[Invited] Design, Fabrication and Dynamic Testing of Insect-Inspired Nano Air Vehicles

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Abstract—**When developing a flying robot on the insect scale, all process must be developed from scratch as usual macroscale solutions for the design and fabrication would not satisfy the extreme mass and power limitations. In this context, the aims of this work are to outline the proposed bioinspired approach and to present the different original concepts deployed to tackle such an issue, before analyzing carefully the simulated and experimental results. More precisely, the presented nano air vehicle is inspired from the diptera order and consists of two pairs of wings micromachined using MicroElectroMechanical Systems technologies and an electromagnetic actuator added to the thorax to control the kinematics of the wings. The prototypes weigh as little as 22 mg with a 25 mm wingspan and 15 mm length and demonstrate a lift force equivalent to their weight.**

***Keywords*—nano aerial vehicles, bioinspired design, microsystem modeling, microsystem manufacturing, vibrating wing.**

I. Introduction

Since a few years, there is a growing interest for small-scale aerial vehicles as they extend the range of UAV's applications in military and civil fields. Major efforts have already been made to develop miniaturized structures for propulsion and navigation systems, flight controllers, on-board electronics and payloads, etc. which explains why Micro air vehicles (MAV) now benefit from the latest technologies and have great maneuverability, portability and propulsion efficiency. This situation is the reflection of abundant scientific research, which is crystallized in particular in dedicated international scientific congresses as for example the International Micro Air Vehicles conferences and competitions (IMAV), during which an international Micro Air Vehicle's competition is systematically held each year [1].

In 2005, the DARPA pushed the limits of aerial robotics by announcing the 'Nano Air Vehicle' (NAV) program [2], which had the requirements of 10 g or less vehicles with 7.5 cm maximum dimension, able to fly 1 km or more. Such kind of new aerial vehicle must also be able to enter buildings, penetrate narrow entrances and transmit data without being detected. Whether in terms of stealth, portability or multiplicity, millimeter-scale systems considerably broaden the scope of applications for more traditional unmanned aerial vehicles, and hovering appears ideal for operating in confined environments. It therefore seems well suited for indoor reconnaissance missions with both military and civilian requirements.

However, NAVs could not be simply smaller versions of full-size MAVs because of extreme mass and specific power requirements at low speeds. They are therefore related to many scientific and technological challenges to be solved before they can become operational for indoor flight. When scaling down, a potential solution is to draw inspiration from nature and especially from the flying insect's species to design and fabricate such NAVs. Flying insects have some amazing characteristics: they can hover, they are highly agile and manoeuvrable, and they can operate in swarms while remaining visually unobtrusive and low noise level.

When surveying the state of the art of flapping wing NAV's, prototypes below 7.5 cm are rare and only four of them, the "RoboBee"[3], the "Flapping wing Robot"[4], the "Robotfly" [5] and the "Robot driven by soft artificial muscles" [6] are currently capable of flying while powered by an external source. These flapping wing NAVs have been fabricated from carbon fiber and thin film laminates. They have a wingspan around 30 mm and weigh under 200 mg. They rely on an articulated drive mechanism and a piezoelectric actuator or an electromagnetic actuator or a dielectric elastomer to enable wing flapping. Given state of art commercial microbatteries [7], their flight time would be 5 to 10 minutes if it was possible to lift the battery, which is unfortunately not the case now.

This paper describes the design, fabrication and dynamic testing of a 25 mm wingspan and 22 mg NAV based upon the morphology of insects of the order Diptera. More precisely, the overall goal is to present the last progresses on the creation of a vibrating-wing NAV that has a maximal lift-to-weight ratio while showing how the bioinspiration has influenced both its design and its fabrication. When designing this kind of NAV, the main challenge is to integrate into the body one or more actuators of sufficient energy density to create kinematics similar to those of insect wings. The latter must generate a lifting force greater than the NAV's weight to enable it to take off. Once this stage would be completed, the remaining work will consist in the search for bio-inspired solutions to achieve performance in terms of communication and orientation in space close to that of social insects. Notice here that little attention is given here to issues such as controllability or powering: this work is purely a stepping-stone on the path toward autonomous flying robotic insects.

