Development and Application of PP-CNT Composite for Hummingbird Inspired MAV Flapping Wings

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ABSTRACT

Micro Air Vehicles (MAVs) are small unmanned aircrafts which have a maximum size limit of 150 mm in any direction. They can be used for surveillance, reconnaissance, targeting, etc. To perform such missions, MAVs are required to hover. Hummingbirds, having excellent flight characteristics (such as hovering, ability to fly in any direction, ability to produce a reverse camber during upstroke for generating lift in both up-down strokes), have been chosen as the bio-inspiration for wing development. Wings are required to be light, strong and fatigue resistant, to be able to properly flap during flight. Therefore, wing-material becomes a crucial component. An optimization analysis, on the basis of density and fundamental frequency values obtained through Ansys, was done for selecting the wing material. Polypropylene (PP) was observed to have desired properties such as light weight, flexibility, strength, fatigue resistance, good heat and chemical resistance etc. Mixing Carbon Nano Tubes (CNTs) with PP can further increase the strength significantly, making it more suitable for large amplitude flapping. The PP-CNT composites were developed using solution casting method. The films were characterized mechanically (using UTM). The wings were characterized by their structural dynamic properties. The modal analysis of wings was done to obtain natural frequencies and mode shapes. The analysis was aimed to get the fundamental mode in the flapping range (8-15 Hz) of hummingbirds, as resonance increases efficiency. It was also done inside vacuum chamber to observe the effect of air on the natural frequency and modes. The Ansys results were compared with the experiments in vacuum for validation of experimental results. Damping coefficient of wings was also determined. In the end, bio-mimicking of hummingbird wing was also tried by doing some material and structural advancements in the wings.

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Keywords: MAVs, Hummingbirds, Bio-mimicking, PP-CNT composites, Structural Dynamic Analysis

1 INTRODUCTION

Micro Air Vehicles (MAVs) are small unmanned aircraft with a maximum size limit, set by DARPA, 150 mm in any direction. MAVs are of three types, namely, fixed wing, rotary wing and flapping wing. The flapping wing MAVs are better than other two, mainly in indoor flights. Fixed wing MAVs cannot hover and its agility is also not good while rotary wing MAVs have wall proximity problem. Also, flapping wings MAVs are able to fly at low speeds or hover for long duration. They generate lift and thrust using their wings only which is advantageous in terms of efficiency.

Natural fliers are the original masters of flight. They are the perfect source of inspiration for development of MAVs. Raney and Slominski [1] developed hummingbird inspired mechanism and wings. They used carbon-epoxy composite, for wing frame, and a thin latex, for wing membrane, as the wing materials. Zduinch et al [2] also made similar structure wing using carbon fiber prepeg strips as vein structure and Mylar as membrane. Wood [3] also designed hummingbird inspired wing and used carbon fiber as wing frame with polyester as wing membrane. Ratti and Vachtsevanos [4] took inspiration from flight mechanism features of dragonfly and developed a bio-inspired MAV. Nakata et al [5] developed and did aerodynamic testing of hummingbird inspired MAV.

During flight, the wing experiences loads due to given acceleration or inertial forces and due to air interaction of aerodynamic forces. For flapping wing MAVs, wings are the only source to generate all the required forces to be able fly and perform missions. So wings have to be light, strong and fatigue resistant to make a successful MAV. To make such wings, appropriate materials have to be chosen. Among most commonly used polymers, Polypropylene (PP) which has light weight, good fatigue resistance, flexibility, chemical and heat resistance etc., can be used as the wing material. For further increase in strength,carbon nanotubes (CNTs) have been used. CNTs are most commonly used inorganic fillers for PP. CNTs can be classified into single-walled CNTs (SWCNTs) and multi-walled CNTs (MWCNTs). CNTs have excellent mechanical, thermal properties which makes them an excellent reinforcing material. Their elastic modulus is $\sim$ 1 TPa for SWCNT, $\sim 0.3 - 1$ for MWCNT and tensile strength is $50 - 500$ GPa for SWCNT; $10 - 60$ GPa for MWCNT [6]. They are very light weight too, their density is one-sixth of steel which can be as low as 1.3 gm/cm^3 [7]. The aspect ratio of CNTs is also high [6] which is advantageous in terms of better reinforcement of the matrix. The PP-CNTs nanocomposite can be prepared using solution mixing, melt blending and in-situ polymerization. The benefit of using solution mixing is that mixing of nanotubes with matrix in proper solvent, through sonication and stirring processes, improves the dispersion quality of composite [8]. The weight concentration percentage of CNTs with respect to PP is a very important factor. At high concentration, agglomeration of nanotubes occurs, which degrades the properties of the composite [9, 10]. Due to agglomeration, the load from matrix to nanotubes cannot be transferred properly [11].

