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A bioinspired MAV with nanocomposite wings and flexure joints: design and structural dynamic analysis

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ABSTRACT

A bioinspired tethered MAV model is designed, constructed and studied for structural dynamic characteristics using novel materials and methods. The model consists of two flapping wings, a compliant flapping mechanism, and a supporting chassis. Large size insects such as dragonfly and cicada are considered as inspiration for the designing purposes. The wings and mechanism designed in this study are a simplified form of the natural counterparts. These idealized bioinspired structures are first studied for structural dynamic characteristics using finite element methods. Carbon nanotubes/polypropylene (CNTs/PP) nanocomposite stiffeners and a thin LDPE membrane are used to realize the designed wing model. The use of this novel material composition resulted in a lightweight, thin, and flexible wing capable of large amplitude passive bending-twisting motion. For constructing the flapping mechanism, a novel compliant mechanism is fabricated and attached with a piezoelectric actuator of cantilever form. The compliant mechanism is designed with CNTs/PP nanocomposite flexure joints supported using rigid carbon fiber/epoxy composite linkages. The fabrication of wing stiffeners and mechanism flexures from lab developed CNTs/PP nanocomposite materials is carried out using laser micromachining based manufacturing technique. The complete MAV model is constructed by assembling the wings and mechanism with a carbon fiber/epoxy composite chassis. The final assemblage is a two-winged MAV model of a total mass, body length, and wingspan of 0.6 1g, 60.46 mm, and 90.14 mm, respectively. An external customized power supply is developed and used with a microcontroller to actuate the flapping mechanism and wings during experiments. The computational structural analysis showed that no resonance occurs at the mechanism, all the first four fundamental modes are at the wings. This is advantageous for accurate and efficient motion transmission to the wings. The model generates large-amplitude wing deflections with a very small amplitude input excitation from the actuator - useful for higher aerodynamic performance. Experimentally, the structural dynamic analysis of the MAV model is carried out using an in-house high-speed 3D digital image correlation (DIC) technique, which reveals that the wings generate bending dominated deforming shape with marginal twisting and positive camber (during downstroke). Structural dynamic results from computations are in good agreement with the experiments that validates both of the approaches for further advancements in the developed MAV model. Overall outcome of the current work is a simplified biomimetic MAV design, a potential candidate for developing mechanically efficient MAV models.

Keywords: MAVs, Flapping wings, Biomimicking, Nanocomposites, Flexure joints, Insects.

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1. INTRODUCTION

Unmanned air vehicles (UAVs) are aircraft without a human pilot aboard. They are generally controlled remotely or autonomously. UAVs can be used for large number of applications including intelligence, surveillance, and reconnaissance (ISR), search and rescue operations, ship inspection, etc... (Valavanis and Vachtsevanos, 2015). Micro aerial vehicles (MAVs) are miniature UAVs characterized by its maximum size 150 mm, a better alternative to large size UAVs because of low weight and cost as well as excellent maneuvering capabilities with rapid response time. These small unmanned systems are useful for search and rescue (S&R) and reconnaissance in urban settings (Valavanis and Vachtsevanos, 2015). MAVs can be of three types; fixed wing, rotary wing and flapping wing. Flapping wings MAVs can fly at low speeds and hover for longer duration. In 2011, a small hovering ornithopter inspired by hummingbird was designed and developed by AeroVironment, Inc. under NAV program from DARPA. The first version of this remote controlled nano air vehicle (NAV) had total mass and wing-span of 19 g and 16.75 cm, respectively. The model flight speed was 18 km/h and can fly in different directions (climb-descend, left-right and forward-backward). The latest version of this robotic flier has a total mass of 10 g, maximum size 7.5 cm, payload capacity 2 g, forward speed of 10 m/s and can perform hovering (Keennon, 2011; Keennon et al., 2012; Wikipedia, 2011). Perhaps the most sophisticated and advanced successful robotic flier is the Robobee (Wood et al., 2013). This insect scale robotic flier is developed by Harvard Microrobotics Laboratory. The first version of the model took-off in 2007. This tethered model with 30 mm wing span and 60 mg mass flew in guided strings using two flapping wings (Wood, 2007). A compliant mechanism was developed to amplify the PZT (lead zirconate titanate) actuator deflections and produce large amplitude simple flapping motion. Wing twisting was achieved passively. Later, the mechanism was upgraded by adding torsional control functionality using another PZT actuator (Finio et al., 2009). The mechanism is designed to use resonance principle to increase lift force and decrease input energy for actuation (Wood, 2007b). Latest model has optical flow sensor and can perch using switchable electrostatic adhesion (Graule et al., 2016; Harvard, 2011).

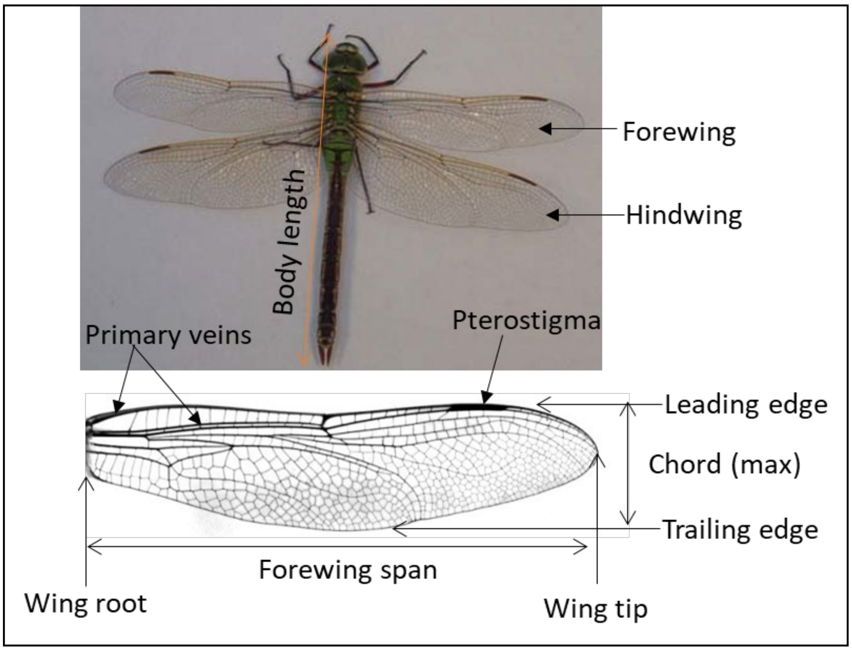
Insects are the masters of flapping flight. They evolved active flight and marveled at it. They still remain unsurpassed in various aspects of flapping flight including aerodynamics and maneuverability (Dickinson et al., 1999). Insects use their extraordinary flapping muscles and wings for performing different flight operations (hovering, take-off, forward-backward, gliding, etc.) by generating desired aerodynamic forces. Their lift and thrust production is based on complex interaction of compliant wings, wing kinematics and the aerodynamics. The production of aerodynamic forces is based on leading edge vortex and rotational circulation (Dickinson et al., 1999; Ellington et al., 1996), and also on clap-fling mechanism (for smaller insects) (Weis-Fogh, 1973). Insect wings are quite complex in structural makeup, and their ability to account for dynamic loads are difficult to mimic mechanically (Smith et al., 2000). Insect wings are made of intricate-form vein skeleton covered with a skin, where each vein specifically designed to generate desired aerodynamic forces (Song et al., 2004). Considering natural flight muscles, insects have two types of flight muscles: direct and indirect. Large size insects such as cicadas and dragonflies use the direct flight muscle system. Each wing is connected to elevator and depressor muscles at its base and able to achieve flapping motion independently. Indirect flight muscles provide the motion to the wings indirectly by changing the conformation of the thorax. This flight muscle system is used by advanced smaller-size insects (such as Dipteran insects) (Klowden, 2013). Greenewalt (1960) found that insects beat their wings at a frequency of highest flapping amplitude (the characteristics frequency or resonant excitation frequency) in order to enhance aerodynamic performance. Jafferis et al. (2016) and Zhang & Xinyan (2017) performed experiments and showed the increase in the efficiency of flapping wings due to resonant excitation. Combes and Daniel (2003) observed that, in wing-bending during a resonant vibration cycle, the influence of aerodynamic forces is relatively insignificant as compared to the inertial–elastic forces. They suggested that only structural dynamic analysis could be sufficient to design small-size efficient flapping wings. Masoud and Alexeev (2010) using FSI (fluid-structure interaction) simulations showed that the large amplitude deflections gained at resonant excitation significantly enhanced aerodynamic lift and efficiency. They reported that the flexible wings of simplified structural form excited with a simple resonant excitation are viable for devising efficient MAVs. Raney and Slominski (2004) developed a vibratory resonant mechanism using two electrodynamic shakers to replicate hummingbird motions. The shoulder joint was made using 3-DOF pinned ball and socket. The authors were able to achieve similar wing motions present in the case of hummingbirds. Bolsman et al. (2009) developed a resonant mechanism for insect inspired MAVs. This ring-formed thorax structure is coupled with its wings. The ring deflections are transformed and amplified to large wing rotation using a compliant mechanism.