II. Design of the Insect-inspired Nano Air Vehicle

A. Actuation and thorax kinematics

Direct action of flight muscles on the wing base (Fig. 1a) is phylogenetically ancestral and is mainly found on odonata and blattaria species [8]. In addition to their role in the downstroke, direct flight muscles also influence wing orientations and allow the flight control. This type of behavior is perfectly suited to low-frequency wing movements.

However, what is quite amazing is that the wings of some flying insects beat at very high cadences: up to kilohertz for example in ceratopogonids. In this case, the wing movement is the consequence of the action of powerful muscles located in the thorax. The impulses sent to the muscles may be at lower frequencies than those of the wings, due to the use of a sustained resonant mode, but the fact remains that these muscles operate at much higher speeds than in other animals.

When observing Diptera species, we notice that these insects use such a comparable behavior since they elevate their wing using indirect flight muscles (Fig. 1b) attached to the exoskeleton dorsally and a deformable section of the exoskeleton call the scutum ventrally. More precisely, the thorax behaves as a damped structure where the wing joints have the function to transmit large strain amplitude from the musculature to the wings while the scutum via indirect actuation stores and recovers elastic energy. Note however that these indirect flight muscles that effect scutum bending and thoracic deformation are physiologically and mechanically distinct from the additional small wing direct muscles (Basalar and Subular) attached at the wing base and used to control the orientation and other kinematic characteristics of the wings.

Although the concise mechanisms involved in Diptera thoracic mechanics have been the source of a lot of discussion, the wing drive system has a few obvious features. First, the presence of elastic recoil within the thorax and antagonistic action between wing depressors and elevators suggests that the thorax contributes to the resonance of all the aeromechanical system. Second, insects use such a mechanical advantage to amplify their wing stroke. Finally, note that some aspects of Diptera wing trajectories are mechanically encoded in their morphologies, while others are adjustable using small direct muscles.

Starting from these initial observations, we proposed to use an indirect actuation scheme based on an electromagnetic actuator and to develop a thorax design with a concise transmission for the nano air vehicle [9]. The electromagnetic actuator choice is motivated by its many advantages: simple operation and design, fast response, wide bandwidth and of course the possibility of miniaturizing and integrating it into the manufacturing process. Similar to the insect model shown in Fig. 1b, the proposed transmission (Fig. 1c) amplifies the actuator motion from a translational input to a rotational output through a sort of point curve joint.

B. Wings dynamic and aeromechanism

The kinematics of insect flight are now very well documented thanks to the work of numerous biologists [10, 11]. Wing flapping corresponds to a periodic motion frequency varying between 5 and 200 Hz [12], depending in particular on the insect's mass and wingspan. As shown on Fig. 2, the kinematics described by the wing cross section in the chord direction [13] is composed of a flapping motion, corresponding to a change of stroke angle θ, whereas supination and pronation result in a twisting motion, i.e. a change in angle of attack ϕ, in quadrature phase shift with the previous one.

This phase quadrature, i.e., when the amplitude is maximal for one motion it is null for the other, is a key element to produce lift although various other aerodynamic mechanisms come into play. Indeed, high-incidence translational phases are usually characterized by the presence of a significant leading-edge vortex without aerodynamic wing stall, whereas rotational movement are characterized by both, added mass, with the air around the wing braking and pushing it, and rotational force (Kramer effect) generated by the combined translational and rotational movement of the wing in an attempt to re-establish normal flow at the wing's trailing edge. In addition, there are

