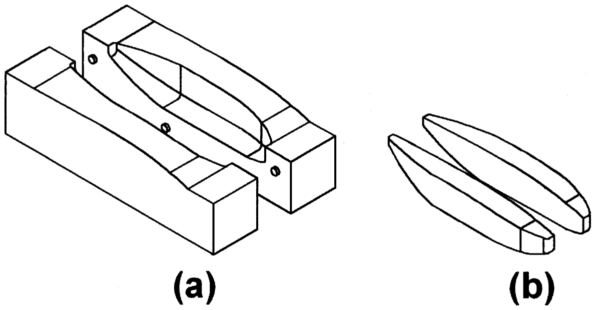

Fig.7 a) Female Core from RPT, b) Male Split Core (LH and RH)

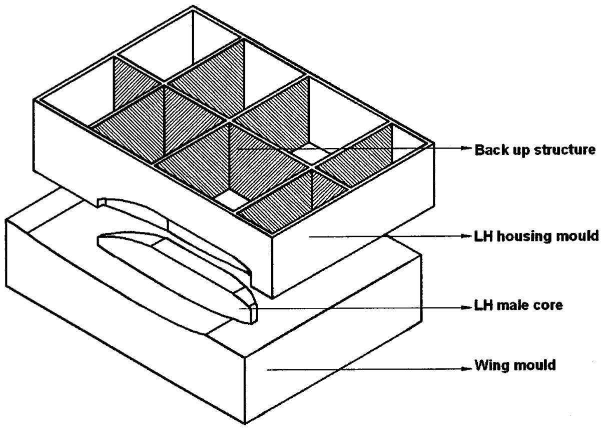

Fig.8 LH Housing Mold Fabrication

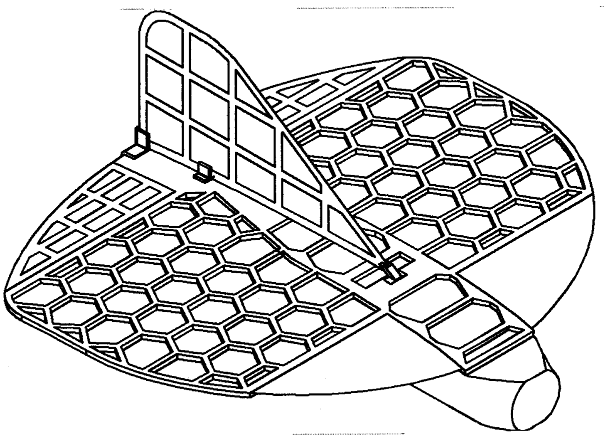

Fig.9 Grid Based Sandwich Construction for MAV Wing

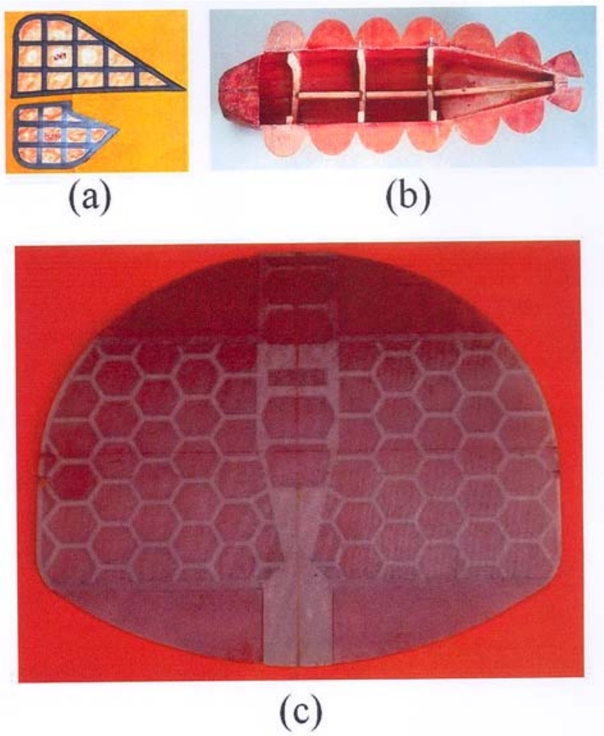

Fig.10 a) Top and Bottom Fins, b) Housing with Ribs and Longerons, c) Wing Based on Grid Construction

Fig.11 First Prototype Airframe

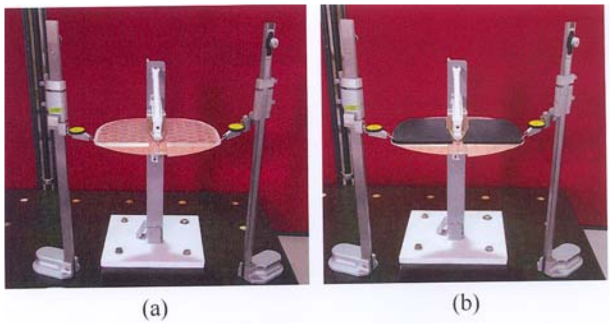

Fig.12 Static Test Setup of MAV Wing with Dial Gauges for Tip Deflection Measurement a) no load, b) loaded

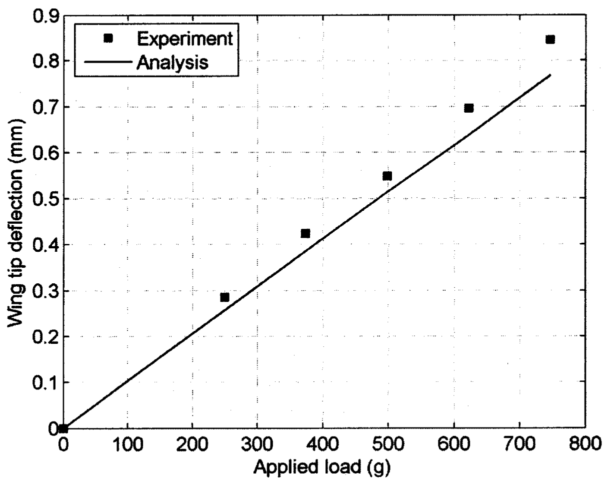

Fig.13 Wing Tip Deflection : Comparison Between Analysis and Static Experiment