Conception of resonant wings on an insect-scale

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The overall goal of this work is to create a biomimetic flapping wings micro air vehicle (MAV) based on microsystems technologies as they provide varied technologies under control to carry out structures conform to the insect ones. With this ultimate goal in mind, we fabricate and test prototypes and develop an aeroelastic model. This paper illustrates the approach and the reasoning done to lead our project. It is expected with aerodynamic and structural optimization to get an airborne MAV.

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Nomenclature

A	Amplification factor $[-]$
c	Wing chord $[m]$
E	Young modulus $[Pa]$
I	Bending moment of inertia $[m^4]$
k	Stiffness of the beam $[Nm^{-1}]$
k_b	Column effective length factor $[-]$
l	Length of a cantilever beam $[m]$
m	Mass of the beam $[kg]$
Re	Reynolds number $[-]$
t	Thickness of a cantilever beam $[m]$
V	Deformation velocity $[m.s^{-1}]$ of the wing
w	Width of a cantilever beam $[m]$

Symbols

α	Mass matrix Rayleigh damping coefficient $[-]$
β	Stiffness matrix Rayleigh damping coefficient $[-]$
Δz	Deflection at the beam end $[m]$
$\Delta\xi$	Amplitude of the shaker $[m]$
ν	Kinematic viscosity $[m^2.s^{-1}]$
ν	Poisson ratio $[-]$
ρ	Density $[kg.m^{-3}]$
σ	Stress $[Pa]$
ζ	Structural damping factor $[-]$
ζ_{aero}	Fictious aerodynamic damping coefficient $[-]$

Introduction

Researches on Micro-robots are in great progress since few years and some teams are currently involved in the fabrication of millimeter scale prototypes. To continue to go down in scale and to approach sizes of the mosquitoes, the Micro-Electro-Mechanical Systems (MEMS) technologies seem to be mandatory as the

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increasing progress in silicon and polymer micromachining have enabled the development of complex and reliable microstructures in microsytem and microfluidic. This experience combined with the knowledge of active and passive materials allows the feasibility of reproducing some biological structures such as flying insect on a scale one to be investigated. The field of the microsystems provides varied technologies under control to carry out structures conform to the insect ones and to enable repeatability, size control, and weight minimization.

The overall goal of this work is to create a flapping-wing MAV micromachined by the use of microsystems. The idea is to get a tiny resonant system, at an insect-like flapping frequency, without articulation and with passive torsion to imitate the insect flight kinematics. This choice allows first the number of actuators to be decreased and second the future control laws to be facilitated. These solutions may minimize the instantaneous and mean supplied power. The frequency of the vibrations of some insects wings are not the resonance frequency, or at least the first eigenfrequency. In any case for small flying robot, it is expected to have the larger amplitudes vibrations with the minimum supplied energy at the resonance. These solutions are at our knowledge only touched by the biologists but not studied for the lift of flapping wing systems.

This paper proposes to explain the approach as well as the methodology, our team developed to define precisely our MAV-concept called OVMI (the french abbreviation for Flying Object Imitating Insect) towards a future flying biomimetic MAV. First, the complete actuation concepts and design will be introduced to apprehend the specificities and advantages of our approach by defining a TWT-(Tergum-Wing-Thorax) structure. With the concepts defined, the next logical step is to validate them. Therefore a material has to be chosen and fabrication processes and methods have to be developed. The validation will be here handled step by step from simple structure toward complete TWT-structure. Afterwards in order to get an airborne OVMI, the aeroelastic phenomena in insect fly have to be introduced to correctly shape the wings-geometry as for hovering fly the wings have to generate his own velocities to arise the aerodynamic forces. It means in particular to introduce the structural damping and the aerodynamic damping in a preliminary approach with a quasi-analytical model based on a mass-spring differential equation. Finally to quantify the aerodynamic performance of our prototypes and to validate further the aeroelastic modeling, a measuring bench is mandatory. A concept and its sizing is here presented in order to measure the lift and the drag of our prototypes.

I. Actuation concept

Motivation of our project is to be biomimetic in many aspects as possible. The energy efficiency is a major concern in our application as the payload is limited due to the expected lift capacity of the insect. Therefore an efficient actuation concept has to be defined with this particular concern in mind, by getting inspired by the insect actuation.

I.A. Insect Actuation

The insect wings are not an articulated system with muscles as the bird wings. As shown in figure 1 , the insect tergum is actuated by muscles (dorsoventral and dorsal longitudinal) to generate wing 'upstroke' and 'downstroke'.

For insects such as flies, bees, wasps and beetles, indirect muscles are coupled to a thorax structure, which is tuned to actuate at an optimal quasi-constant flapping frequency[2–4] . Insect wings are described as largely passive structures, in which muscular forces transmitted by the wing base interact with aerodynamic and inertial forces generated by the wing's motions. The architecture of the wing (vein arrangement, three-dimensional relief, flexion lines, etc) and the material properties of its elements determine how the wing will change shape in response to these forces[5] and also will allow a certain beneficial passive deformation while minimizing detrimental bending that would compromise force production.

Insect wing veins are the primary supporting structures in wings and their arrangement and branching-complexity vary widely among insects. The membrane slightly modifies the stiffness, but it has essentially

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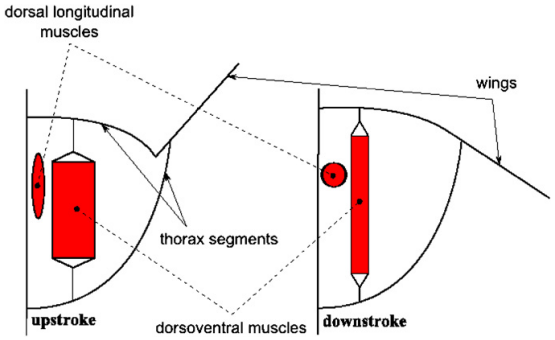

Figure 1: Schematic representation of the cross section of an insect thorax with muscle connected indirectly to the wing[1] .

an aerodynamic effect on the wing. The functional significance of phylogenetic trends in wing venation remains unknown, and the basic material and mechanical properties of insect wing veins and membranes, as well as its microstructure, are not understood very well[6–9] . Nevertheless the material and structural properties of the membranes, together with the venations of insect wings, are associated with insect flight.

As our objective is to obtain a flying object, it is also essential to have aerodynamic forces such as lift force which are greater than weight. The observation of insects in stationary flight shows that the movement of the wings is similar to a flapping rotation at nearly constant velocity with a high effective angle of attack during the downstroke and the upstroke[10–12] . At the end of the flapping, the wings turn rapidly in a supination or pronation movement. Usually the flapping frequency of insect wing is dictated by scaling laws as reported by Ellington[13] . It seems that only the flapping oscillations are controlled and that the pitch rotation is partly obtained passively. For insects, the wing twist varies with the insect size, from almost no twist in fruit flies to significant twist in dragonflies as is described by Combes and Daniel[7,8] ; in any case, for some insects, a controlled twist might be necessary to provide lift if there is not enough twist.

I.B. OVMI concepts and design

I.B.1. Actuation concepts

Our structural concept of vibrating wings is not based on an exchange of elastic and kinetic energy between the tergum and the wings like in insects. In our system, the elastic energy is stored directly in the wings that vibrate at their natural frequency. Although the frequency of the vibrations of some insect wings is not the resonance frequency, or at least the first eigenvalue frequency, it is expected to obtain, for small flying robots, larger amplitude vibrations with a minimal energy supply at the first resonance frequency. A correct wing pattern can be determined to obtain bending and twisting using a combination of tailored wing and wing root stiffness. Wing bending contributes to the wing strokes whereas a good positioning of the wing's center of mass allows the twist to be created passively. This passive deformation can induce an angle of attack favourable for lift production.

Furthermore due to the small size, it seems necessary to produce flexible wings without joint between the tergum and the wings. Therefore, a pivot zone must be created between the tergum and the wing root. In fact, this zone acts like a swing since the pivot allows more freedom in the wing's angle of attack and passive torsion. This pivot corresponds to a rigid passage between the tergum and the wing root. The latter part rests on two fixed points that belong to the rigid exoskeleton as shown in figure 2. Actuation just has to initiate and maintain the resonance of the wings.