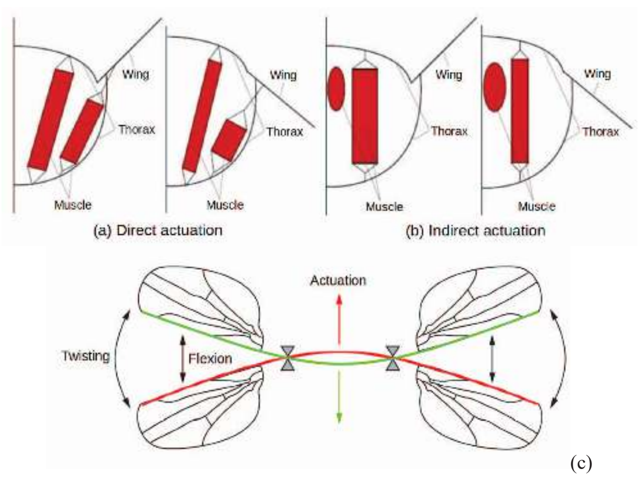

Fig. 1. (a) Diptera direct actuation, (b) Diptera indirect actuation, (c) Electromagnetic indirect actuation.

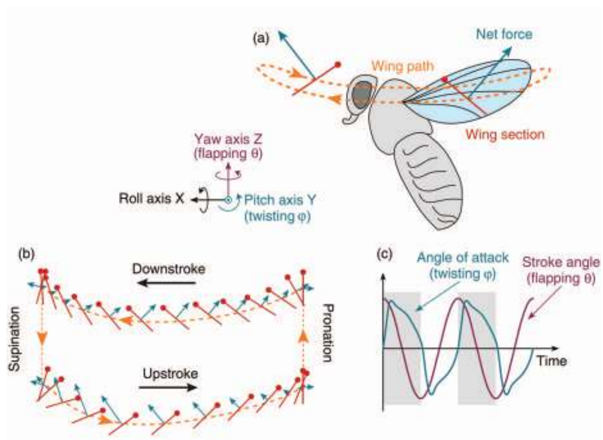

Fig. 2. (a) Schematic of the insect motion, (b) Tracking of the wing chord session during translation motion (Upstroke and Downstroke) and rotation motion (pronation and supination), (c) Evolution of stroke angle and angle of attack in quadrature phase mode.

other phenomena such as the delay in establishing lift (Wagner effect) and wake capture. It should be also noted that the forward and backward flapping phases offer maximum speed with minimum angle of attack, and generate consistent, stable lift whereas the pronation and supination phases generate more lift, but in a much more punctual manner [14, 15].

From these observations, it is therefore obvious that it is essential for producing lift to reproduce the complex kinematic of the insect and in particular to maximize the amplitude of the flapping forward and backward flapping phases while maintaining a quadrature phase between the flapping and twisting motion.

Rather than to add wing's orientation control muscles, the original concept chosen for the design of the NAV was to use the resonant properties of the wing structure in order to combine the motion of two vibration modes, a flapping and a twisting mode, in a vibration modes phase shift. One way of achieve this particular combination was to optimize the geometry and elastic characteristics of the flexible structure such that the two modes are successive in the eigenspectrum and close in frequency. For such a purpose, a semi-analytical model, based on assembled Euler-Bernoulli beams (Fig. 3), was developed to understand, compute and optimize the artificial wing dynamic vibrations [16, 17]. This model served to show that it was possible to obtain several artificial wing structures with a flapping and a twisting mode close in frequency.

