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The Use of Resonant Structures for Miniaturizing FMAVs

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The use of resonant structures in FMAVs is an idea inspired by nature. The application of resonance in an oscillating system requires a careful analysis of the involved structures in insects. The application of this concept in FMAVs yields opportunities for size reduction. As one moves away from standard constructional principles. The latter become less feasible at the small scale. It is mandatory to include the control mechanism in the design loop from the start. Control over wing kinematics in insects relies on complex wing root structures, for FMAVs other solutions are possible and needed. This article provides an overview on structures and their functions in insects and the engineering alternatives. Emphasis is on techniques which are applicable in smaller designs. In particular, control mechanisms and thorax structures are covered. Initial concepts are analyzed and presented based on multi-body and FE representation.

I. Introduction

The design of Flapping Wing Micro Air Vehicles (FMAVs) is a field which is rapidly developing. However, compared to fixed wing MAVs, it has received considerably less attention; the field of flapping wing MAVs can be considered a niche. Partly accountable is the unavailability of of-the-shelf parts for flapping wing designs as opposed to fixed wing designs. Approximately one decade passed since renewed interest in FMAVs started, see Smith.[1]

Historically, insects, and to a lesser extent birds, are a large source of inspiration for the development of FMAVs. The engineer might be tempted to try to copy nature, but this is not a good choice since the materials and functions available are different in origin, see Michelson and Naqvi.[2] Summarizing, bio inspiration is a good source of ideas while the direct copying of nature will probably not lead to feasible or optimal solutions. When compared to insects, a FMAV will look pretty static. The features demonstrated by insects in flight are remarkable and it will take a long time before FMAVs are able to even come close to the aerial control performance demonstrated by even the most docile insect.

Different groups spearhead the research in unraveling the mysteries of insect flight by laboratory and numerical experiments or a combination of them (see , for example, Dickinson *et al.*,[3] Ellington *et al.*,[4] Sane[5] and Żbikowski[6]). Other groups run projects aimed at the development of FMAVs using data and ideas from aerodynamic research.

The present paper is part of a larger project which aims at the development of an insect-like FMAV. The intent is to develop a FMAV with a wing span of 10 cm and 4 $gram$ mass, capable of hovering and slow flight in an indoor

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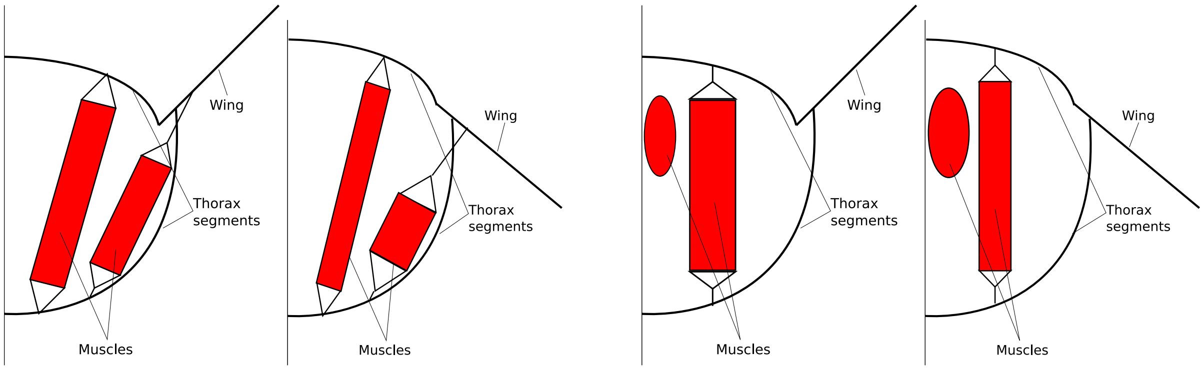
environment. When looking at these dimensions a number of disciplines come together, for example, aerodynamics, mechanics, electronics, control engineering and informatics. These disciplines are very closely connected and they can be hard to separate. The targeted dimensions, are feasible using conventional technologies (gears, links and electric motors), see, for example, Galinski and Żbikowski[7],[8] Malolan *et al*.[9] and Keennon and Grasmeyer.[10] These dimensions are also the starting point for other technologies (linear actuators and compliant mechanisms), see for example Cox *et al*.,[11] Yan *et al*.[12] and Deng *et al*.[13],[14] which are more interesting when moving to even smaller scales. This paper has its focus on the realization of the mechanical part of the FMAV. The goal of the present study is to outline difficulties and propose solutions to problems which arise in the development of wing actuation mechanisms on a smaller scale. The development is influenced by studying the resonant properties of the insect thorax and its general structure. The possibilities for control will be implemented by methods of disturbing the basic oscillating state of the mechanism.

First, an introduction will be given toward insects and why they are a source of inspiration. In Section III, this will be expanded to the current setting and the challenges which arise when designing an insect-based FMAV. The study will concentrate on the wing actuation mechanism. The control of the aerodynamic forces is covered in Section IV. The choice of actuator is the subject of Section V. Results of modeling and prototypes are shown in Section VI. Finally conclusion are given in Section VII.