The wings, during flight, get subjected to the interaction of kinematics, structural dynamics and aerodynamics [12]. Much experimental and computational work has been done in the field of kinematics and aerodynamics. The structural dynamics analysis of wings is very important and has yet to be explored. Sladek et al [13] did aerodynamic and structural dynamic testing of wings, and obtained results for determination of the repeat-ability of their manufacturing technique.

The objective of this study is to make PP-CNTs composites and use them for development of MAVs flapping wings. The performance of nanocomposite will be evaluated by mechanical, physical and thermal characterization methods. The wing will be designed using dimensional parameters of the hummingbird wing. The wing manufacturing technique will also be evaluated on the its repeat-ability. The fabricated wings will be characterized on the basis of their structural dynamic characteristics. The validation of experimental results will be done by doing analysis using commercial finite element analysis software ANSYS. The modal testing of wings was also carried out inside a vacuum chamber. The results from ANSYS and vacuum testing will be compared for validation of results later. At last, bio-mimicking design of the hummingbird wing will be discussed.

2 Wing Designing and Material Development

The most of the research related to MAVs is based on kinematics, controls and aerodynamics. To make a successful MAV, the wings have to be designed properly and appropriate materials have to used for fabricating them. The wings have to be light, flexible, structurally strong and aerodynamically efficient. The flexibility of wings affects the efficiency of MAV. Controlled flexibility along the wing span can be beneficial in terms of thrust production [14].

2.1 Wing Designing

Nature serves as an effective tool to study the way MAVs should be operated. Natural fliers, use flapping wings to produce lift and thrust. Among the numerous examples of highly successful flapping fliers that exist in nature, the Hummingbird is chosen as the biological inspiration. The Hummingbirds, because of their specific flapping mechanism and wings, have excellent characteristics such as long duration hovering, backward motion, high agility, etc. They produce a reverse camber during upstroke to generate lift in both up & down strokes during hovering [1]. There characteristics, taken from various sources, also lie in the range of parameters set by DARPA for MAVs. The comparison of MAVs and hummingbirds is shown in Table 1.

Parameter	MAVs	Hummingbirds
Max size (mm)	150	50-305
Weight (gm)	10-100	2-24
Payload (gm)	1-18	NA
Endurance (min)	20-60	>120
Airspeed (km/h)	35-60	40-54
Range (km)	1-10	>6
Hovering	Hover is trade-off with endurance/range	∼Hour

Table 1: Comparison of hummingbirds and MAVs characteristics.

Here, Pantagona Gigas (Giant Hummingbirds) is chosen as the bio-inspiration for development of wings. They are largest hummingbirds among all hummingbird species.

Parameter	Giant Hummingbirds
Body Mass (gm)	18-24
Wing Length (mm)	∼135
Wing Chord (mm)	∼45
Flapping Frequency (Hz)	10-15
Top speed (km/h)	∼43.44

Table 2: Giant hummingbird characteristics.

The wing design development was done using Gambit software. A printed image of actual Giant hummingbird wing was used for recording the dimensions. The profile of wing on the printed image was marked to create guide lines for generating data points. A digitizer was used to generate the data points. Large number of data points were generated for making smooth 2D profile of wing. Generated data points were imported into Gambit for making computational wing sketch. The designed wing sketch is shown in Figure 1.