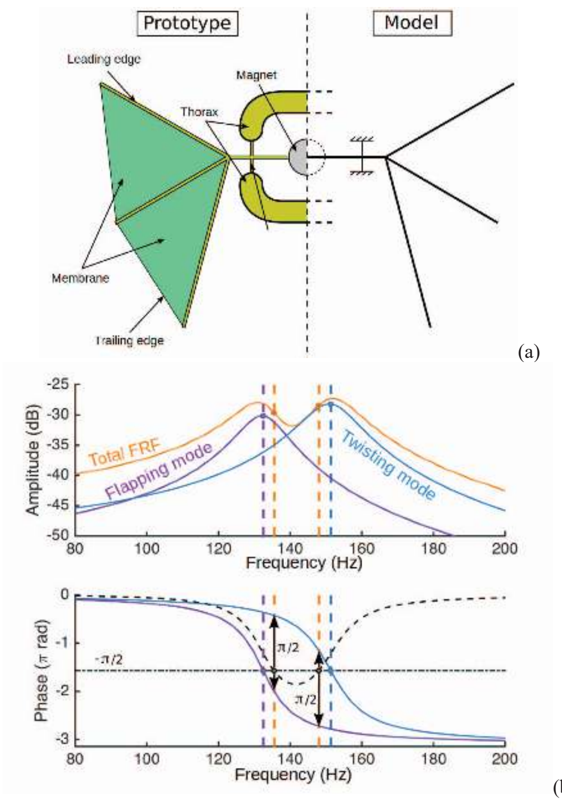

Fig. 3. (a) Prototype design and modeling, (b) Simulated Frequency response functions.

III. Fabrication

A. Material and technology selection

As insect wings consist of a complex geometry with supporting veins and very thin flexible membranes, it was also essential to find a technology able to realize microstructures with a high precision, a good reproducibility and with the adapted materials. To answer this problem, the novelty was to use the standard technologies developed for MicroElectroMechanical Systems (MEMS) [18, 19]. Such a technology not only allows selecting appropriate materials for the artificial wings but also paves the way to a future fully integrated micro device in the thorax, i.e. including a microcontroller, sensors and a micro battery.

The first solution explored was to opt for an etched silicon structure, but this was soon discarded in favor of other materials. Although silicon has the advantage of being widely used in micro-fabrication and compatible with the implementation of electronic functions, its flexibility is not sufficient to allow deformation to achieve the desired wing amplitudes without the need for articulated systems.

In order to select the material, their mechanical behavior was compared to that observed on insect wings, depending on whether the material was used for veins or membranes [20]. The choice fell on a new type of material, the photosensitive polymer resin SU-8, because this family of polymer resins offers mechanical characteristics similar to those found in insect wing skeletons. To illustrate this point, Fig. 4a shows the various mechanical properties of SU-8 polymer and compares them with those of insect wing veins. It can be seen

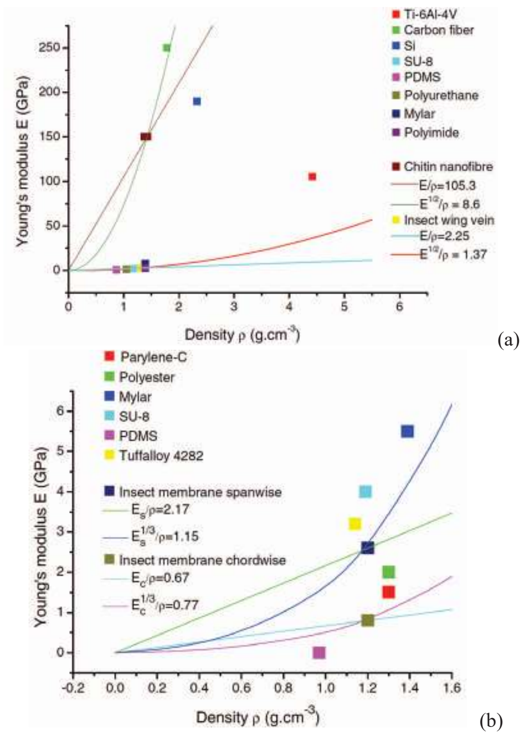

Fig. 4. Comparison of the mechanical performance of different materials with those found in insects for vein operation (a) and membrane operation (b).

that a number of polymers (SU-8, PDMS, polyimide) share a similar flexural behavior to that of insect veins. For ease of manufacture and use, the SU-8 resin was selected as it is readily available and widely used in the manufacture of microsystems.

Once this had been achieved, the next step was to find a suitable material for the wing membrane. In keeping with a bio-inspired approach, Fig. 4.b shows the stiffness characteristics of the different materials considered for its construction, and compares them with those observed in insects. It can be seen that the stiffness of an insect wing differs according to direction. In fact, in the axis of the leading edge ("spanwise" longitudinal stiffness), stiffness is greater than along the chord ("chordwise" transverse stiffness).