Obviously the choice of actuating our prototypes at their first eigenfrequency, the mode-shape being a bending mode plus passive torsion of the wing, and designing prototypes without articulations seems to be wise in order to sustain a robust design and a higher energetic efficiency by reducing the instantaneous and mean power supply. A system with no joint and passive twist allows first the number of actuators to be decreased and second simple control systems to be implemented.

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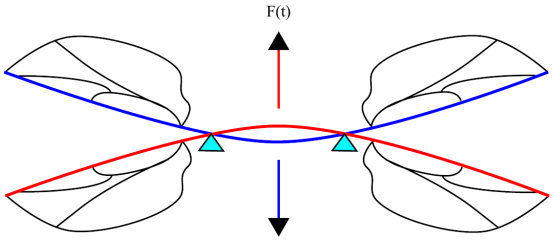

Figure 2: Simplified diagram of the future flapping-wing flying MEMS concept.

I.B.2. Design of a TWT-structure

In order to imitate the biological system as closely as possible, we have designed a flexible structure consisting of a thorax, two wings and a tergum, with an actuation inside the thorax to achieve the flapping of the wings as described in our previous work[14] . Here, we only sum up briefly the concept and design of the TWT-(Tergum-Wing-Thorax) structure. Actuators will be mounted in the middle of the tergum and will actuate the tergum to drive the wings as an insect does.

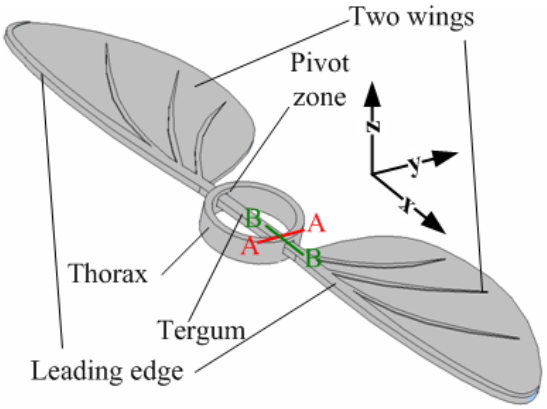

Figure 3: Schematic illustration of the TWT-structure.

Figure 3 shows the tergum directly connected to the leading edge of the wings: the tergum and the wings are incorporated into one deformable part supported by the thorax, which is rigid and not deformable. In this system, the elastic energy is delivered by the actuation and is stored directly in the wings that vibrate at their resonant frequency. A proper wing structure can be designed to obtain the desired bending and twisting by adjusting the stiffness over the complete wing. Moreover, the wing root must possess a large rotational compliance to achieve enough stroke amplitude. Due to the necessity to transfer energy efficiently and due to the small sizes to be realized, direct coupling between the tergum and the wings seems necessary. So, the wing position directly depends on the tergum position. It is safe to say that stiffer couplings will transfer more energy from the actuator through the tergum to the wing. Therefore, a pivot zone (see figure 2) corresponding to a rigid passage in the thorax should be created between the tergum and the wing root.

The pivot zones consist in a microchannel (in the thorax), which sustains one movable central beam (the tergum) through the wall of the thorax. As explained in our previous work[14,15] the presence of this microchannel will contribute to the bending and torsion angle of the wing increasing those angles and thus increasing the amount of aerodynamics forces generated during a stroke.

Currently the wings are actuated with very light magnet and coil and work are in progress to develop a more efficient actuation based on electro active polymers at low voltage.

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II. Material and Fabrication of wings

Mechanisms to reproduce the kinematics at the size of insect require new technologies[2,16] such as another Onera system consisting of a resonant thorax which drives wings in flap and pitch[17] . As explained in section I, an actuation concept based on no articulation was developed. Defining a concept is something important but more important is to be able to produce such TWT-structure by choosing the correct material and developing the correct micromachining techniques to validate steps by steps our concepts.

II.A. Choosing the wing material

For a flying Microelectromechanical system (MEMS) with no joint at the wing base and large wing displacement, the choice of material is a crucial parameter. It must be very flexible and elastic after large deflections but must not be plastically deformed. To select our material a simple and good modeling of the wing could be undertaken using a cantilever beam.

Such cantilever beam is defined by the bending moment of inertia I, the length l and the rigidity of the material (EI) with E being the Young Modulus. The relations between a load and the deflection at the beam Δz in one hand and the stress at the beam root σ in another hand are well known. By elimination of the charge between those relations, we get for a beam of rectangular shape a relation defined in equation 1.

$$\frac{\Delta z}{l} = \frac{2}{3}\frac{\sigma}{E} \cdot \frac{l}{t} \tag{1}$$

To get large displacements Δz, relative to the span l of the wing, with a stress smaller than the elastic limit, this relation shows that it is necessary to have flexible material with a large ratio between the length l and the thickness t. So resonant wings have to be very thins with small E and large σ_{max}.

We developed, at first, a MEMS fabrication process[18] using silicon and polydimethylsiloxane PDMS to make wing-frame and membrane, respectively. However, early conducted tests showed that the silicon wings are too weak and still too rigid to allow a good transmission of the movement between the thorax and the wing; moreover the ratio $\frac{\Delta z}{l}$ appeared to be small. The bending was obtained but not the torsion.

In the field of microsystem technologies, one material appears to approach the insect wing characteristics: the negative photoresist SU-8. The SU-8 has a Young's modulus E about forty times lower than silicon and its rigidity and elastic limit of the SU-8 makes it possible to obtain larger bending without breaking the structure. The SU-8 material[19] density ρ and its Poisson's ratio ν are respectively 1190 $kg.m^{-3}$ and 0.22 and its Young Modulus e is around 4.6 GPa. This density is consistent with the 1200 $kg.m^{-3}$ density measured in insect wings by Wainwright[20] . However, the Poisson's ratio ν reached 0.49 for insect wings. Using finite element modeling, to explore how wing venation contributes to the flexural stiffness of the wing, Combes and Daniel[8] tested the effects of using a Poisson's ratio ν of 0.3 instead of 0.49 and found that the difference in model behavior was negligible. Furthermore the rigidity EI of our SU-8 wing was calculated[21] and results were found in the range of insect wings[8] .

It is also necessary to have a material with a low damping parameter because the wings vibrate at their natural frequency and it is expected that the energy supplied is useful for the aerodynamic lift and for propulsion. The damping characteristics of the SU-8 will be reviewed later in section III.B.1. Therefore for the above-mentioned reasons[21,22] , SU-8 photoresist was the chosen material to fabricate our TWT-structure.

II.B. Validation of our concepts

To verify the assumptions made on our materials and to get one's hand in handling the fabrication process, only the tergum and the wing were first fabricated[22] . Various processes were tested in order to have a robust and simple methodology to fabricate the complete TWT-structure. The actuation concept based on the eigenfrequency of the wing was also experimentally tested as seen in figure 4 on a L-Beam actuated by a shaker. The longitudinal beam allows bending and twisting study of the main vein at the leading edge

whereas the transversal beam allows having the right center of gravity position and the evolution of the wing camber.

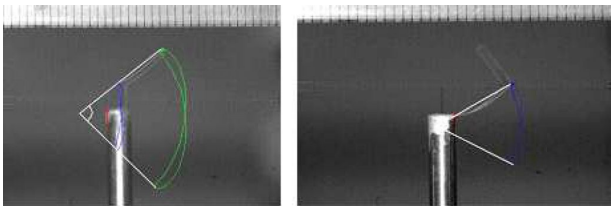
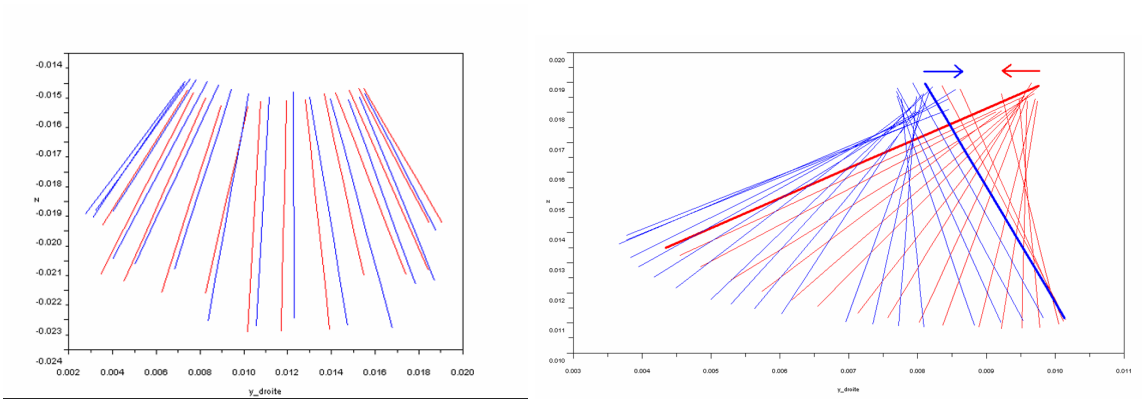


Figure 4: Measurement of the twist angle (left) and the bending angle (right). Length of the leading edge: 7.5 mm, length of the chord: 7.5 mm, width of the L-Beam: 0.9 mm, thickness of the L-Beam: 44 μm, frequency of the shaker: 82 Hz, amplitude of the shaker: $\sim$3 mm. The red line shows the shaker's total amplitude, the blue line shows the bending angle and the green line shows the twisting angle.