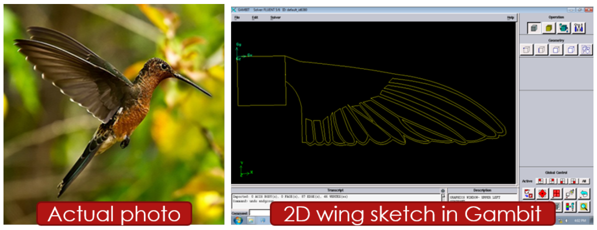

Figure 1: Designed wing sketch.

The Table 3 shows the dimensions of designed wing sketch. The dimensions are in the range of giant hummingbird values which validates the design.

Parameter	Designed Wing
Wing Length (mm)	120.18
Wing Chord (mm)	44.0
Wing Area (mm^2)	7894

Table 3: Designed wing characteristics.

The design has been validated using relations given in Equations 1, 2, 3 between wing length (L, cm), wing area (S, cm^2) and body weight (W, gm) determined by Greenewalt [15]. Using wing length of designed wing as a reference parameter, other parameters such as wing area, body weight determined and validated.

$$L = 2.329W^{0.556} \tag{1}$$

$$L = 1.0537S^{0.5556} \tag{2}$$

$$S = 4.1712W \tag{3}$$

Another equation (4) was given by Greenewalt (used by Raney and Slominski [1]) for determining flapping frequency (f, Hz) these relations for a particular wing length (L, m).

$$f = L^{-\frac{5}{4}} \tag{4}$$

Using all the above relations, given by Greenewalt, some parameters for a hummingbird based on length of designed wing can be determined. The Table 4 shows the parameters obtained using Equations 1, 2, 3, 4. These parameters fall in the range of giant hummingbirds characteristics values.

Parameter	Designed Hummingbird
Wing Length (mm)	120.18
Body Mass (gm)	19.12
Wing Area (mm^2)	7992
Flapping Frequency (Hz)	14.12

Table 4: Designed hummingbird parameters.

2.2 *Wing Material Optimization*

The material of wings should be light weight, flexible, fatigue resistance, strong etc. Materials should also have heat resistance for high temperature application and chemical resistance for application in chemically dangerous environment. Hummingbirds, during hovering, flap their wings at high amplitude and frequency. The idea here is to develop a wing which has a fundamental frequency in the flapping frequency range of hummingbirds. We then use the phenomena of resonance, to get a higher amplitude flapping at approximately the same power input. Many insects and birds flap their wings at resonance or fundamental natural frequency of the wings[1].

For selecting wing material, an optimization analysis will be carried out on the basis of material density and the fundamental natural frequency of the wing.

Commonly used polymeric MAV wing materials such as polypropylene (PP), polyethylene (PE), polyvinyl chloride (PVC), polycarbonate (PC), polystyrene (PS), polyvinylidene fluoride (PVDF), acrylonitrile butadiene styrene (ABS) and polytetrafluoroethylene (PTFE) or teflon, polyamide (PA) or nylon, polyethylene terephthalate (PET) or Mylar are chosen as wing material. The essential input material data required for performing modal analysis in ANSYS are density, elastic modulus and Poisson's ratio. The material properties of all the polymers, except PP, were taken for analysis from reliable sources such as MatWeb (http://www.matweb.com/), Wikipedia (http://en.wikipedia.org/wiki/Main_Page), Goodfellow (http://www.goodfellow.com/) and INEOS (http://www.ineos.com). For input data of PP the experimental values were taken from tensile testing of films.

A simple 3D tapered (1.1 mm thickness at root to 0.36 mm thickness at tip) model of wing from designed 2D sketch was developed in Gambit. The analysis parameters except material data were same for all the cases. The wing was meshed into 102416 elements using tetrahedrons. The figure 2 shows the comparison plot of fundamental frequency vs. density for all materials.

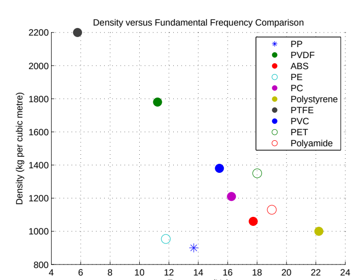

Figure 2: Modal Analysis: Wing material optimization.