It has been understood that the insect-inspired mechanical designs may help develop superior artificial flyers as compared to non-bio-inspired designs. Therefore, natural wings and mechanisms could be explored and considered as an inspiration for developing agile and efficient MAVs. The vision of the ongoing research is to develop an efficient untethered hovering MAV model (a robotic flyer) by mimicking insects and hummingbirds (Kumar et al., 2014; Kumar et al., 2019; Kumar et al., 2020). The present article focuses on the design and structural analysis aspects of a simplified insect-inspired tethered MAV model developed using novel materials and methods. Large size insects such as dragonfly and cicada are considered as inspiration for the designing purposes. The wings and mechanism designed in this study are a simplified form of the natural counterparts. These idealized bioinspired structures are characterized for structural dynamic characteristics using experimental and computational methods. The realization of flapping wings and mechanism is carried out using carbon nanotubes (CNTs) based nanocomposite materials and laser micromachining based manufacturing methods. In the end, a two-winged tethered MAV model is successfully developed with similar morphological characteristics and wing kinematics as compared to the considered natural counterparts.

2. BIOINSPIRATION AND DESIGNS

2.1 Bioinspiration

Insects are unique flyers of natural world having exceptional flying capabilities compared to other flying species. Particularly dragonfly and cicada are two species who further stand apart in their extraordinary flight characteristics. High maneuverability with omnidirectional flight capabilities, they are nearly unmatched in nature. Hence, these superior flying insects, shown in Fig. 1, are chosen as an inspiration in the present work for design and development of the bioinspired MAV model. Their morphological and other parameters are listed in Table 1.



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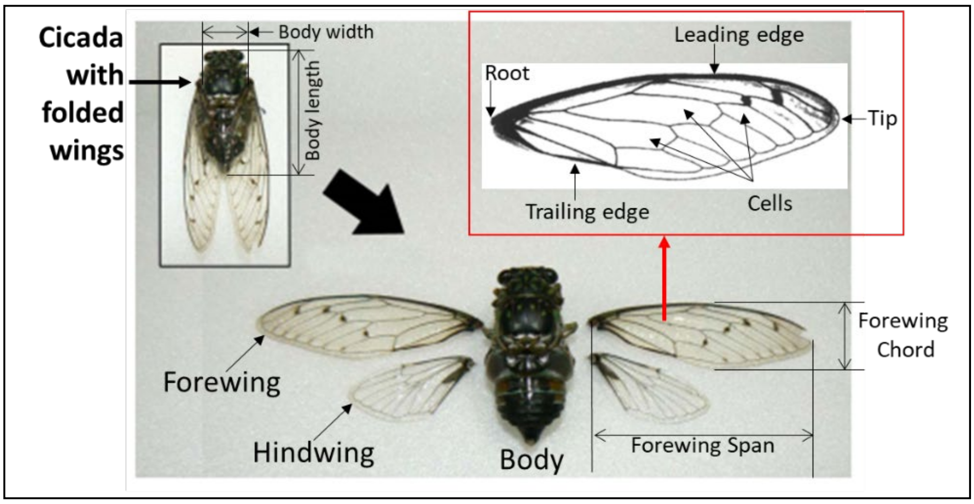


(b)

Fig. 1. Bioinspiration and their components with description (a) Dragonfly, reproduced from (Azuma and Watanabe, 1988; Okamoto et al., 1996) (b) Cicada, reproduced from (Park et al., 2007; Song et al., 2004; Sudo et al., 2005)

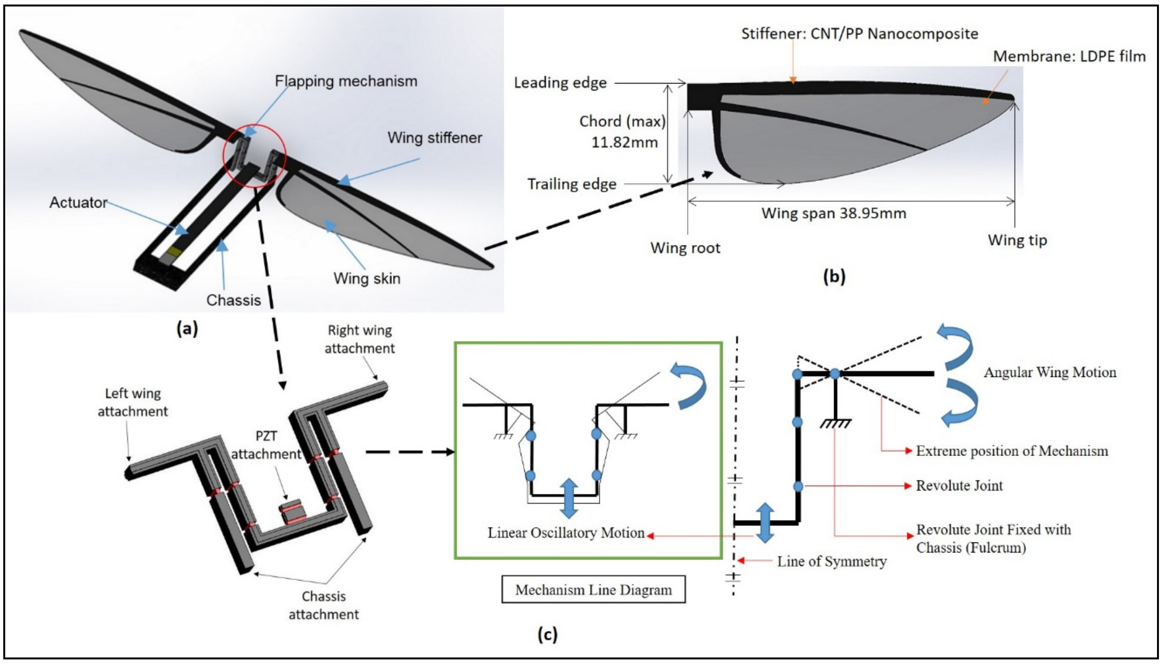


Fig. 2. Bioinspired designs, (a) MAV model (b) Flapping wing (c) Flapping mechanism