Figure 4 shows a large bending and a passive twisting at the resonance frequency of the L-Beam without any break or crack in the material. Indeed, a maximum bending angle of 52 $^\circ$ and a twisting angle of 82 $^\circ$ have been measured simultaneously for the L-Beam which gives large displacements at the tip end of the L-Beam and also a large amplification. So the concept of vibrating wings without any joint is validated. Furthermore the implementation of a membrane was also experimentally tested using a very thin layer of SU-8 added next to the L-Beam. The kinematics of the tip of such a wing is given in figure 5.



(a) Without membrane (b) With membrane

Figure 5: L-Beam kinematics without and with membrane. The same parameters as in figure 4 are used and the following for the membrane: width of the membrane: 5 mm, thickness of the membrane: 10 μm

When a membrane is added, the kinematics is modified due essentially to the aerodynamic forces such that at midstroke an effective angle of attack is obtained and lift could be generated. Moreover, we found that the addition of a thin SU-8 membrane of a few microns does not modify significantly the frequency but decreases the amplification factor due to an increase in aerodynamic forces applied on the wing that depend on the membrane surface. Nevertheless, the displacements remain large enough. A non-linear model of the aerodynamic forces has to be developed to compute the wing movement and deformation: the stroke amplitude being strongly coupled with the aerodynamic forces. Such an implicit model has to be solved numerically. To get more flexibility and eventually lighter wings, other materials compatible with the SU-8 can be used as membrane (PDMS, etc).

II.C. Multi-process approach for a complete TWT

To form a complete TWT-structure as seen in figure 3, a natural way is to fabricate several discrete components and to assemble them afterwards. Such approach will here be called the multi-process approach

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and was detailed in our previous work[21] . To sum up this multi-process approach, three components: an upper ring, a lower ring and the wings, which constitute the TWT-structure, are fabricated separately using similar processes as shown in figure 6 for example in the case of the upper ring.

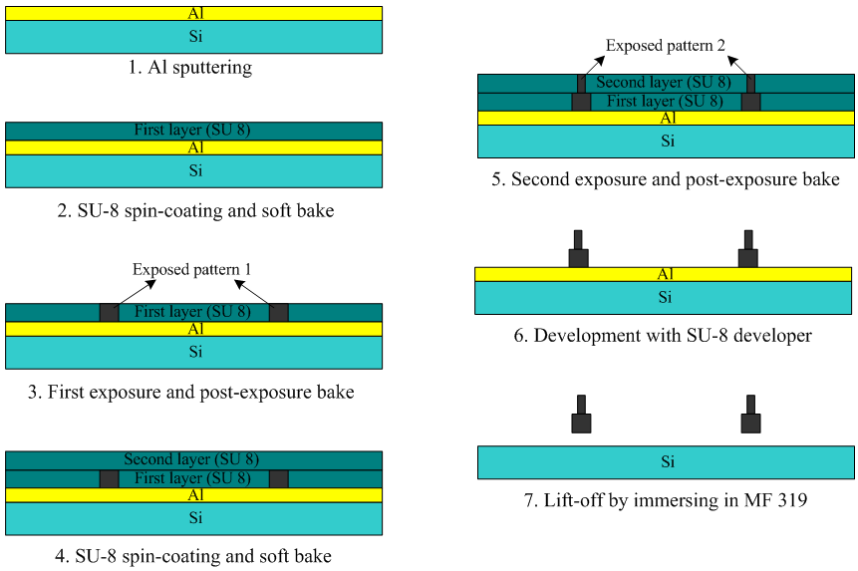

Figure 6: Fabrication process of the upper ring structure.

Then, with the help of a microscope and glue, the three components are assembled very carefully together by hand as too much handling could damage or break any component. The assembly-process itself requires some dexterity and is time-consuming. During assembly, the lower ring and the upper ring are fitted into each other and glued in order to constitute the thorax of the TWT-structure. The wings and the tergum are incorporated into one component as explained in section I.B.2 and thus are fabricated in one consecutive process. To correctly align and tightly join the lower and upper rings, a concave structure in the lower ring and a convex structure in the upper ring need to be designed as shown in figure 7, thus complicating the design and the subsequent fabrication.

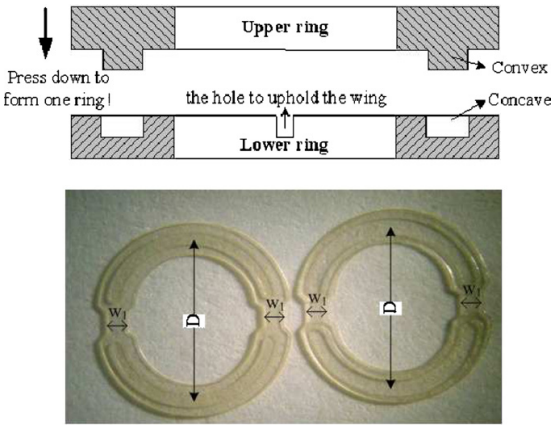

Figure 7: Schematic picture of the rings assembly (up) and photo of upper (down left) and lower (down right) SU-8 rings.

Nevertheless as shown in figure 8, when the TWT-structure is experimentally investigated its behavior is correct with the one expected and already presented in section II.B. The L-Beam is generating similar bending and torsion angles and thus validating our concept of TWT-structure.

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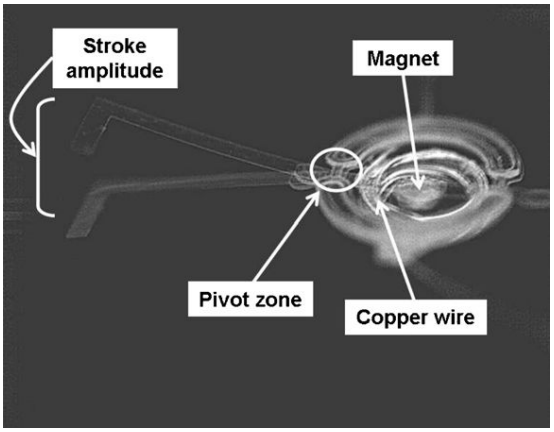

Figure 8: Both SU-8 structure and actuator are visible in this figure. The magnet is placed in the center of the tergum while the coil fixed on the thorax is positionned very close to the magnet. The tergum is prolonged by an L-Beam through the pivot zone which is a narrower zone on the thorax. The pivot zone is sized to affect the least possible transfer of energy from the actuator to the wings.

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Depending on the tolerance of the design, the amount of glue used and of skills needed for the assembly, the alignment between the lower and the upper rings may be inherently inaccurate thus reducing the gap size. Furthermore the assembled structure may not be sufficiently robust regarding its mechanical strength. Additionally, due to the glue used, the weight of the TWT-structure cannot be precisely controlled and some difficulties are popping up concerning the final weight of prototypes. Generally, this multi-process approach presents some obvious drawbacks resulting in a low yield. Thus a more coherent and powerful approach was then introduced to outperform the time-consuming and demanding multi-process approach: the one-process approach.

II.D. One-process approach for a complete TWT

To outperform the multi-process approach, a novel fabrication method with no assembly was developed: the one-process approach[15] . With it, the fabrication of TWT-structure is performed in one consecutive process and no additional steps are further required to assemble the TWT. The complete process is illustrated in figure 9.