Based on this information, it appears that a criterion based on the longitudinal stiffness of the membrane, i.e. the ratio between Young's modulus along the leading edge and density, converges on materials such as Mylar, SU-8 and Tuffalloy 4282. On the other hand, when it comes to the transverse stiffness of the membrane, i.e. the ratio between Young's modulus along the chord and density, PDMS, Parylene C and Polyester appear to be potential candidates. Among the limiting factors, it should be noted that the deposition methods for PDMS and Polyester do not permit thicknesses of less than ten micrometers. For all these reasons, and in order to ensure a high degree of torsional flexibility for the artificial wing, we decided to give priority to the criterion of transverse stiffness. Therefore our choice was to use the Parylene C to fabricate the membrane.

B. Fabrication steps

Prototype production takes place in two stages: the first stage, carried out in a clean room, is the photolithography of the prototype skeleton, consisting of the body and the support. The body comprises a mobile part, the wings and tergum, and a rigid part, the thorax. The second stage consists of assembling the actuator onto the prototype, a delicate phase in the manufacturing process.

As shown in Fig. 5a, the manufacturing process for the prototype SU-8 structure, comprising the skeleton of the wings, the thorax and the links connecting them, is split into eight stages themselves divided into four categories: deposition of a sacrificial layer, deposition of resins, insulations and resin development. The resin deposition and insulation stages are also accompanied by an annealing step to remove the solvent present in the resin in the first case, and to initiate the cross-linking process of the exposed areas in the second.

The manufacturing process involves the use of three layers of SU-8 2075 resin to produce the prototype structure, each corresponding to a different geometry and thickness. The first layer produces the thinnest elements which are the links, while laying the foundations for the prototype's entire structure. The second layer completes the skeleton of the wings, while the third layer helps thicken the thorax. Note also that the resin thicknesses to be developed here vary from 40 m to 300 m.

With the prototype structure in place, we can now move on to the process of manufacturing the wing membranes (Fig. 5b). This consists of four phases: deposition of Parylene C, installation of an etching mask, etching and final "lift-off". The material chosen for the membranes is Parylene C. It is deposited by evaporation, using a Comelec C20S deposition machine, producing a film thickness of less than one micrometer.

The coil support is manufactured using the same type of photolithography process as that described in Fig. 5a for the prototype structure. It is composed of two layers of SU-8 2075 resin, the first 150 m thick, and 215 m for the second. As illustrated in Fig. 6.a, the first layer forms the support body, while the second is used to integrate two centering semi-circles to facilitate coil positioning. Following the structure manufacturing process, a sacrificial layer of Omnicoat resin precedes those of the SU-8 resin layers, and the developed parts are then recovered via a liftoff in a bath of MF319 to solubilize the sacrificial layer. Once released from the substrate, the coil carriers are rinsed with alcohol and dried with nitrogen.