Table 1. Morphological and other characteristics of dragonfly and cicada

Parameter	Unit	Dragonfly	Cicada
Body length	mm	40-75	37.44 ± 3.30
Total mass	g	0.79-1.18	1.60 ± 0.21
Forewing length	mm	44-100	49.20 ± 2.60
Forewing chord	mm	~11	16.45 ± 1.13
Forewing area	mm^2	442-1000	326 ± 2
Flapping frequency	Hz	~27.53	40-48
Wing loading	N/m^2	3.5	11.8 ± 0.2

(Azuma and Watanabe, 1988; Azuma et al., 1985; Ren et al., 2013; Schilder and Marden, 2004; Song et al., 2004; Wan et al., 2015; Wu et al., 2011)

2.2 Bioinspired Designs

The developed MAV design is a simplified version of the chosen bio-inspirations. The MAV has two wings considering only the forewings of the natural counterparts. To reproduce the wing motion like insects, the whole MAV body is designed with subsystems acting as substitutes to each of the natural counterparts. Hence, different natural parts such as wing, muscle, body and joints are substituted with artificial wing, actuator, chassis and flexure linkages, respectively. Overall, the designed MAV model consists of a compliant mechanism, two flapping wings, a PZT (lead zirconate titanate) actuator and a composite chassis. The designed MAV model and its parts are presented in Fig. 2. CAD (computer-aided design) modelling of these designs is done using SolidWorks. The miniature compliant mechanism works as a mediator mechanism between actuator and the wings. The flapping motion to the wings is provided using the mediator mechanism by transforming the tip displacement of the cantilever beam type PZT actuator into the desired flapping motion. The beam actuator with the mechanism and wings are supported by a carbon fiber/epoxy composite chassis.

Generally, insects have two pairs of wings among them more important is forewing pair while other is sometimes used for flight and also for sensory purposes in some species. Natural wings have longitudinal and cross veins, and also an outer skin around the vein skeleton. Vein pattern is characteristic to a particular species, for example, some have corrugated forms (Combes and Daniel, 2003a). These variations in structural forms and sizes of veins affect the stiffness, that in turn affects bending, torsion and dynamic pressure during flight (Brodsky, 1994). In the present study, a simplified wing is designed as shown in Fig. 2(b). Basically, the natural wings are idealized as the combination of stiffeners and membrane. The stiffeners are made up of CNTs/PP nanocomposites while a LDPE membrane is used to make the wing skin. Since the wing is flexible and will undergo cycles of completely reversed loading, high fatigue resistant material polypropylene (PP) in combination with CNTs is chosen. Using CNTs based polymer in wings makes a smart structure which could be used to generate strain (active morphing of wing) or sensing wing deformation (strain sensing).

Insects employ complex mechanism to undertake the wing motions. Here, a flexure joint based compliant mechanism is designed in order to reproduce insect-like flapping motion for the wings. It is a simplified version of insects' flapping mechanisms. The mechanism is also modelled using SolidWorks as shown in Fig. 2(c). Wood et al. (2008) utilized commercial polyimide polymer (Kapton) for making the flexure joints, while in the current work, CNTs/PP nanocomposite is used for flexure joint development. Since this nanocomposite is developed in laboratory, its mechanical properties could be tailored to best suit the design requirements. The flexure sheet of nanocomposite is sandwiched between two layers of carbon fiber composite sheets on either side using cyanoacrylate based adhesive. The mechanism is made up of these flexure joints and rigid carbon fiber composite links. The actuator tip is attached with mechanism (see Fig. 2(a)) which transforms tip displacements into angular flapping motion for the wings (as described in Fig. 2(c)).

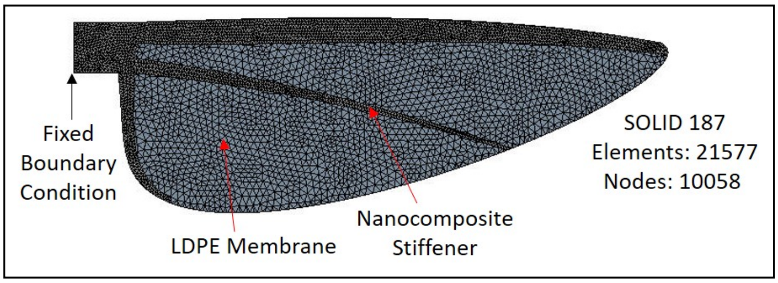
3. COMPUTATIONAL MODAL ANALYSIS

3.1 Flapping Wing

The computational modal analysis of the designed flapping wing is carried out using Modal Analysis Package in ANSYS Workbench 2020-R2. The meshing of the wing model is created using SOLID 187 elements (10-node 3D tetrahedral structural solid). The input values of the material properties, i.e., elastic modulus, Poisson's ratio and density for CNTs/PP nanocomposite stiffener are 1.31 GPa, 0.45 and 904 kg/m^3, respectively (Kumar et al., 2014; Kumar et al., 2019). Similarly, the values of elastic modulus, Poisson's ratio and density for LDPE membrane are 0.297 GPa, 0.45 and 920 kg/m^3, respectively (Kumar et al., 2019). The meshed wing with the applied boundary condition is shown in Fig. 3(a). The first four fundamental natural frequencies and the corresponding mode shapes are shown in Fig. 3(b). The mode shape for first mode is dominated by the bending deformations whereas other modes show coupled behavior. The characteristic frequency of first natural frequency at which the wing has highest amplitude deflections is observed at 19.65 Hz. The wings should be excited near this frequency to achieve higher aerodynamic efficiency.

3.2 Flapping Mechanism

The modal analysis of the designed flapping mechanism is also performed using Modal Analysis Package in ANSYS Workbench 2020-R2. Due to complexity and small flexure joints, the meshing is done carefully with large number of elements. Two types meshing elements are used that are SOLID186 (20-node 3D structural solid) and SOLID 187 (10-node 3D tetrahedral structural solid). Total number of nodes and elements used in meshing are 212714 and 121226, respectively. The mechanism with the description of materials and applied boundary conditions is shown in Fig. 4. The input values of the material properties for CNTs/PP nanocomposite stiffener are taken from Section 3.1. The input material properties for carbon fiber composite components are taken from ANSYS material library. The results are shown in Fig. 5. It can be seen that the values of natural frequencies are very high as compared to the first four natural frequencies of the designed wing and way beyond the beat rate of large size insects such as cicada and dragonfly (see Table 1). Hence, the mechanism would be transferring the desired motion efficiently.