Here, AZ 4562 was employed as direct sacrificial layers in order to successfully create 3D SU-8 pivot structures and the inherent gap. By adjusting the number of layers of AZ 4562 or SU-8 during fabrication, the complete size of the TWT-structure can be easily adjusted especially for the pivot i.e. gap. By controlling its size, the added bending- and torsion- angles generated by the pivot could be more precisely designed and quantified when compared to the multi-process approach. Although several sacrificial methods could be used for SU-8 structure, we chosed a quite simple one, that is additionnaly low cost and overall compatible with standard MEMS technology, when the scission and outgassing effects are properly handled. Thus this one-step approach leads to a higher and more reliable quality of the final SU-8 TWT-structure and could produce 3D pivot structure as seen in figure 10.

As explained in sections I and II, we develop an actuation concept and then the micromachining techniques to produce our TWT-structure. To get lift it is necessary that the wing rotates around its leading edge, so it is necessary to have a structural first mode of vibration in a pitching bending mode. In this concept no mechanical articulation is needed. The wing fabrication with the complete TWT-structure with a L-Beam wing is simple and have kinematics close to the one observed with the wing alone agitated by a shaker. Different concepts of structures have been tested with prototypes, 3D structures or artificial articulations[23] , but further improvements on the wing design are required to generate sufficient lift.

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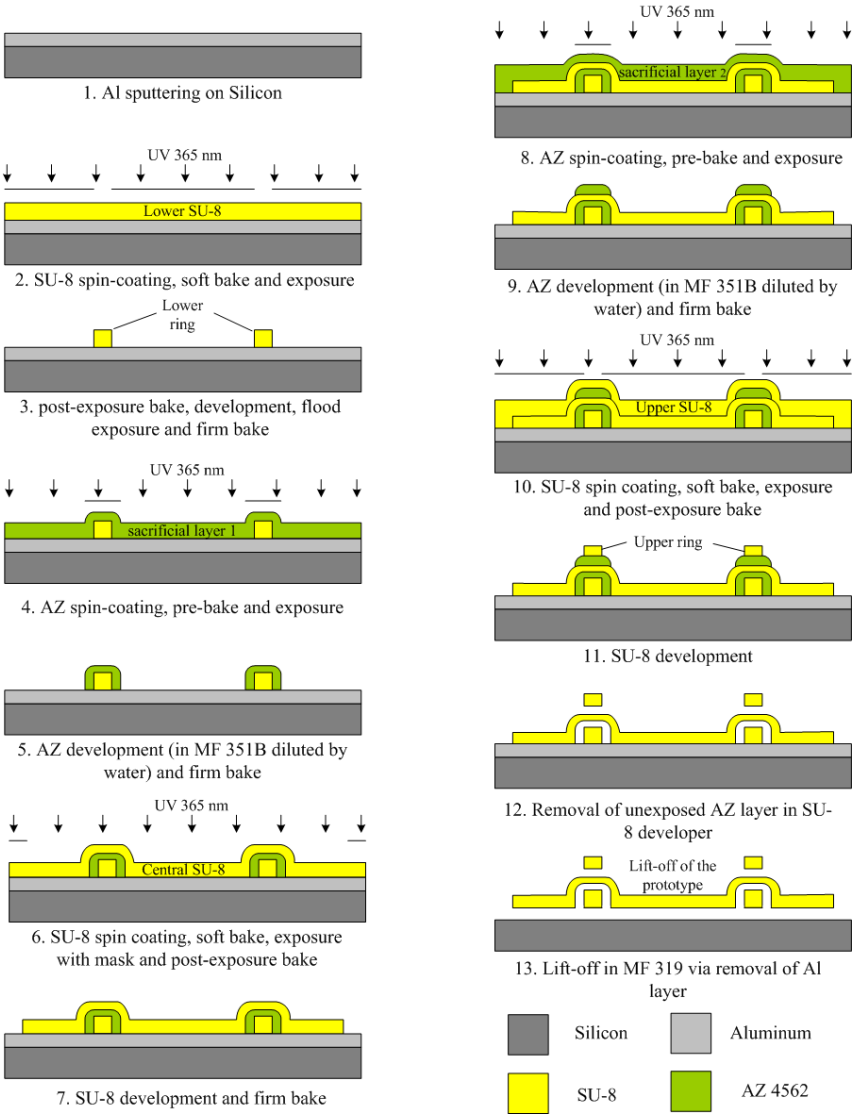

Figure 9: Fabrication sequence for a beam passing freely through two pivot zones.

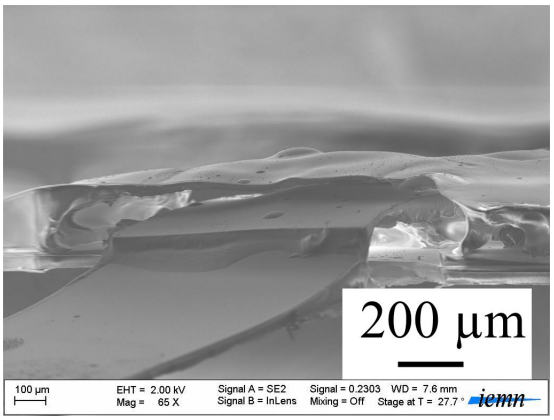

Figure 10: SEM of the SU-8 TWT-structure: one pivot zone where the beam between the tergum and the wing is released.

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III. Insect fly and aeroelasticity

With our fabrication and propulsion concepts validated and in order to get an airborne OVMI, the aeroelastic phenomena in insect fly have to be introduced to correctly shape the wings geometry. To size our prototypes, the critical point is the hovering flight which differs considerably from the flapping flight as for hovering fly the wings have to generate their own velocities to arise the aerodynamic forces. Therefore a quasi-analytical model based on a mass-spring differential equation will be here introduced to take into account the structural damping and the aerodynamic damping in order to validate the airborne concept and to size better prototypes.

III.A. From flapping flight to hovering flight modeling

The aerodynamic of flapping wings has been intensively studied these last years[24] with numerical, experimental and some model approaches. For small insects' size, the wings are flexible and the aerodynamic is then more complex as it is necessary to have stationary flight. Thus the kinematics for hovering flight is more complex than for flapping flight as the wings have to generate the velocities necessary to the aerodynamics forces in contrary to the large longitudinal velocities present in flapping flight. To sum up for flexible wings, aerodynamic forces depend on the deformations of wing which depend on the aerodynamic forces, thus defining an aeroelastic interactions with large deformations, angles of attack and dynamic effects.

The aeroelastic problem for flapping wings has already been studied. For flapping wings, tests have been done with rigid wings and kinematics similar to insect wings[25] and some formulations containing quasi-static forces, added mass forces, rotational forces and eventually wake capture effects tried to reproduce the periodic variation of the measured forces[11,26] . Nevertheless the aerodynamic part of such a model is currently not well established despite the recent developments: the predictions of the mean forces and of the forces during the stroke reversal are not sufficiently accurate. With flexible wings the difficulty comes from the degree of freedom due to the structural design. The determination of the large dynamic deformations of the structure may be computed but their effects on the aerodynamic remain unknown. Furthermore the aerodynamic forces during the reversal of the wings, between the upstroke and downstroke, are not well predicted because of the large vortices interactions with stalled flow. Large numerical aero-elastic codes have to be used while experimental approach is not easy.

For rigid wings, tests were done in water such that the hydrodynamic forces are larger than the structural forces and thus that the instantaneous aerodynamic forces are measured accurately. But the force measurement at the root of flexible wings integrates the inertial forces on each part of the wing where different accelerations are acting. It is necessary to know the instantaneous shape of the wing to estimate the inertial forces which are larger than the aerodynamic forces. So it is difficult to deduce the instantaneous aerodynamic forces from global force measurements. In any case the number of degrees of freedom on the kinematics and the structure is large; it is not possible to test or compute a lot of structures and kinematics. Nevertheless for rigid wings some tests of kinematics optimization were realized directly in water with step by step control motors able to reproduce any kinematics[25] (under some mechanical constraints) and show comprehensive results.