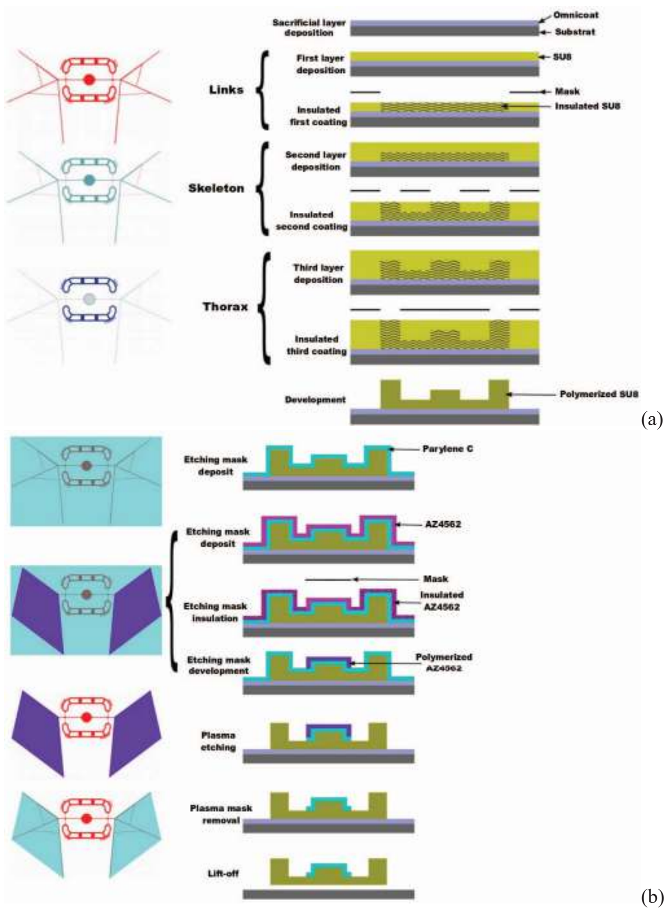

Fig. 5. (a) Diagram of the 8 stages of the photolithography process used to manufacture the prototype structure (links, wing skeleton and thorax), (b) Schematic diagram of the process used to deposit and etch Parylene C membranes.

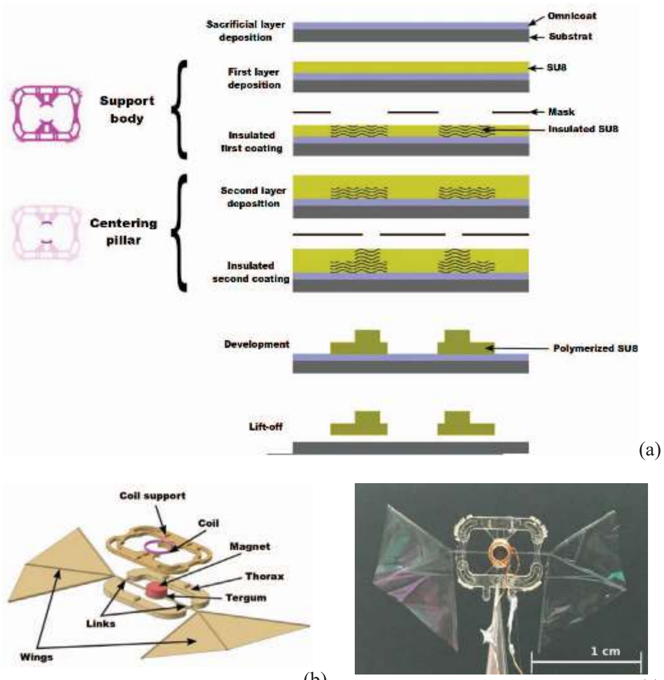

Fig. 6. (a) Diagram of the photolithography process used to manufacture the OVMI nano-drone coil carrier, (b) Exploded-view diagram of the various components of a prototype, (c) Prototype OVMI nano-drone with 25 mm wingspan and total weight of 22 mg.

All that remains is to assemble the prototype (Fig. 6b and Fig. 6c). To this end, water-soluble glue (composed of water and polyvinyl acetate) is applied to the centering studs to bond the coil support, coil and magnet. The choice of this type of glue is motivated by its rapid drying (a few tens of seconds) and relative flexibility. Finally, the two coil feed wires are tin-soldered to smaller diameter wires connected to the power source.

IV. Dynamic Testing

A. Experimental setup

In order to limit the number of manipulations required on a prototype, a single measurement bench [16] has been developed for all experiments. A Polytec PSV400 scanning laser vibrometer is used to measure wing kinematics whereas the prototype is glued to a thin brass beam in order to correlate the cantilever displacement with the aerodynamic forces.

More precisely, the lift force is obtained by measuring the displacement of the cantilever using a laser (LK-G32 Keyence) while the prototype's wings are actuated. After calibration of this laser, the resolution obtained in terms of displacements is of the order of 0.1 µm, so that a minimum force of around 18 µN can be measured.

Concerning the wing kinematics, the Polytec PSV400 laser vibrometer features a scanning system that directs the laser beam and automatically measures the vibration velocity of the structure at various points. As a result, it is possible to reconstruct the operational deformations of the prototype's wings according to the excitation frequency. It should be also noted that the frequency spectrum of the velocity signal is divided by that of the electrical input current to the coil to obtain the frequency response function (FRF) of the corresponding point.