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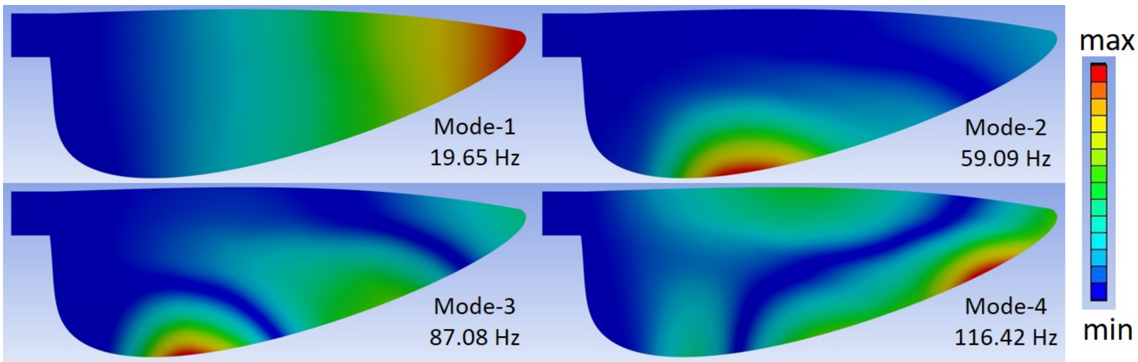
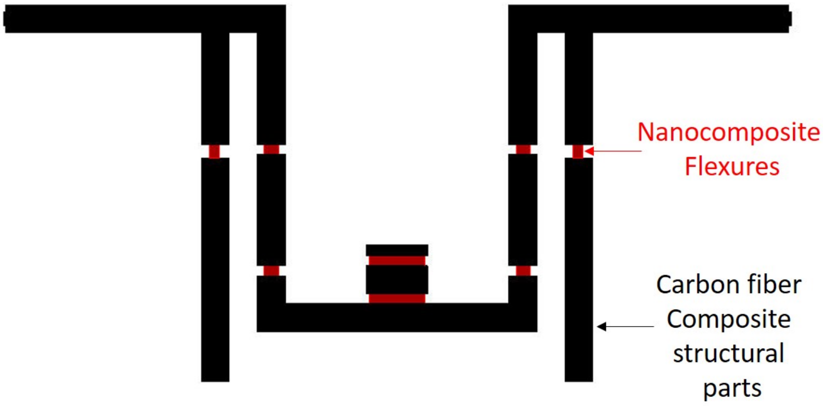


(b)

Fig. 3. (a) Mesh details and boundary conditions (b) Modal analysis results for the wing



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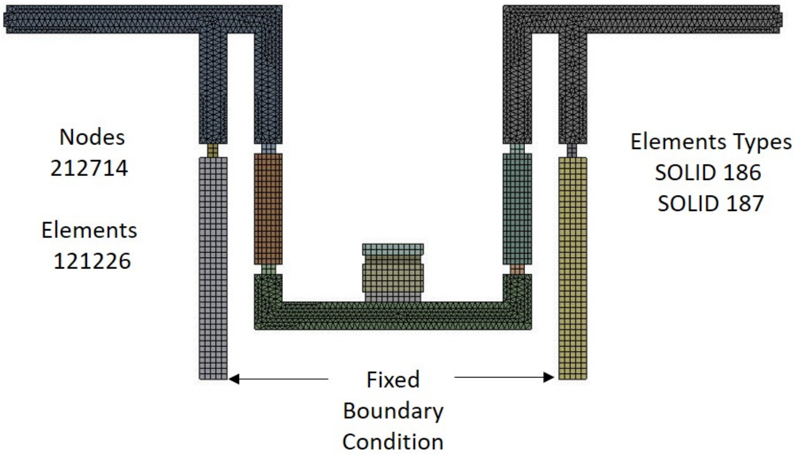


(b)

Fig. 4. Mechanism model used for modal analysis (a) mechanism components and corresponding materials (b) mesh details and boundary conditions

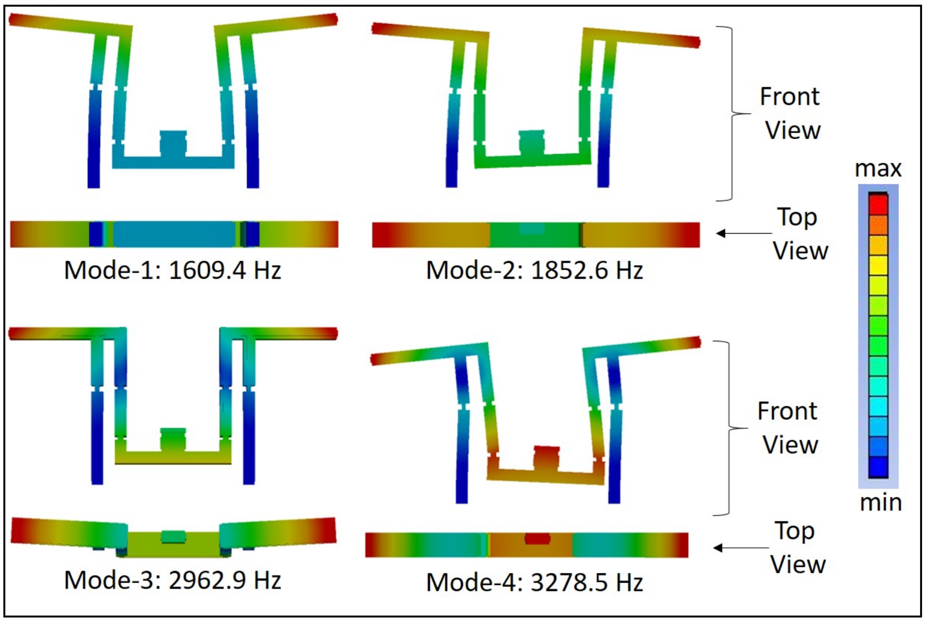


Fig. 5. Modal analysis results for flapping mechanism

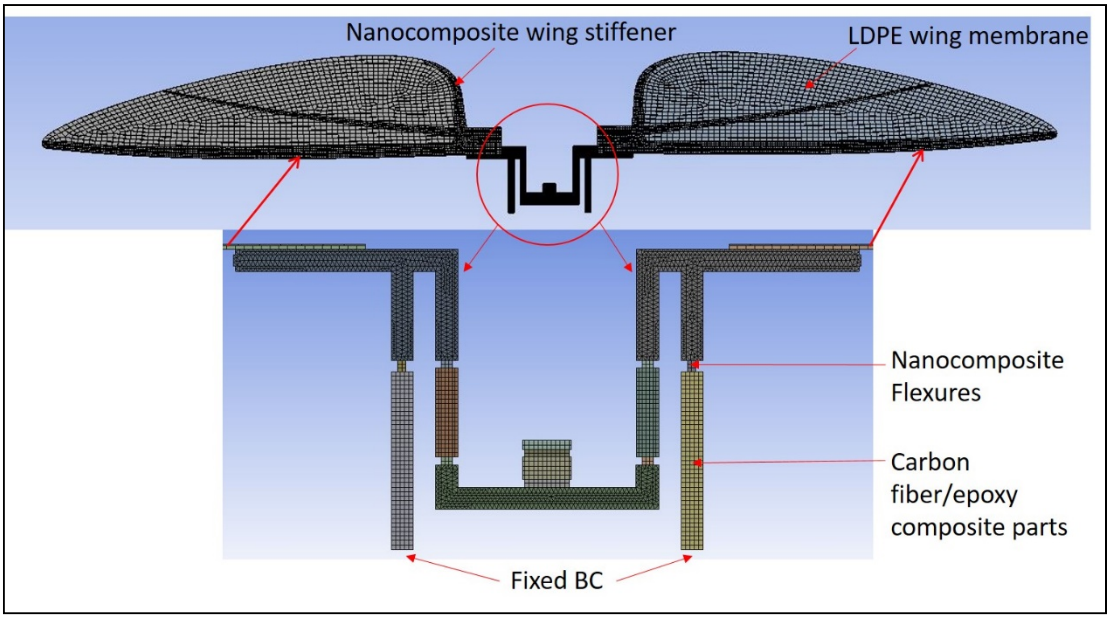


Fig. 6. The mechanism-wing design under structural dynamic analysis

3.3 Flapping Mechanism with Wings

The computational modal analysis of the mechanism with flapping wings is also done using the same commercial finite element method (Modal Analysis Package in ANSYS Workbench 2020-R2). The combined model is presented in Fig. 6. All the components and the corresponding materials are also described in this figure. The input values of the material properties for CNTs/PP nanocomposite stiffener as well as for the LDPE membrane are taken from Section 3.1. The input material properties for carbon fiber composite components are taken from ANSYS material library. The meshing of the model is done using SOLID 186 (Hex20: 20-nodes hexahedron) and SOLID 187 (10-node 3D tetrahedral structural solid) elements. Total number of nodes and elements used in meshing are 268830 and 128578, respectively.