When any structure is reduced in size using similitude, it tends to become stiffer as the size decreases. Nevertheless observations of insect wings show large deformations of their wings. At the scale of insects, wings structure is composed of nervures and thin membranes defining its rigidity especially regarding the nervures. The inertial and aerodynamic forces decrease both with the size of the wings as the inertial forces vary with the complete geometry (thickness, span, and chord) and the aerodynamic forces vary only with the wing surface. It can still be shown that the structural inertial forces are still larger than the aerodynamic forces on insect-scale. For the conception and a first design, the aeroelastic problem can be therefore decoupled[22] : the deformation depends essentially on the structural inertial forces and thus the aerodynamic flow and forces can be estimated based on these structural deformations.

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III.B. Aeroelastic forces

In the resonant system the aerodynamic forces are generated by the displacements of the wing in stationary flight. So it is necessary to get large displacements which are obtained by deformations at the resonance of a TWT-structure. The amplitude of a wing at the resonance depends on the structural and aerodynamic damping. The structural damping defines the shape of the deformations and the aerodynamic forces are then determined by those deformations introducing an aerodynamic damping.

III.B.1. Structural Damping

For flexible or quasi-rigid flapping wings, the main dynamic forces are the inertial structural ones. The maximum instantaneous energy necessary to move the wing in usual mechanisms is essentially due to the inertial forces multiplied by the velocity. Nevertheless the instantaneous energy is not relevant as it does not directly generate lift and thrust. As our actuation concept of a vibrating wing on its first frequency mode consists on accumulating the maximum of elastic energy, the dissipation of energy due to mechanical frictions in the gear and to the movement transmission has to be minimized to increase its use for aerodynamic purpose. At small size the mechanical dissipation of energy generally increases with the flapping frequency and with the wing span[13] . Theoretically some power can be recovered during the deceleration of the wing. The energy can be stored in the elastic material; flexible structure can accumulate the energy during the deceleration and a large part of it can be restored during the acceleration.

The energy dissipated by the structure is first estimated using the mass-spring model of a beam whose linear second order differential equation is given in equation 2 where m is the mass of the beam, k the stiffness and with ζ the structural damping factor.

$$m\ddot{z} + 2\zeta\sqrt{km}\dot{z} + kz = F(t) \tag{2}$$

Knowing that the solution of this equation when submitted to a sinusoidal forced oscillation is sinusoidal for each beam particle, the movement amplitude at each point is thus proportional to the shaker amplitudes. The ratio $\Delta z/\Delta\xi$ of the movements amplitude at any point Δz to the shaker amplitude $\Delta\xi$ is defined as the amplification factor A. For small deformation, A is equal to $1/(2\zeta)$. The determination of ζ is for us primordial to get large deformations i.e. to generate sufficient lift and also to show how small our structural damping factor is in order to evaluate the dissipation of energy.

Some damping coefficients of material and especially the SU8 photoresist have been identified[27,28] ; as this coefficient is crucial for the validation of the vibrating wing concept, tests with prototypes of different sizes were conducted for small and large displacements[22,29] . As the aerodynamic damping is important even on simple structure, like simple cantilever or L beams, experiments were done in a vacuum chamber to dissociate the structural and the aerodynamic damping. For small deformations, ζ was identified for our SU-8 wing using cantilever and L-Beam[22] enabling us to pursue basic study. As the structural damping depends on the amplitude of the deformations and also on the fastening of the structure[30] , works are in progress to take care of those points. In MEMS some results show that the intrinsic damping of the material depends on the pressure even when it is very low ($< 1\ Pa$)[31] . In an upcoming paper[29] , the structural damping for our SU-8 structure in case of large deformations will be presented.

For computation of the dynamic behavior of the structure, it is also necessary to know the material damping which varies in particular with the frequency. Identifications of the first two resonant frequencies are used to get the Rayleigh Damping coefficients[32,33] α and β. Values for our SU-8 material were determined[29] and are introduced to compute our large deformations using Finite-Element-Methods. Thus the aerodynamic forces can be computed using the large deformations of our wing.

III.B.2. aerodynamic damping

The aerodynamic forces are not well known, but in first approximation a quasi-static model with a span integration of a 2D formulation is applied. For a L-Beam on a shaker at its resonant frequency, the local velocities, acceleration and rotation rates have to be computed in all the section along the beam and a correct

estimation of them is mandatory. In stationary flight these velocities come only from the structural deformations. If the only damping coefficient ζ used is the structural one, the estimated velocities are quite too large. So tests are done in the air at different pressure values to measure the deformations on the tip of the beam. The amplifications of the oscillations with a shaker are globally inversely proportional to the global damping coefficient: structure plus aerodynamic. A preliminary estimation of the quasi static aerodynamic forces is thus obtained with a linear formulation of the damping forces similar to the structural damping forces; the quasi-static aerodynamic forces are supposed proportional to the deformation velocities. In other words, the damping coefficient ζ will be replaced by an artificial aerodynamic damping coefficient ζ_{aero} in equation 2.

Generally in aerodynamic the Reynolds number Re is sufficiently high such that the flow regime is turbulent. When taking a flat plate at high angle of attack, similar to the beams tested in preliminary approaches, the aerodynamic forces are proportional to the square of the velocity V^2. So, in the simple mass-spring model, the aerodynamic forces have to be introduced, and they are non-linear. This means that for small displacements, the aerodynamic forces, and especially the damping ones, are relatively small. Inversely for large displacements the aerodynamic forces, growing as the deformation velocities to the square, become predominant. To study this non-linear effect, tests with a shaker were done on L-Beams with different vertical amplitudes[22] . At the scale of 2 cm in span, the Reynolds numbers Re ($V.c/\nu$) based on the wing chord c (ν being the kinematic viscosity of the air) are relatively small ($Re<$ 100) and depend on the deformation velocities V. So for the formulation of the static aerodynamic forces, it is necessary to combine forces proportional to V and to the square of the velocity V^2. Some results of the tests of a vibrating beam are presented on the figure 11.

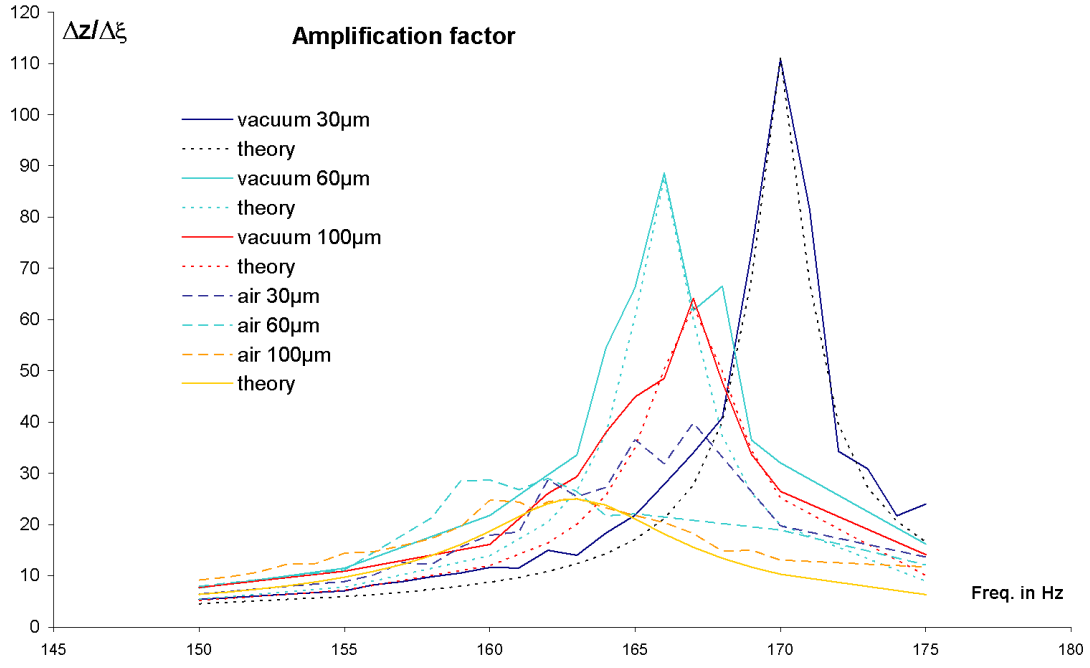

Figure 11: Three values of the vertical displacements of the shaker $\Delta\xi$ are presented 30, 60 and 100 μm. The amplitude of the tip beam of 7.5 mm length reaches an amplification factor A of 70 in the vacuum and crashes around 30 in the air. The resonance frequency ($\sim$ 165 Hz) is similar to the frequency of insect wings of 7.5 mm span in the vacuum and decreases significantly in the air but still having a broader eigenfrequency bandwidth.