B. Results

The experimental set-up described previously has been used to test the performance of a batch of 8 prototypes (Fig. 6c) which all have the same qualitative and quantitative behavior. The quantitative results experimental results shown in Fig. 7 are those of one of the prototypes.

Fig. 7a illustrates first the experimental deformed shapes measured at frequency resonances of 140 Hz and 195 Hz and that correspond to the flapping and twisting modes respectively. Using the experimental test bench, it was also possible to draw simultaneously the Function Response Frequency (Fig. 7b) and the lift force (Fig. 7 c) curves. Results show that two local maxima of the averaged lift force are observed near the flapping and twisting modes at 133.5Hz and 190.8Hz, respectively. At these maximum lift frequencies, high-speed camera measurements have been performed and confirmed a kinematics of the flexible wings with flapping and twisting motions in phase quadrature as expected. Finally, it could be noted that the lift force reaches 240 µN at the high-frequency maxima, near the twisting mode. This is clearly a value sufficient to overcome the prototype weight, equivalent to 220 µN.

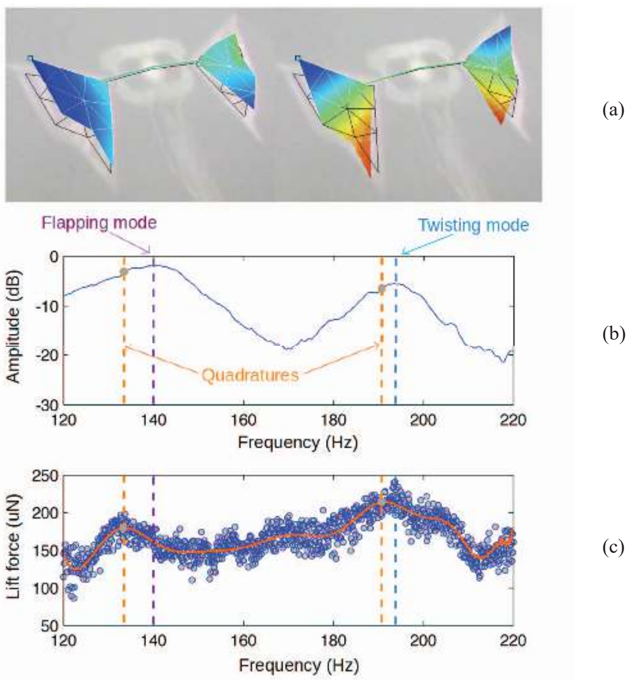

Fig. 7. a) Experimental deflection shapes at resonance: flapping mode and twisting mode respectively, (b) FRF of the prototype taken at the leading edge left wing extremity, zoomed over the frequency range of interest. (c) Average lift force over one period for several excitation frequencies with a polynomial curve fit.

V. Concluding Remarks

In this paper, a new methodology to design and fabricate a nano aerial vehicle has been proposed. At that scale, it is no longer possible to use traditional techniques. Consequently, the choice of the materials and of the wings actuations and motions are directly inspired by those of small flying insects. More precisely, the approach developed is based on two major innovations. First microfabrication techniques are used to produce a fully flexible polymer structure with the veins of the wings in SU-8 and the membrane in Parylene whereas at the same time a lift-generating mechanism based on the combination of two modes of vibration, bending and twisting, excited in phase quadrature by a point harmonic forcing is proposed. Results show that the particular wing trajectory thus created reproduces well the movement of a dipteran wing and generates lift. In addition, this prototype is a priori the first insect-sized one capable of creating lift without any articulation.

Future goals are, on the one hand, to produce sufficient lift for flight, and on the other, to design and implement the electronic functionalities required for remote control. Work is currently in progress first to better understand the aeroelastic phenomena and to optimize the structure [21] and second, to perform analyses on power generation and navigation control [22].

Acknowledgment

The authors thank the ANR ASTRID financing the work through the project ANR-19- ASTR-0023-01 as well as the French national nanofabrication network called Renatech and the Region Hauts-de-France.

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