In the present study, first four fundamental modes and the corresponding natural frequencies are obtained. They are presented in Fig. 7. It can be seen that all of these modes occurred on the wings, none of them on the mechanism. From the modal analysis of only mechanism (Section 3.2), the natural frequencies of the mechanism are very high as compared the wing-mechanism assembly. Hence, it can be said that the designed mechanism can transfer the motion to the wings accurately and efficiently. We have considered only the first natural frequency as the driving frequency, because there will be smaller amplitude deflections at higher modes and more power will be required at higher frequencies. Here, the first mode is of bending in nature with marginal twisting. A systematic modal analysis could be performed to optimize the wing designs to achieve desired bending-twisting deformations.

4. COMPUTATIONAL STRUCTURAL DYNAMIC ANALYSIS

A computational structural dynamic study of MAV model is performed to study motion transmission capability of the mechanism as well as investigate stresses and strains to ensure a safe design under extreme conditions (resonance excitation is an unconventional excitation method). Results of this study will be further used to optimize the model characteristics and flexural stiffness of joints. The analysis is carried out in Transient Structural Analysis Package of ANSYS Workbench 2020-R2. Mesh parameters and material properties are similar to the ones used in modal analysis of combined wing-mechanism assembly (Section 3.3). Combined wing-mechanism assembly (excluding chassis and substituting actuator with point load) is given excitation at mechanism where actuator tip will be attached (see Fig. 8). Sinusoidal excitation of 0.1 mm amplitude is applied at a frequency of 17.25 Hz, which is the first mode frequency obtained from the modal analysis (refer Fig. 7).

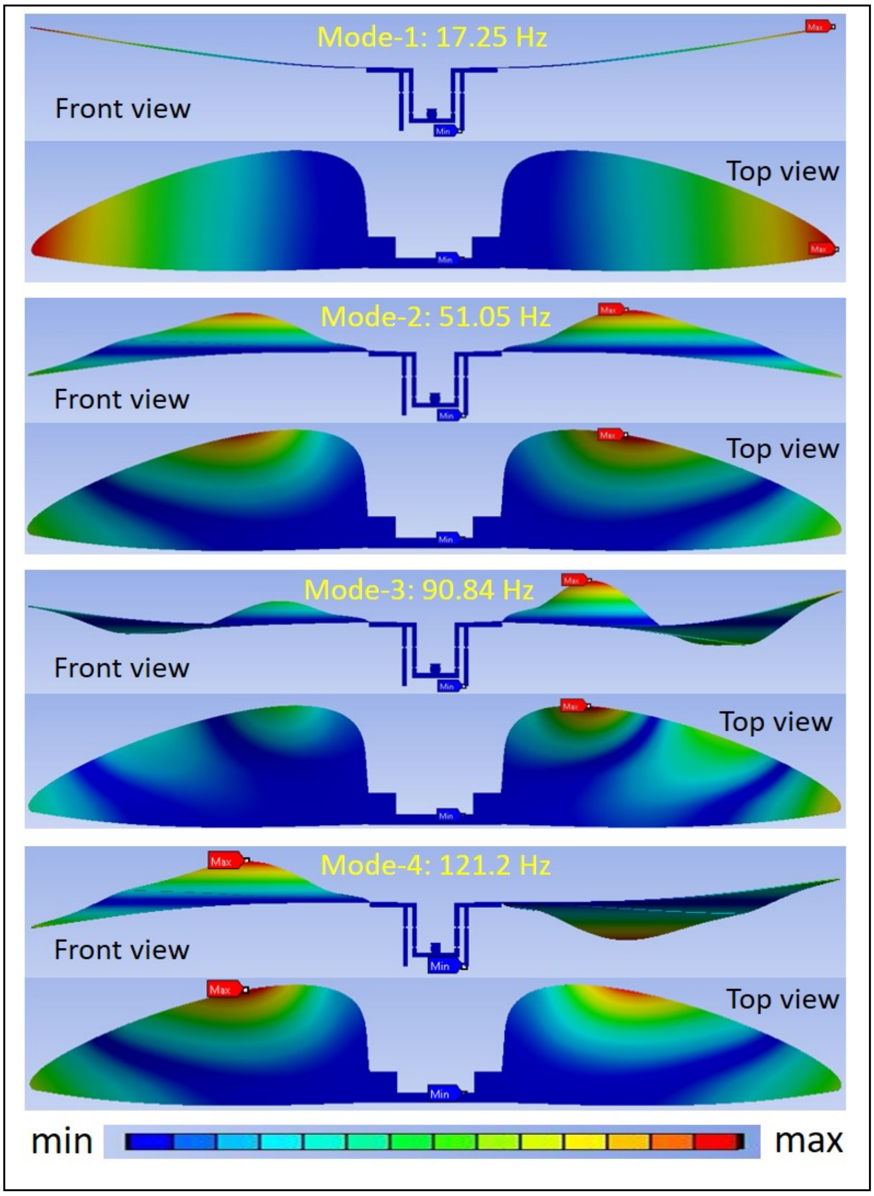


Fig. 7. Four fundamental modes for the combined wing-mechanism model

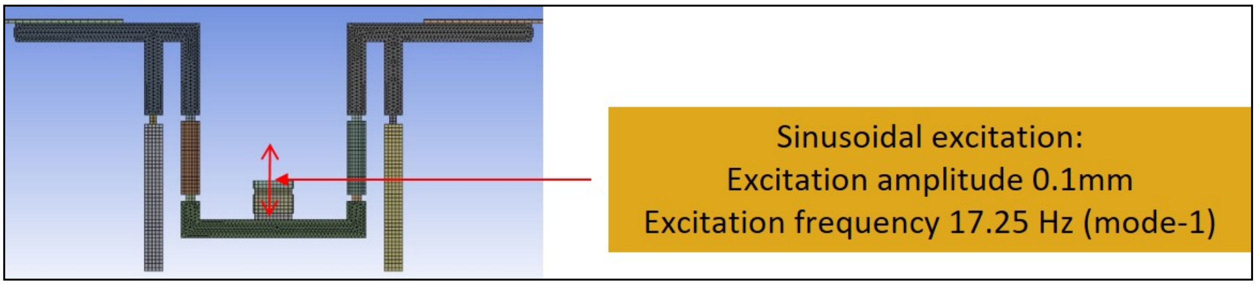
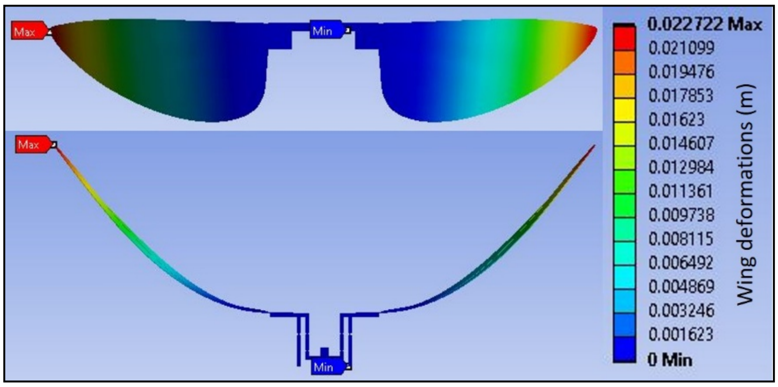