As can be seen, the PP and PE data fall in the desirable range. We chose PP over PE because it has better fatigue resistance, lower density, higher softening and melting point, higher rigidity and hardness etc.

2.3 PP-CNT Composite Development

Polypropylene, a thermoplastic semi-rigid polymer, is widely used in a variety of industrial applications including plastic hinges, packaging, reusable containers etc. It is an addition polymer made from Propene and is known for good fatigue resistance, mechanical strength, chemical resistance, toughness, heat resistance etc. A CNT is a tube shaped material made of carbon, having a diameter measuring on nanometer scale (ranging from ¡1 nm up to 50 nm) approximately 1/50000th of the width of human hair and length several microns to centimeters (18 centimeters). Basically, a Carbon Nano Tube (CNT) is a new form of carbon, equivalent to two dimensional graphene sheet rolled into a tube, by configuration. CNTs are known as excellent nano fillers because of their properties such as high tensile strength (60GPa), modulus of elasticity (around 1TPa), light weight and high aspect ratio.

2.3.1 Composite Development Procedure

Materials used for composite development are Polypropylene from Oddo, MWCNTs from Nanoshel and Xylene from Merck.
20ml of xylene is added to 20gms of PP and heated in a beaker to 210○ at 60rpm. simultaneously, 0.02gms(0.1wt% of PP) is added to 20ml of xylene and sonicated for 45min. Both the solution are mixed and stir for 30min, till the solution becomes homogeneous. Solution is taken in petri dish and heated in oven at 140○ till the solvent gets evaporated. The composite film of PP-CNT is obtained.

For making thinner and uniform films, the final composite sample was put between film mold plates and pressed using UTM in compression mode. The processing temperature was maintained at 230-240 °C. The applying load (around 9 kN) was optimized to get the film thickness below the 0.1-0.2 mm mark. A similar procedure was used for making neat PP films.

2.3.2 Composite Characterization

The developed films were characterized using UTM for mechanical performance.

Mechanical Characterization:

The tensile film testing standard ASTM D1708-13 was used for making specimen. Instron 3345 was used for testing the composites. 5 specimens were tested for each category, at 1 mm/min speed. The Figure 3 shows the tensile testing results. The tensile strength and Young's modulus of composite increased with MWCNTs weight concentration till 0.1 %. After 0.1 wt % there was a continuous decrement in the performance.

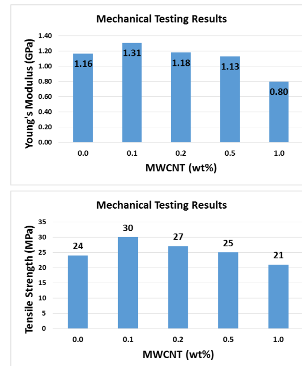

Figure 3: Mechanical results of composites.

3 WING DEVELOPMENT AND TESTING SETUP

In this section, we discuss the development procedure of a Bio Mimetic Hummingbird Wing using polypropylene and PP-CNT composites. Modal coupling of bending and torsion was to be achieved. This is because, it provides flap and passive pitching motions required for controlled and efficient flapping flight as seen from the studies on bird wing motion. The fabricated wings were tested using electro-dynamic shaker for modal analysis.

3.1 Wing Fabrication

Repeat-ability is one of the key factors of manufacturing techniques. One must be able to manufacture the same object with same properties repeatedly. Here, we need at least two wings for MAV application with same characteristics to avoid uncontrolled asymmetric flapping. A mold was designed to cast the desired wing shape. The mold for the polypropylene wing was made out of brass from the 3-Axis CNC Machine at the 4i Laboratory, IIT Kanpur. The wing shape designed in Gambit was extended to a both side tapered solid model. The thickness was varied from root (0.8 mm thick) to tip (0.3 mm thick), to facilitate good bending and utilizing the favorable properties of the polymer. The thickness gradation leads to a variation in the value of flexural stiffness along the wing span from the root to the tips and mimics the variation in a bird wing, qualitatively. The objective is to obtain coupled bending and torsional modes which can represent flapping and passive pitching motion, at this very small size scale, thus simplifying the actuation mechanism which is one of the major causes of weight in the flapping wing MAV.