The resonance frequency changes slightly with the vibration amplitudes thus the large deformations have only a limited effect on the resonance frequency. More accurate tests to characterize the small variations of f with the amplitude will be necessary. The variation of the amplitude with the frequency is relatively well predicted with the mass-spring-damper model. In the air, the frequency slightly decreases as air in the

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neighborhood is alternatively accelerated and decelerated adding a virtual mass effect[23] to the structure. This virtual mass represents the weighted average mass of air accelerated with the structure and could be estimated as a virtual mass equal to the air in the cylinder surrounding the beam. As the virtual mass increases the global mass, the frequency will be subject to a small decrease in the air. As shown in figure 11, the aerodynamic damping for a simple beam is larger than the structural damping, meaning that the energy is mainly dissipated by the air. It is not really useful to search a material with a lower damping coefficient because the structural dissipation is already small[22] . Furthermore those tests were done with cantilever and L-Beams and thus for a complete wing (nervures plus membrane) the air damping is larger, and the amplification factor is even lower. To get sufficient lift, it is necessary to optimize the amplification factor i.e. to study the aerodynamic damping further.

A more accurate model for aerodynamic forces i.e. damping could be found in the litterature[10,34,35] . Several effects of this model are visible in our test such as the added mass forces. As aerodynamic forces i.e. damping have to be further studied in order to be optimized, a first attempt could be to implement a model derivated from the model developed by Sane and Dickinson[11] . Such computation could be made as the structural damping is accurately known and therefore the aerodynamic forces could be calculated. More generally a complex aeroelastic model based on Finite-Element-Method and the *ANSYS* code need to be developed. The objective of the FEM aeroelastic computations is to optimize the structure to get lift with the minimum of energy supplied.

IV. Test bench measuring aerodynamic forces

To measure the aerodynamic performance of our prototypes, the forces have to be quantified especially the lift and therefore a measuring bench should be developped. Since the actuation is based on the first eigenfrequency of the wing structure, a concept have to be drawn compatible with this specific constraint in mind and size to reach a sufficient sensitivity without being interfered by the wing actuation.

IV.A. Concept

The principle of our measuring bench relies on a shaker, a beam which supports at its end the wing to be characterized and a strain gage glued at the beam root as illustrated in the figure 12 in the drag measurement configuration with the measuring beam horizontal and in the lift configuration with the measuring beam vertical. The shaker moving at the eigenfrequency of the wing, the beam will transmit the excitation to the wings. Those will generate a flapping movement and should generate lift and thrust and thus strain the beam. By the means of the beam dimensions, the generated strain will be amplified and quantified by the strain gage. To convert the strain into a force, calibration has to be made for example with a static load of 1 g at the end of the beam inducing a certain strain and thus a certain voltage. Therefore the aerodynamic forces can be quantified as a function of the excitation amplitude and the wing geometry. Other measuring force concepts can be found in the literature[36,37] but are applied to larger structures and different actuations.

With the excitation of the wings comes also an excitation of the beam used as excitation transmitter. As any structure the beam will respond by adding his own displacement to the one induced by the wing. To avoid this dynamic effect on the measurement, the first eigenfrequency of the beam has to be sufficiently high with respect to the one of the wing. Thus the beam will be seen as static enduring only the variable load of the wing in other words the aerodynamic forces. In another way, the beam response could be seen as the equation 3 which is the standard equation of motion for a structure with $\mathbf{M}$ the mass matrix, $\mathbf{C}$ the damping matrix and $\mathbf{K}$ the stiffness matrix of the beam, X the displacement vector of the beam and F the time-depend external forces.

$$\mathbf{M}\ddot{X} + \mathbf{C}\dot{X} + \mathbf{K}X = F(t) \tag{3}$$

In our application, by choosing the first eigenfrequency of beam support high enough, the $\ddot{X}$ and the $\dot{X}$ can be neglected and thus we can consider just a static relationship between the displacement of the beam and the applied forces. Furthermore we assume that in the lift-configuration the acceleration and the velocity of

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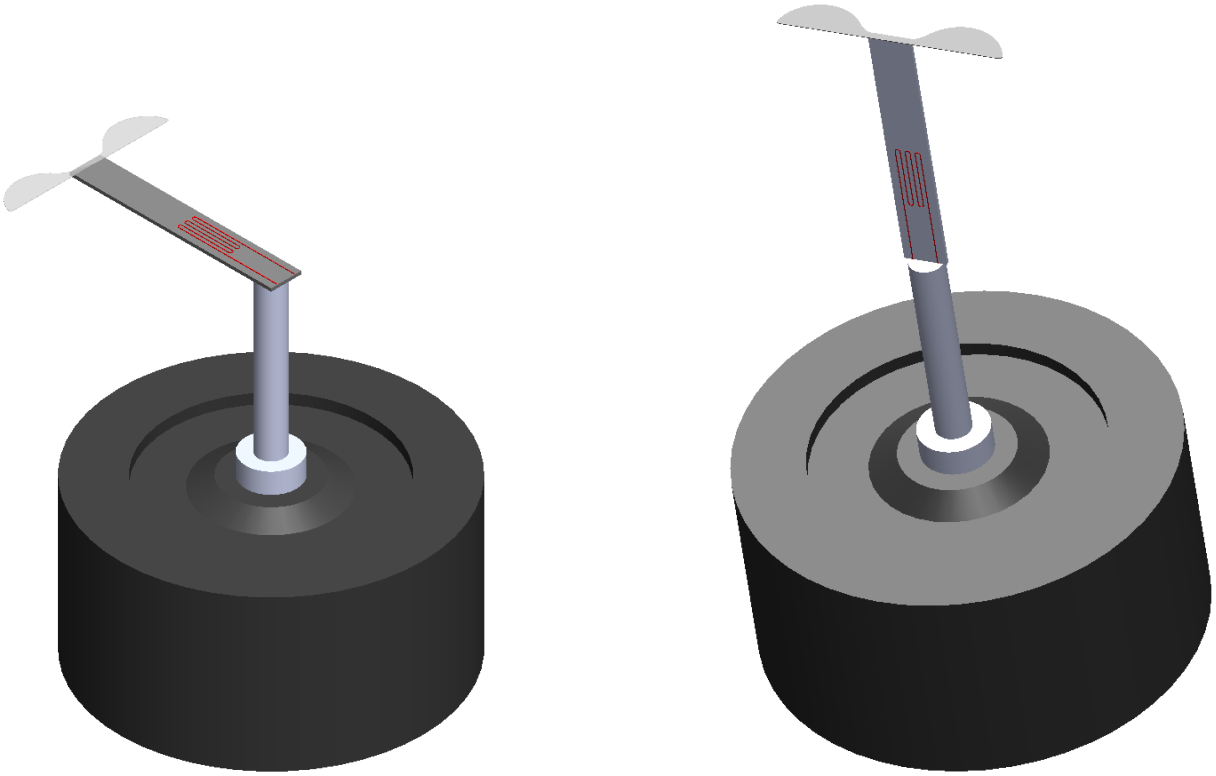

Figure 12: Configuration of our aerodynamic forces measuring bench: Drag (left) and Lift (right).

the beam could be neglected as no significant lever arm and so almost no inertia forces exist in contrary to the drag configuration. So only the drag configuration will be here further discussed. To check the compatibility with the lift-configuration only a buckling check is done with the final beam dimensions.

IV.B. Development

To size the beam correctly several steps are necessary, first from a static point of view to quickly calculate the beam dimensions using the literature and then the dynamic behavior using Finite-Element-Method to refine the dimensions.

The idea behind this process is to find the correct dimensions for the beam i.e. the length l, the thickness t and the width w to amplify the tiny strain signal due to the wing forces high enough to be first noticeable and then sensitive enough without introducing the dynamic behavior of the beam.

IV.B.1. Static analysis

To size the beam correctly from a static point of view, two characteristics of the beam need to be analyzed: the eigenfrequency f and the strain on beam skin at the root $\frac{\Delta l}{l}$. A compromise must be found between those two parameters as a high eigenfrequency depends on a high rigidity and a maximal strain on a small rigidity as it will be shown further. First those two parameters have to be expressed as functions of the beam dimensions.