Fig. 8. Wing-mechanism design under resonance excitation

Results of this excitation could be seen in Fig. 9(a), it can be observed that wing-mechanism assembly is able to generate very high amplitude (22.72 mm) of flapping motion compared to small excitation (0.1 mm) provided at mechanism. This amplification of motion achieved with wing-mechanism assembly will generate large aerodynamic forces thus increasing energy efficiency. Further optimization of wing design tailored to generate bending-twisting deformation could benefit from this mechanism to generate both lift and thrust forces. The wing deformation behavior is dominated by bending deformations and less flapping-like feature which is in agreement with modal analysis for the first resonance mode (Section 3.1). This behavior can be attributed to wing joint stiffness, design and attachment to mechanism. Fixed attachment of wing with mechanism is also a reason for high strains observed at wing root (see Fig. 9(b)). Stiffeners of the wing are under high strains compared to wing membrane and other parts of assembly. This can also be attributed to fixed joint of wing root with mechanism with wing stiffener acting as a connecting element. These high strains of veins could be avoided by attaching wings with mechanism using a flexure joint, it will also ensure a flapping like motion as exists in nature. Further modification of wing attachment flexure to generate pitching motion will reproduce motions by natural flyers more closely together with introducing more variables to be optimized. Stress distribution can be observed in Fig. 9(c). Maximum stress can be observed at corner of rigid link and flexure joint interface. The flexure joint (CNTs/PP nanocomposite element) undergoes completely reversed bending. High stresses are developing at outermost surface with maximum at corner, while minimum stresses are developing in the central surface. It is under tension and compression during positive and negative parts of resonant excitation cycle. The rigid link made of carbon fibre and epoxy composite applies dynamic load on flexure element in between them.



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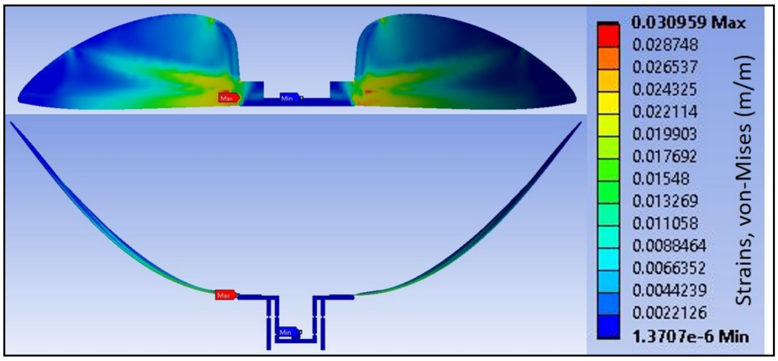

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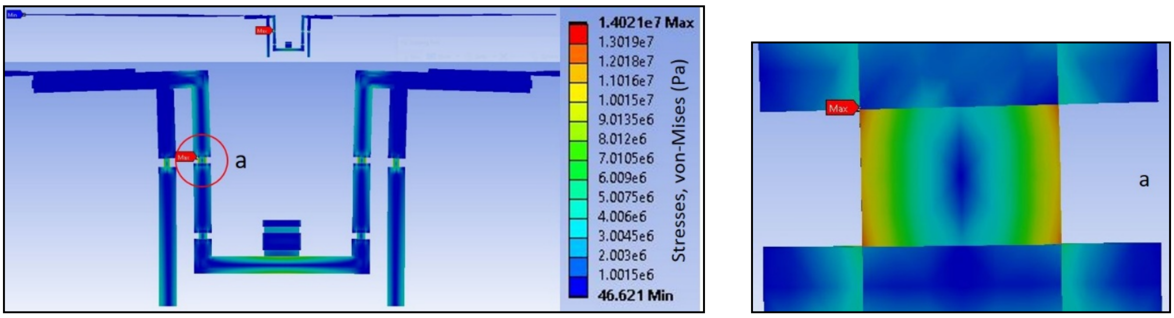

(c)

Fig. 9. Computational structural dynamic study results for combined wing-mechanism model (a) wing deflections (b) strains distribution (c) stress distribution

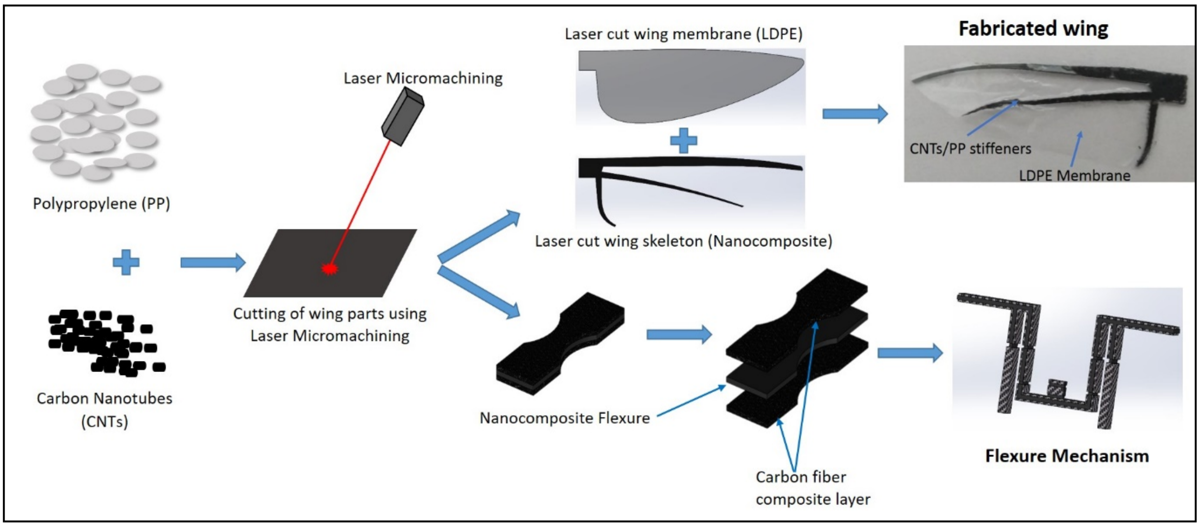

Fig. 10. Manufacturing process for wing and mechanism

5. DEVELOPMENT AND TESTING OF THE MAV MODEL

5.1 Fabrication of Flapping Wings and Compliant Mechanism

The wings of designed MAV are miniature in size and flexible in nature. Real wings of considered insects were idealized and traced to develop a 2D sketch of MAV wing. This wing sketch was then laser micro-machined on a CNTs/PP nanocomposite sheet of (~0.08 mm) thickness to generate veins. The laser-cut vein skeleton was later attached to the LDPE membrane of 0.014 mm thickness to develop the complete wing. Final wings are very light (26 milligram), thin (maximum thickness of 0.094 mm) and flexible (less resistance while bending and twisting modes). High accuracy and precision was achieved through laser micro-machining process. The wing and mechanism manufacturing is shown in Fig. 10.

Mechanism manufacturing process shown above is similar to wing manufacturing process. Started with laser micromachining of CNTs/PP nanocomposite sheet in rectangular shapes having two circular arcs at center (flexures). These flexures were sandwiched in between rectangular pieces of carbon fiber composite sheet leaving the circular arc portion of flexures. This structure shows compliance only in certain direction (bending) and approximately acts as a revolute joint. Pieces of carbon fiber composite sheet are rigid in nature and bonded with the CNTs/PP nanocomposite flexure using cyanoacrylate based adhesive. Pieces being small and thin were aligned and maneuvered with forceps manually at this stage of development. In future manufacturing and assembly process could be automated to reduce time and effort while attaining high precision and accuracy.