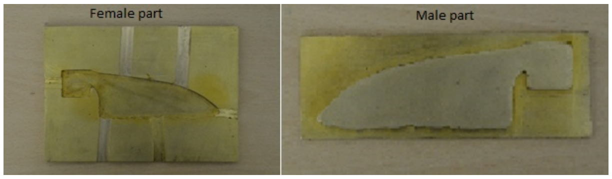

Figure 4: Manufactured Lower and Upper Mold for PP Wing.

For fabrication of the mold, with the wing polymer material in it, was put in the thermal chamber of UTM in compression mode. The temperature of chamber was set up to 230-240 $^{\mathrm{deg}}$C. As the temperature increases, the force reading on the machine increases as the material expands. Once it crosses the glass transition temperature and begins to flow the force applied starts reducing. The molds are compressed till they completely fit as designed. The thickness of the wing varied from 1.1 mm at the leading edge of the root to 0.5 mm at the trailing edge, despite the designed mold having variation from 0.8 mm to 0.3 mm because of inaccuracy in manufacturing of mold and the casting process not being perfect because of the low tendency of propylene to flow.

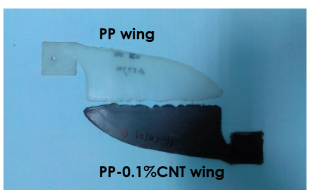

Figure 5: Fabricated wings.

3.2 *Wing Testing Setup*

An electrodynamic shaker was used to vibrate the wings for performing modal analysis. The natural frequencies and mode shapes were found with the help of Stroboscope and laser displacement sensor. The Figure6 shows the experimental setup for modal analysis in open air.

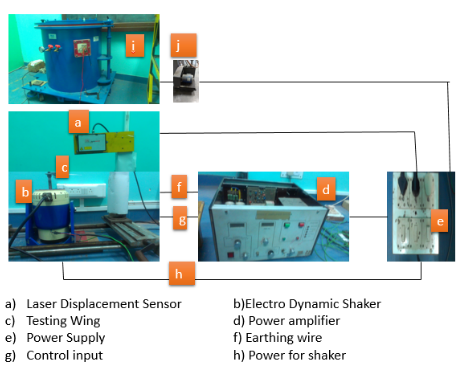

Figure 6: Wing testing setup

For modal analysis in vacuum, same setup is used but the shaker is kept inside the vacuum chamber and using compressor pump vacuum is created. For actuation of wing all the wires(f,g,h in 6) are taken out from the vacuum chamber through the holes(can be seen in vacuum chamber(h) in 6). This holes are packed with adhesives.

3.3 *Damping Coefficient Calculation Experiment*

Damping study of the hummingbird wings is an important aspect of study because the wing must be able to reduce unwanted vibrations due to sudden wind gusts. This requires an estimate of the logarithmic decrement (δ) and the damping ratio (ξ) of the polypropylene wing. The mathematical relations used for calculating these quantities are given in Equation 5 and 6.

$$\delta = ln\frac{x_1}{x_2} \tag{5}$$

$$\xi = \frac{1}{\sqrt{1+(\frac{2\pi}{\delta})^2}} \tag{6}$$

Where, x_1 and x_2 are the first and second maximum positive amplitudes. An experimental setup consisting of a Laser Displacement Sensor, a LabVIEW program for data acquisition and a wing clamp was made. The wing was clamped at the root section and excited by a sudden jerk at the tip. Tip displacements were measured via laser and recorded as a function of time to study the damping characteristics. The laser sensor was first calibrated before being used in the damping experiment to obtain a relation (Equation 7) between the laser displacement voltages (V) and the physical displacements (d).

$$d = 29.444 * V - 0.0404 \tag{7}$$

4 Results and Discussion

Here Modal analysis and damping results will be discussed.

4.1 *Experimental Modal Analysis Results*

The fundamental frequency is closer to the flapping range of designed wing.