II. Insects

The development of FMAV has historically been inspired by birds and insects. Early research tested made birdwing-like structures to invoke flight, see, for example, Lilienthal.[15] Later interest in smaller and smaller aerial vehicles led to the change of focus to insect flight. Insect flight, although flapping in origin, is significantly different from bird flight. Especially real hovering, for example hover flies, is a feature which has puzzled scientists for a long time. Inspiration for FMAV flight is usually restricted to the wings and aerodynamics. In fact, the aerodynamics should be more or less copied from insects. New flapping strategies are very hard to develop and will probably not exceed the performance delivered by insects at the same efficiency levels. Experimental research has been done to search for other flapping strategies, see Salles and Schiele.[16] Insects can also be used as inspiration for the development of the wing actuation mechanism. For this purpose, a short overview of the systems concerned is given. There are two types of flying insects. The first group consists of insects having muscles that directly drive the wings, the dragonflies and damselflies (infraclass *Paleoptera*). For the second group, muscles drive the wings indirectly, for example, flies, bees, wasps and beetles, among others (infraclass *Neoptera*). In these insects the drive muscles are coupled to a thorax structure which is tuned to resonate at an optimal flapping frequency. In the direct drive insects the flight muscles are synchronous, meaning they are controlled by the nervous system on a wingbeat-to-wingbeat basis. In the case of indirect drive, the drive muscles are asynchronous, that is they have an on-off switch which toggles a resonating contraction mode, see Josepson *et al*.[17] For clarity, a diagrammatic reproduction of the two different systems are shown in Fig. 1(a) and Fig. 1(b), These figures are inspired by Chapman.[18] When looking at insects as an inspiration, the present focus is mainly on the insects that show significant resonance in their wing driving mechanism. The indirect drive insects are more attractive to inspire FMAVs since they offer the possibilities to effectively reduce the inertial cost of wing movement. These properties have been described by Greenewalt[19] and Ellington,[20] among others. Insects are an incredible example of successful scaling of a design, the basic structure is the same for a large size range.



(a) Muscle Connected directly to the wing

(b) Muscle connected indirectly to the wing

Figure 1. Diagrammatic representation of the cross section of the two main insect thorax types

The wing movement in insects is complex. The flapping cycle is approximately sinusoidal in origin. Two other movements are important. The first is the out-of-plane movement of the wing, i.e. the tip of the wing makes a banana- or figure-eight type of motion. The second is the wing rotation. Wing rotation is the key to efficient lift generation. For an overview of wing kinematics and modeling techniques see Ansari *et al.*[21] For this paper the sources of the wing movements are most important. The source of the complex wing movements are the sclerites and the attached muscles at the wing base. These structures and muscles configure the wing joint for each stroke. These synchronous muscles are controlled on a wingbeat-to-wingbeat basis. These muscles do not do work when flying, but solely function as control actuators. For a description of the anatomy of this system see, for example, Chapman.[18] A more detailed functional analysis of the muscles and control signals for this system is provided by Lehman[22] and Tu and Dickinson.[23]

III. Thorax design

Hovering flight requires a specific mechanism. This mechanism has to be able to produce a certain kinematic pattern in order to hover with some efficiency and endurance. Steady forward flight can be achieved by simpler mechanisms. This article restricts to wing actuation at the wing base. Viewed from an engineer's viewpoint, the insect thorax structure is a damped compliant mechanism which has resonant properties. The development of FMAVs requires a technical equivalent for this structure. At larger scales, gears, linkages and rotational electric motors provide excellent results in terms of performance and flexibility in the design space. At smaller scales the use of these structures and actuators proves more difficult. The higher wingbeat frequencies needed in smaller designs makes the translation from rotational to reciprocating motion less and less desirable. Scaling of efficiency and power density of rotational electric actuators is less favorable as compared to other technologies. The definition of small in the current setting refers to FMAV which have wingspan smaller than $\sim 5cm$. FMAVs larger than $\sim 5cm$ should be possible using conventional technologies. Below $\sim 5cm$ wingspan the realm of FMAVs will be more filled with designs which use linear actuator technologies and a mix of compliant mechanisms and elastic hinges, see, for example Deng *et al.*[1314] and Yan *et al.*[12]