5.2 Complete MAV Construction and its Actuation System

After developing the subsystems, i.e., the wing and mechanism, they were assembled manually as shown in Fig. 11. Wings were bonded to the mechanism and mechanism was bonded to chassis at the anchor points through adhesive. Completed prototype had morphological characteristics similar to the inspirations i.e. dragonfly and cicada (see Table 1). The total mass, length of the body, and wingspan of the developed model are 0.61 g, 60.46 mm, and 90.14 mm, respectively. After analyzing several actuation methods generally used for micro-air vehicles, piezoelectric mode of actuation is selected in the present study. Several favorable characteristics were identified namely short response time, light weight, high energy density. Generally used in stack configuration but here they are used in cantilever configuration to achieve maximum tip deflection. BA series piezoelectric actuator from PIEZODRIVE company is used, it provides peak deflection of ±7 mm while operating at ±250 volts electric signal. Actuator excites the mechanism which converts the linear oscillation to angular which is transferred to wings. To provide this unique motion, corresponding electric signal is required which is generated through a customized power supply. This power supply subsystem is designed to provide high voltage (i.e. order of 100s of volt) with varying frequency and phase. A simple H-bridge using four MOSFET is made which could be controlled using a microcontroller at desired duty cycle. To isolate high power MOSFET bridge from low power microcontroller (Arduino) an optocoupler is used. Arduino IDE control program is developed to actuate piezoelectric actuator at a particular voltage, frequency and duty cycle.

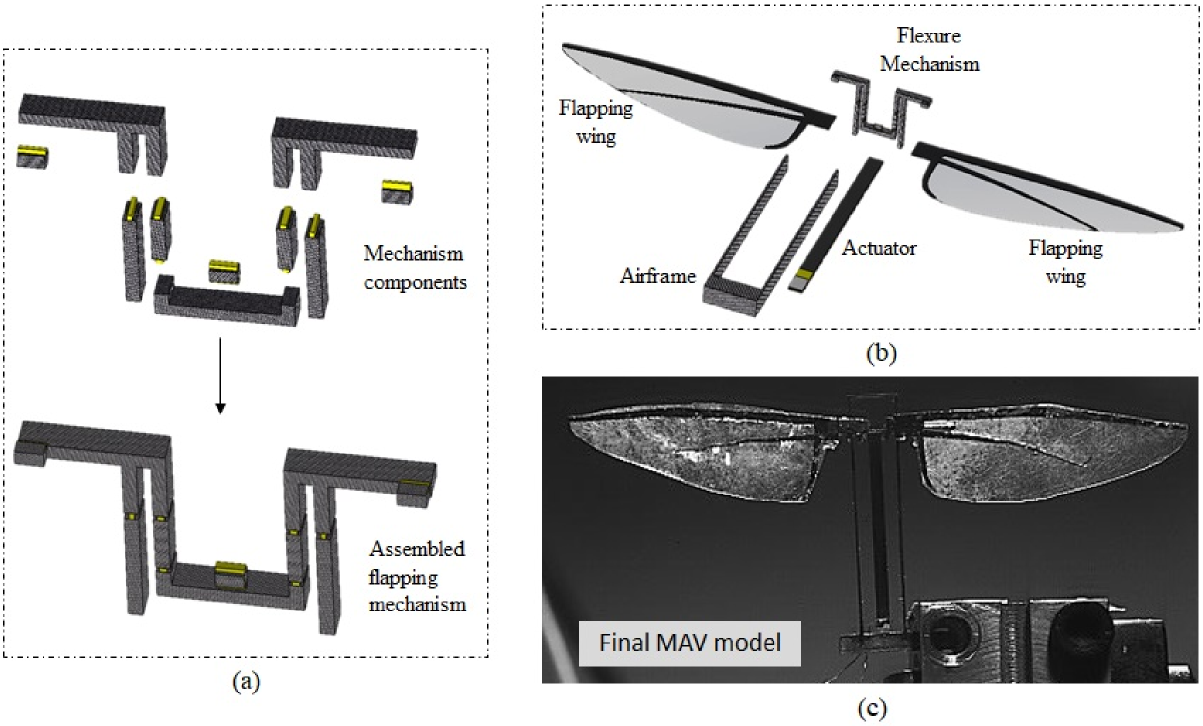

Fig. 11. Development process for the MAV model, (a) Assembly of the compliant mechanism (b) Assembly of the MAV model (c) Fabricated two-winged insect-inspired MAV model

5.3 Experimental Structural Dynamic Analysis

An in-house high-speed camera based 3D digital image correlation (DIC) non-contact technique, developed in other study (Kumar et al., 2019), is used to obtain the characteristic (resonance) frequency and the structural deformations of the wings. The complete setup, shown in Fig. 12, consists of two high-speed cameras, the tethered MAV model, a customized power supply and a motion signal generator. The cameras, the i-Speed TR models, were procured from Olympus, UK. These cameras were used to record images (at 1000fps) of the wings painted with black and white speckles (as shown in Fig. 12). The recorded images are correlated using an open source software known as DICe to obtain 3D displacements of the wings under the flapping motion driven by the mechanism. The wing deforming shapes are derived from the measured displacement data using ParaView. The characteristic frequency of the model is calculated by performing FFT of the time domain displacement data.

Fig. 13 presents the deforming shape of the wing at end of the upstroke. The displacements at the wing tip and trailing edge are higher as compared to the root and leading edge. However, tip displacements are significantly higher than other locations. Such deformation patterns attribute to the bending and marginal twisting. The maximum tip deflection, i.e. 22 mm, is close to that observed in computational study performed at resonance, see Fig. 9(a). The characteristic frequency of flapping of the developed model is 20 Hz. There were correlation errors observed due to wrinkling or curved edge of the wing membrane near tip. This is an artefact of the unsupported thin membrane at the trailing edge.

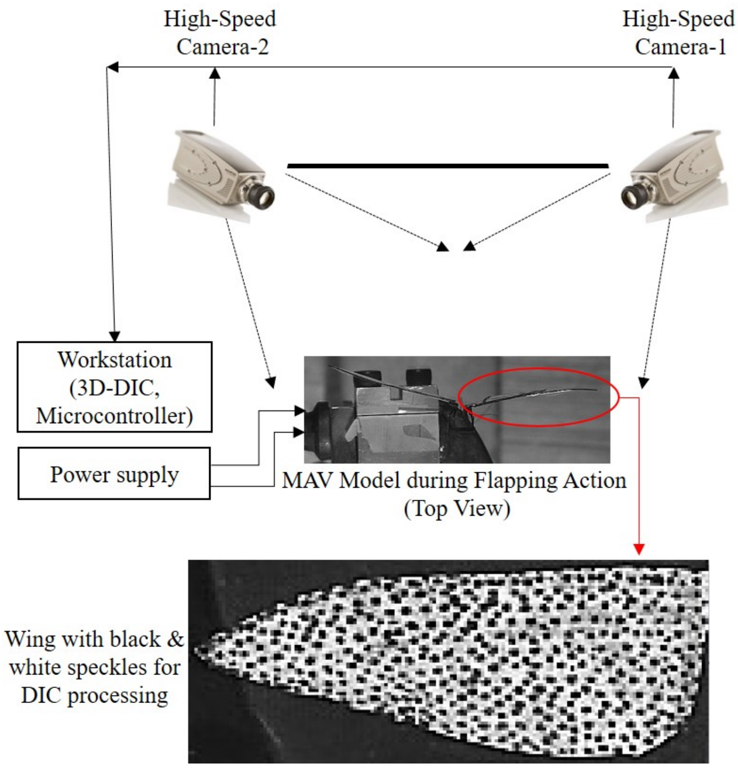

Fig. 12. In-house 3D-DIC setup for experimental structural dynamic testing of MAV wings