Modes	PP wings (Avg. of 3)	PP-0.1CNT wings (Avg. of 3)	Mode shapes
1st	16	16	Bending
2nd	63	66	Coupled
3rd	95	95	Torsional
4th	146	152	Coupled

Table 5: Modal analysis: Experimental results.

It is observed that resonance frequency remains almost equal with increase in the strength and stiffness.

4.2 Damping Experimental Results

The nature of amplitude variation with respect to time, shown in Figure 7, was observed for the polypropylene wing.

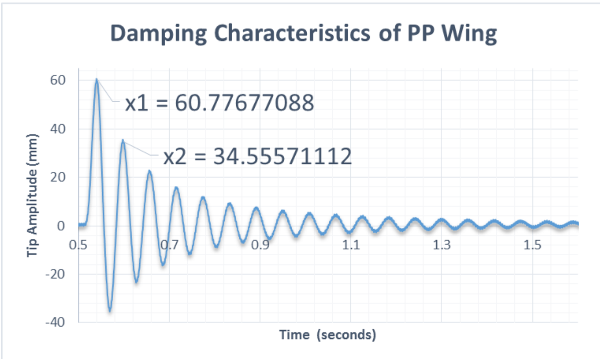

Figure 7: Damping Characteristics Plot

Using the relations mentioned in Equation 5, the logarithmic decrement and the damping ratio were obtained as 0.5646 and 0.0895, respectively.

4.3 Modal Analysis using Ansys

ANSYS 14 was used for modal analysis of designed wings. The 3D model of wing was imported from Gambit to ANSYS Design Modeler. The input material data, given for analysis, was taken from the film testing results, barring the Poisson's ratio data, which was taken from literature as stated earlier. The Table 6 shows the input material data.

Density $(kg/m3)$	901
Modulus (GPa)	1.16
Poisson′s ratio	0.45

Table 6: Ansys modal analysis: Input material data

The meshing of wings, shown in Figure 8 was done using patch conforming method. Tetrahedron elements were used for meshing the wings. Pre-Stress is not applied and the wing is fixed at the root of the wing.

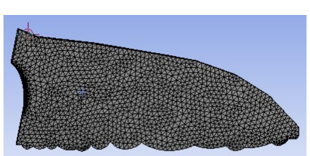

Figure 8: Ansys modal analysis: Meshed wing.

The convergence analysis, shown in Table7 was done on the basis of number of elements. This analysis is done to check the developed finite element modal analysis code. Frequency drops, for first mode, at an exponential rate with respect to the number of elements and saturates at 13.68 Hz beyond 200,000 elements, which was obtained by increasing the number elements in steps. Hence, convergence of solution was obtained.

Modes	Natural Frequency (Hz)		
	Elements (1940)	Elements (18990)	Elements (102383)
1st	15.007	14.191	13.768
2nd	64.76	58.536	53.312
3rd	84.73	78.666	74.653
4th	184.39	149.78	125.12

Table 7: Ansys modal anlaysis: Convergence

4.4 Validation of Experimental Results: Ansys Results vs. Vacuum Results

The free undamped vibration case was considered for solving the problem computationally in ANSYS. However, in the actual case, the wing is subjected to two types of damping, namely the damping due to the system itself and due to the surroundings. The system damping is due to the viscoelastic nature of wing material and the surrounding damping is due to fluid or air interactions. A vacuum chamber was designed, developed and used for wing testing. Using the vacuum chamber, the contribution of fluid damping (due to air resistance) can be eliminated. Therefore, for validation of experiments, the results from ANSYS are compared with vacuum testing result and shown in table8.

Modes	**Vacuum**	**Ansys**	**Mode shape**
1st	16	13.7	Bending
2nd	62	53.3	Coupled
3rd	96	74.6	Torsional
4th	147	125.1	Coupled

Table 8: Comparison of ANSYS and Vacuum results

4.5 Effect of Air loads

It is observed, there is not much change in value of modal frequencies in air and vacuum. This is because of stiff structure and a very small surface area for any significant air interaction to occur. Hence the damping due to air does not affect the modal frequencies of these particular wings. So it can be concluded that the aerodynamic loading or air interaction, for the wing designed in present study, does not affect the mode frequencies (at least for first three measured modes).