The eigenfrequency f of a rectangular clamped-free beam is easily expressed, using the simple expression for the eigenpulsation[38] and the geometrical parameter of the beam, as a function of the beam dimensions, the

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Young modulus E and the density ρ as seen in equation 4.

$$f = 0.1615 \frac{t}{l^2} \sqrt{\frac{E}{\rho}} \tag{4}$$

Similarly the strain at the beam root on his top can be expressed, using the definition of strain and the second order derivative of the deflection[39] , as a function of the beam dimensions, the Young Modulus E and the bending force F as seen in equation 5.

$$\varepsilon_{xx-root} = \frac{\Delta l}{l} = \frac{6Fl}{Ewt^2} \tag{5}$$

With the expression of f and $\frac{\Delta l}{l}$ written in terms of beam dimensions, those can be determined using several assumptions on the beam dimensions (w=4mm) and material (E and ρ are known), on the maximal forces F (F=0.01N), on the expected eigenfrequency of the beam f (f=500 Hz) and on the maximal $\frac{\Delta l}{l}$ ($\frac{\Delta l}{l}$=0.001 to remain into the typical elastic domain). With those assumptions the calculation of the other beam dimensions l and t is possible by solving a simple system of equations 6.

$$\begin{cases} t = \frac{f}{0.1615} \sqrt{\frac{\rho}{E}} l^2 \\ \\ l = \frac{\Delta l}{l} \frac{Ewt^2}{6F} \end{cases} \tag{6}$$

The result of this system of equations is summarized in the table 1 for different material. For the silicon, the

Material	Silicon	Steel	SU-8
Density ρ $[kg.m^{-3}]$	2329	7800	1200
Young Modulus E $[GPa]$	185	200	4.4
Length l $[mm]$	8.8	5.9	10.9
Thickness t $[\mu m]$	26.65	20.95	193

Table 1: Dimensions of the beam after the static analysis

computed thickness are quite thinner than the usual available silicon wafer thickness so to keep a fair behavior the thickness had to be increased and the length extended. In the same way, the steel beam thickness is quite under the one easily available and thus to compensate the length should be also extended. Thus the silicon and steel beams could be also further investigated but the strain at beam root representative of the bench sensitivity should be much smaller and won't be discussed in the present paper. The dimensions obtained for the SU-8 are manageable and coherent with the fabrication process and thus are qualified for further investigations. Furthermore our default assumption on $\frac{\Delta l}{l}$ could be slightly relaxed as it has a larger elastic domain in comparison with steel elastic domain. Also due to supply-chain availability, we choose to pursue the sizing of the SU-8 beam with dynamic analysis.

IV.B.2. Dynamic analysis

With the static analysis done, dynamic analysis has to be processed in order to analyze the effect of the excitation imposed to the beam. The frequency of this excitation has to be the first eigenfrequency of the wing and thus generating the flapping motion and forces. To be effective our measuring bench has to get rid of those dynamic effects induced by the beam at the best. To study those effects the commercial software *Ansys* was introduced to model our analysis using a clamped-free beam with an imposed sinusoidal vertical tip displacement $v(t)$ at one end i.e. beam root (the shaker excitation) and a mass at the other end i.e. beam tip (the wing force). The beam was modeled with the BEAM4-Element. Rayleigh damping constants α and β were introduced to take into account the material damping as explained in section III.B.1.

The tested dimensions are a little over the values calculated in the static analysis in order to take into

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account the dynamic behavior of the beam in some kind of safety coefficients. The SU-8 beam were here 400 μm for the thickness, 15 mm for the length and 4 mm for the width. With the static analysis a mass of 1 g has been used for sizing. Nevertheless this mass value is not representative of the expected wing-lift. Assuming that an insect can lift five times his weight it means in our case, that a 10 mg wing weight could lift up to 50 mg. The approximation of a maximal lift of 50 mg is then appropriate and intermediate analysis were down with a 10 mg mass. Only the results for the 50 mg added mass will be discussed here.

In *Ansys*, two kinds of investigation were done: analysis with and without the added mass at the beam tip. In one hand the beam without a mass is investigated in order to check if the beam alone has a significant behavior in terms of tip displacements. In another hand the beam with an added mass is studied to check and estimate his 'real' behavior under excitation. In both cases modal and transient analyses were undergone with different amplitudes and frequencies to prospect our expected measuring range. Due to technical limitations of our shaker, the root excitation amplitude can vary only between 10 μm and 200 μm, so the transient analyses were limited to the 50 μm, 100 μm and 200 μm displacement amplitudes. Root excitation frequencies of 100 Hz and 50 Hz were also investigated as they are representative of the expected wing-eigenfrequency range.

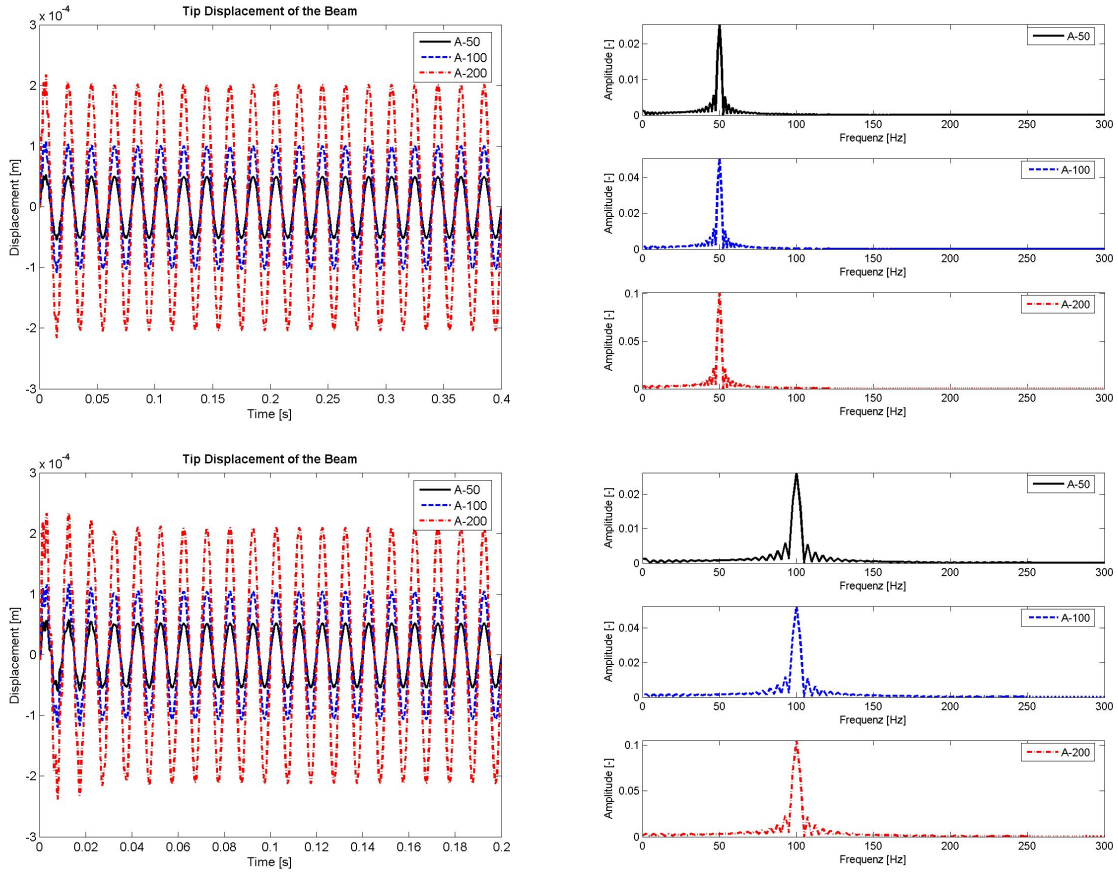

Figure 13: Numerical simulation of the tip displacement of the SU-8 beam with a 50 Hz (up) and a 100 Hz (down) excitation and a 50, 100 and 200 μm amplitude. A FFT-analysis of those displacements is shown on the right hand side to check the frequency response of the beam.

A correct behavior is observed in figure 13 for this SU-8 beam without load. For the 50 Hz as well as for the 100 Hz excitation the tip displacement is close to the one of the beam root whatever the amplitudes are. From a frequency point of view the tip response is always the one of the excitation due to the high beam eigenfrequency f at 549.84 Hz. The beam behaves here almost as a static beam just transmitting

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the vibration to the wing which should generate the aerodynamic forces. The behavior of this beam when loaded at its end with a virtual mass of 50 mg is shown in figure 14.