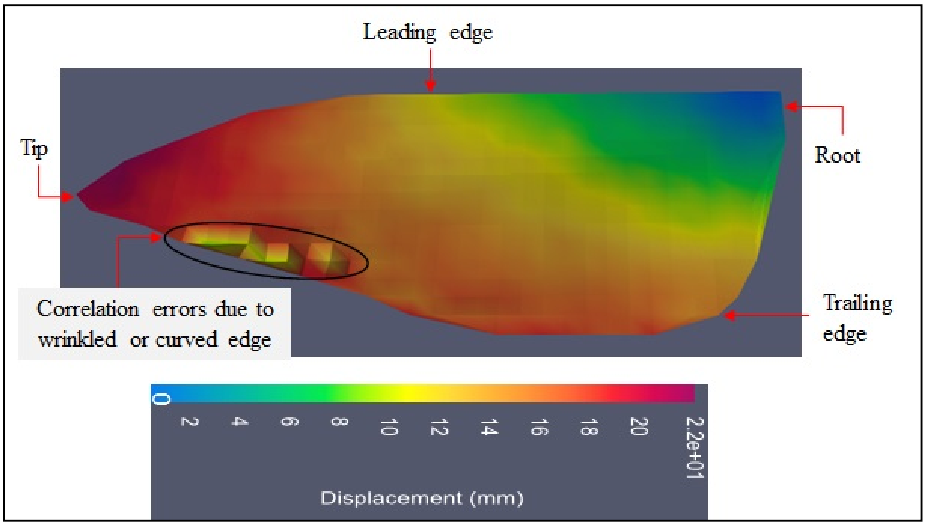

Fig. 13. Wing deforming shape measured using 3D-DIC, at the end of upstroke

We have also recorded the wing motions using high-speed camera viewing from the top. The recorded images are shown in Fig. 14. As shown in the figure, two different types of wings are attached to the model, one is actual designed wing with CNTs/PP nanocomposite stiffeners (left wing) and another a stiffer wing with carbon fiber composite stiffeners (right wing). Both of them have same skeleton designed in the present study. This experiment is carried out to observe the effect of flexibility on the deformation characteristics of the wings. It can be seen that the actual designed nanocomposite wing, i.e. flexible wing, is able to generate desired positive camber in both spanwise and chordwise directions. On the other hand, stiffer wings fail to generate the same. Further optimization of the wing designs could be performed to generate desired combination of bending and twisting deformations. Apart from that, modification in the flapping mechanism to achieve flapping as well as pitching motions would provide the wings with favorable kinematics. The MAV model with optimized aeroelastic wings and modified flapping-pitching mechanism will be able to produce natural wing deformations and kinematics such as positive camber,

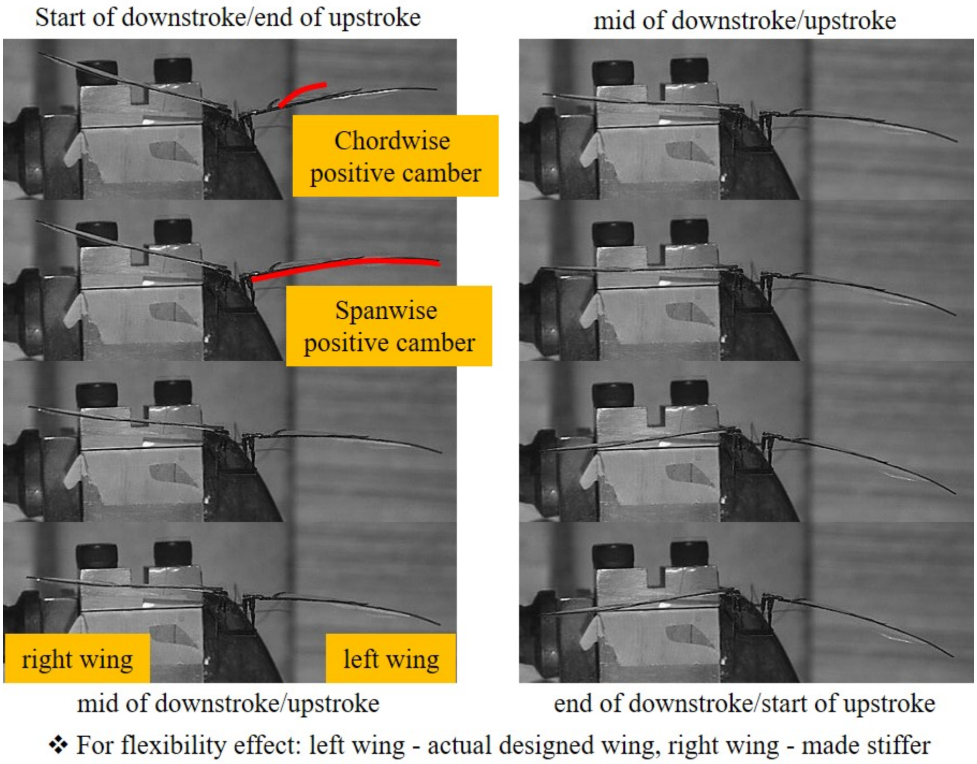

Fig. 14. Wing motion recorded using a high-speed camera at 1000fps. Left side of the image shows start to mid of the flapping stroke, Right side of the image shows mid to end of the flapping stroke

reverse camber and figure-8 motion - the flapping miracles explored and established by insects and hummingbirds (Warrick et al., 2005).

6. CONCLUSION

A bioinspired two-winged tethered MAV model is successfully designed, realized and studied using novel materials and methods. The design of flapping wings and mechanism are inspired by large size insects such as dragonfly and cicada. CNTs/PP nanocomposite material is used for the stiffeners in the flapping wing and flexure joints in the compliant flapping mechanism.

The designs of the wings and the mechanism are studied computationally for structural dynamic characteristics using commercial finite element methods. From computations, it was observed that no resonance has occurred at the mechanism, all first four modes occurred at the wings. This is advantageous for accurate and efficient motion transmission to the wings. The mechanism generates large deflections with small input excitation useful for enhancing aerodynamic efficiency.

After design and analysis of the wings and mechanism, they were successfully fabricated from lab developed CNTs/PP nanocomposite sheets using laser micromachining technique, along with carbon fiber/epoxy composite rigid elements for mechanism and LPDE film for wing membrane. Final two-winged MAV model was developed by assembling wings and mechanism with a composite chassis. The morphological and other characteristics of the MAV model are closely matching with the considered natural counterparts, i.e., dragonfly and cicada. The total mass, body length, and wingspan of the developed MAV model are 0.61 g, 60.46 mm, and 90.14 mm, respectively. An external customized power supply was developed and used with a microcontroller to actuate the flapping mechanism and wings during experiments. Experimental structural dynamic study of the wings is carried out using an in-house high-speed 3D-DIC technique. The characteristic frequency of two-winged MAV model is 20 Hz. The simplified insect-inspired wing has bending dominated wing motion with marginal twisting and positive camber during downstroke.

The structural dynamic results from computations match with the experiments that validates both of the approaches for further advancements in the developed MAV model. The outcome of the current work is a successful biomimetic MAV design, a potential candidate for developing mechanically efficient MAV models that can generate desired aerodynamic forces.

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