4.6 *Nature of Mode Shapes: Experiments vs. Ansys*

The mode shapes from Experiments and Ansys are matching.

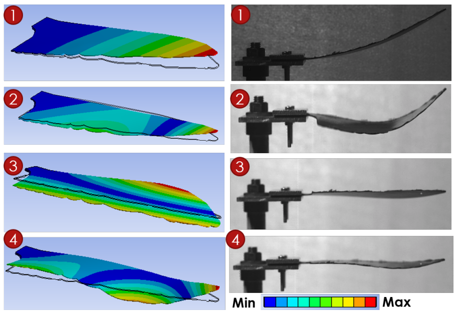

Figure 9: Modal Analysis: Nature of mode shapes.

4.7 *Repeatability of Wing Manufacturing Technique*

Repeat-ability of wing manufacturing technique is very important. The technique should be able to produce the wings with same characteristics (mass, structural and aerodynamics). Here the repeat-ability is determined on the basis of mass and structural dynamic characteristics. For evaluating the repeatable wing producing capability of manufacturing technique different composite, epoxy-CNT , wings were developed and tested. These wings are shown in the Figure 10. For epoxy-CNT composite case, the 0.2 wt% MWCNTs concentration performed well.

Figure 10: Epoxy-CNT composite wings.

In the Table 9 the small values of standard deviation indicates that the technique is able to produce same mass wings.

Wing type	Average (gm)	Standard Deviation
Neat PP wings	2.74	0.15
Epoxy-0.2CNT wings	6.4	0.26

Table 9: Repeatability by mass characteristics.

The Table 10 also indicates that the manufacturing technique is able to make wings with same structural dynamic characteristics.

Modes	PP wings		Epoxy-0.2CNT wings	
	Average	Standard Deviation	Average	Standard Deviation
1st	16	0.58	40	1.15
2nd	63	2.52	171	5.69
3rd	95	3.51	242	11.59
4th	146	5.13	419	19.43

Table 10: Repeatability by structural dynamic characteristics.

4.7.1 Bio-mimicking of Hummingbird Wing using PP-CNT Composite Membrane

For mimicking of wing frame, carbon fiber epoxy composite is used. Developed PP-0.1%CNT composite film is used as the wing membrane. Same PP wing mold was also used to make this composite structure wing. This wing is also tested for its natural frequencies and mode shapes which are shown in Table 11.

Figure 11: Bio-mimicked hummingbird wing.

Modes	Natural frequency (Hz)
1st	21
2nd	83
3rd	109
4th	126

Table 11: Bio-mimicked wing's experimental results.

5 Conclusion

A simple tapered hummingbird inspired wing was designed and validated for its properties. The modal analysis of wings using different materials was done and used for optimizing the material for wing. Polypropylene was chosen over other commonly used polymeric materials on the basis of density and fundamental frequency. The testing of developed composites showed that CNT (at 0.1 wt%) enhanced the stiffness and strength of neat PP. After successful composite development and mechanical testing, the wing fabrication was carried out using a mold. Both neat PP and optimized PP-CNT (0.1 wt%) combination composite were used for wing fabrication. Modal analysis of wings was done using electromagnetic shaker, stroboscope, laser displacement sensor and high speed camera. The natural frequencies and corresponding mode shapes of the wings were recorded using a high speed camera. The validation of experimental values was done by results from ANSYS. These computational results were compared with the experimental values from wing testing inside the indigenously developed vacuum chamber. Interesting conclusion from this study is that the CNTs do not increase the fundamental frequency, stiffness and density, but increases the strength of wings significantly. The fundamental frequency of neat PP and PP-0.1CNT is 16 Hz which is very close the flapping range(8-15 Hz) of chosen hummingbird. Hence, by using these wings, lift and aerodynamic efficiency of hummingbird inspired MAV can be increased, as the wings flap at resonance. The damping coefficient of developed wings was determined using logarithmic decrement method. In the end, some advancements were done in the design and structure of wings to mimic the hummingbird wing. Hence, PP-CNT composite wing was developed which has potential application in a hummingbird-type MAV.

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