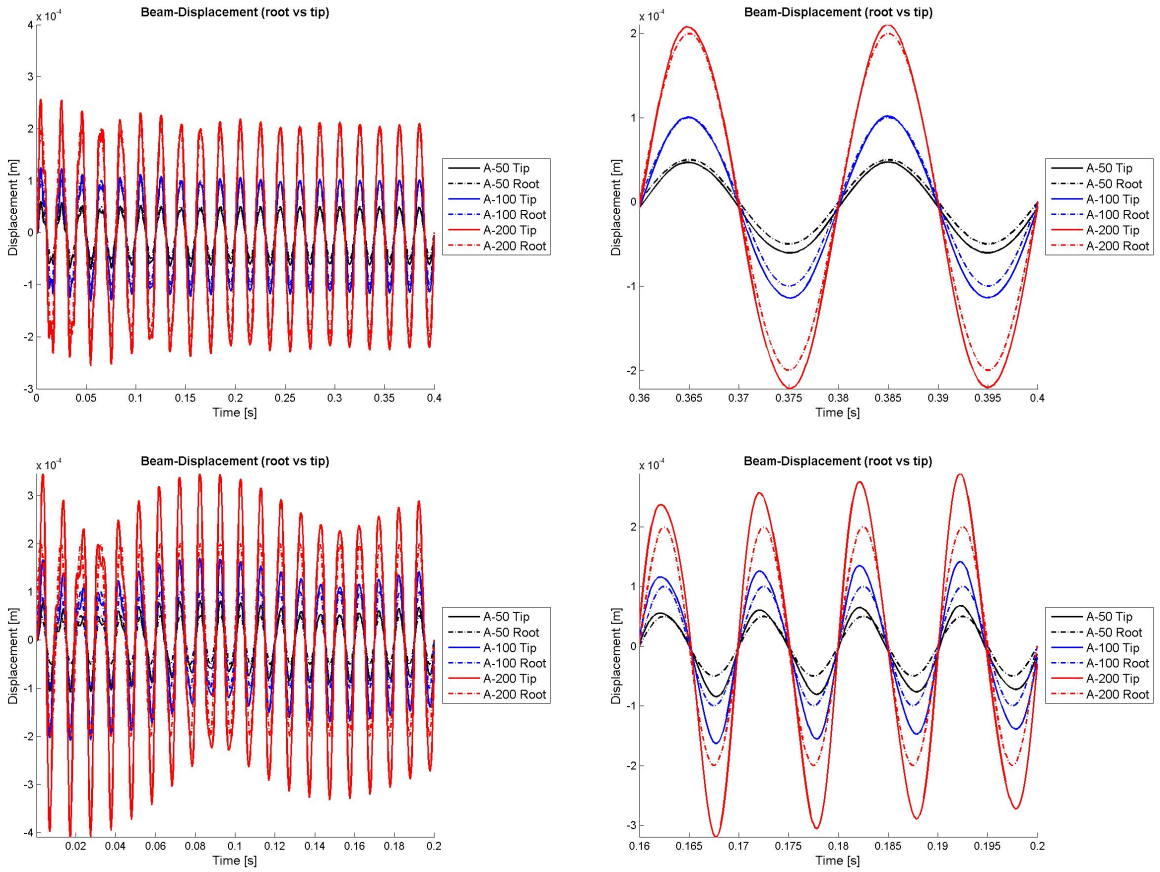

Figure 14: Numerical simulation of the tip displacement of the SU-8 beam with a 50 Hz (up) and a 100 Hz (down) excitation and a 50, 100 and 200 μm amplitude for a 50 mg added mass at the beam end. A zoomed view on the last periods is shown on the right hand-side.

By the 50 mg added mass the behavior of the beam is also as expected after a relative quick transient phase. The tip displacement is slightly higher than the root displacement for the 50 Hz excitation. For the 100 Hz excitation the transient phase lasts longer and can possibly shift the time response of the gage but nevertheless the amplification factor is here more important as by the 50 Hz excitation. Instead of 549.84 Hz, the new eigenfrequency of the system literally crashes around 192.87 Hz with the added mass of 50 mg and thus it explains easily those effects. However this virtual mass of 50 mg is a crude approximation of the expected force and should be considered as an extreme upper limit.

To check the validity of our assumption on neglecting the buckling, a quick calculation of the critical load for a 1 g mass is given in equation 7 (here k_b is the column effective length factor and is defined to $k_b = 2$ for a clamped-free beam) which is the double from the maximal sizing inertial forces F of about 0.5 N with an acceleration of 50 g corresponding to a mass of 1 g which is a very crude value for the expected lift force. So it is expected to use this beam to build up our measuring bench.

$$F = \frac{\pi^2 EI}{(k_b l)^2} = 1.03N \tag{7}$$

With the beam defined, the electrical measurement of the strain has to be processed. For our problematic a quarter-bridge-circuit or a half-bridge depending on the heat dissipation of the SU-8 could be used to lower

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the costs. The experimental validation is currently in progress with the above calculated dimensions.

Conclusion

The insect wings are not an articulated system with muscles as the bird wings. Direct and indirect muscles placed inside the thorax control the vibrations of the wings and also the motion of the wings with autoadaptive deformations of the wing-shape. For small sizes MAVs it is necessary to get flexible wings without articulations and actuated on a resonant mode to sustain a higher energetic efficiency; the mode-shape and eigenfrequency being similar to the ones observed for insect. So those specifications define the core of our MAV project and our TWT-(Tergum-Wing-Thorax) structure. In our case a micro-mechanism in the thorax initiates and maintains the resonance of our not-articulated wings. The mode shape defined by our wing-geometry in order to imitate the kinematics of insect wings and to create the aerodynamic forces is a combination of bending and passive torsion. Currently the wings are actuated with very light magnet and coil; it is expected to replace them by electro active polymers at low voltage.

As insect wings are submitted to large deformations over a thin cross-section and large area inducing large stresses, our material have to be chosen carefully to fabricate our TWT-structure. Therefore a negative photoresist SU-8, frequently used in the field of microelectromechanical systems (MEMS), and a photolithographic process was introduced and developed to take advantages of the relatively easy and flexible fabrication process for such material and also to validate the fabrication of our complete TWT-structure. Following this process, many wing structures allowing various thicknesses and shapes to imitate insect-wings were fabricated and tested to validate our actuation concept as well as our TWT-structure showing similar kinematics with the one observed for insects. Further developments are in progress to optimize the structure in order to get larger deformation through the pivot zone and a better thorax behavior.

With our fabrication and propulsion concepts validated, we define an aeroelastic problem for hovering: the velocities mandatory for flight are defined by the large deformations of the structure which are greatly impacted by the structural and overall by the aerodynamic damping. A quasi-analytical model based on a mass-spring differential equation has been used and validated with beams. To determine the structural damping, several experiments were made in vacuum enabling to define the structural damping factor ζ for small and large displacements. In parallel experiments were also conducted, to calculate the aerodynamic damping factor and to provide an example of virtual mass effects. To go further and to optimize the structure with nervures, a weakly coupled aeroelastic model is developed; the dynamic of the structure is computed with the *ANSYS* code and the aerodynamic forces are estimated under a quasi-static hypothesis with quasi-static, added masses and rotation components. The validation of the aeroelastic approach, which is done preliminary with L beams, is still under development. It is intended to optimize the structure design with respect to the lift coefficient. More complicated and actuated wing shapes with veins and membranes will also be tested to get large flexion and passive torsion with not-articulated flexible wings.

With different wing geometries defined and an aeroelastic model in development, it is also necessary to quantify the aerodynamic performance of our prototype especially the lift as it will be the objective function during the optimization process. Therefore a measuring bench concept has been developed relying on a shaker, a beam which holds up at its end an aerodynamic performance-unknown wing and at its root a strain gage: the beam acting as a passive vibration transmitter. Two configurations of this measuring bench enable the measurement of the lift and the drag. The sizing was done for the most critical configuration i.e. the drag configuration and was checked against buckling for the lift configuration. Its experimental validation is still under development but it could be expected to measure the micro-forces generated by our wings and thus to validate our aeroelastic model furthermore.

Acknowledgements

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