Flying insect thorax properties are well researched from a biological point of view. The engineering disciplines have, due to recent increased interest in insect sized FMAVs, shown a substantial increase in number of papers. A number of factors are important for when looking at insects as inspiration. Ellington[20] showed that the Q factor (the ratio between energy dissipated per cycle and energy in the resonator) in the resonating insects is very high (5-19), which is remarkable for biological structures. Combes and Daniel[24] showed for large insects, which are interesting for FMAV design, that wing torsion is dominantly caused by wing inertia and not aerodynamic loads. The ratio between inertia and aerodynamic effects in the wings is around 6-7 for larger insects. Due to these large ratios the assumption of low damping is justified. The structure should therefore be driven with frequencies close to the natural frequency, denoted ω_n. Due to this large ratio, the energy savings can be significant when resonance is exploited. The high Q factor also opens possibilities for different actuation strategies in which actuators do not provide a typical sinusoidal driving force but a force with another distribution in time to influence the actuator, more on this in Section V. Schematically seen, an insect-inspired resonator consists of four parts: a springlike structure (the thorax), the wings, the actuator(s) (which provides mechanical work) and the aerodynamics which acts like a damper. A schematic representation is given in Fig. 2. For simplicity, energy losses due to friction and hysteresis are not taken into account. When designing the actuation mechanism, the wings and the accompanying aerodynamics are considered to be given. For design purposes the quasi-steady aerodynamic models are accurate enough, see for example Sane and Dickinson[25] and Żbikowski.[6] CFD experiments are currently too costly to include in a design setting.

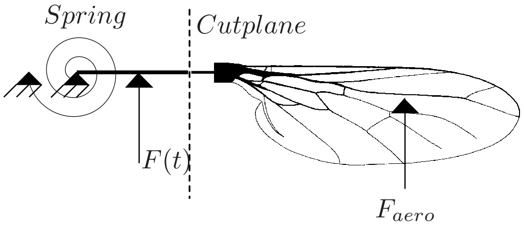
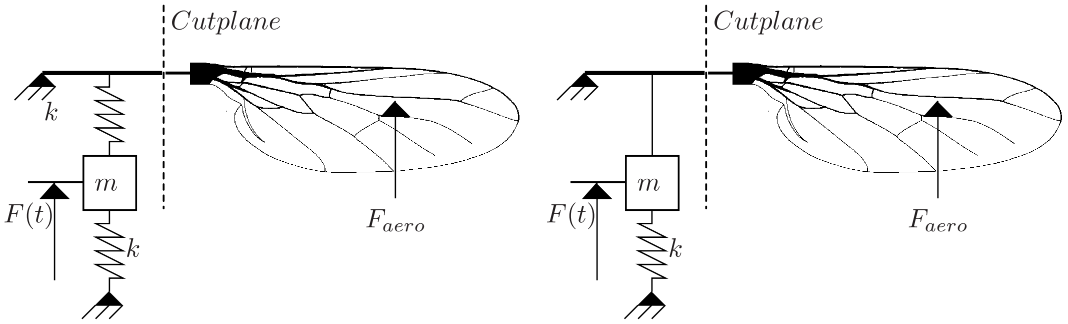


Figure 2. Systematic view of the resonant system

The goal is to design a structure that provides elastic energy storage, low mass, and a resonating frequency around 40 Hz, while providing large wing rotation to be able to drive the wing base. The flapping frequency is dictated by scaling laws, see Ellington.[20] Wing bending may contribute to the wing stroke and, consequently, reduces the rotations needed at the wing base, in fact it is torsion that is the dominant mode. This torsion can be exploited to create a wing which can passively deform such that the angle of attack is favorable for lift production. Tailoring the wing stiffness for both bending and torsion can be used to improve the wing kinematics for efficient lift production. In insects, the wing torsion scales with insect size, from almost no torsion in fruit flies to significant torsion in dragonflies, see Combes and Daniel[24].[26] Although wing torsion can be designed to be large. It might be necessary to create a joint in the wing root which allows for more freedom in the angle of attack of the wing. If present this joint has to be elastic in origin, or accompanied by a spring.

As mentioned, the design of the thorax structure cannot be decoupled from the type of actuator. However, in this stage of the design, choices have to be made in the thorax structure which influence the topology of the structure

and, thus, influence the number an type of actuators needed to drive and control the wings. A ring-type structure has been chosen as an initial structure for energy storage. The ring is a very basic structure and can be configured in a multitude of ways. It is able to perform a resonating motion in free-free conditions without the need for support structures. Although not a strict requirement within this setting, the requirements for the overall design impose very stringent boundaries on the weight, and thus render support structures undesirable.
Besides the energy storage and spring function that the described ring must fulfill, there is also the need to couple this to the wings. There are multiple ways in which this can be done. At this stage it is assumed that the wing rotation can be accomplished by passive means so that only the flapping movement of the wing has to be coupled to the thorax structure. The first method of transferring energy from thorax to the wing is to apply a weak coupling to the wing and have this system resonating, see Fig 3(a). The second is to apply a more deterministic method of wing coupling, that is to say that the wing position is dictated by the position of the thorax structure, see Fig. 3(b). Within the setting of compliant and flexible systems the boundary between stiff and weak couling are not obvious.



(a) Weakly coupled wing (b) Rigidly coupled wing

Figure 3. Wing coupling strategies

Many intermediate forms exist. It is safe to assume that the stiffer couplings will be closer to the final design. Preliminary estimates suggest that very weakly systems are not able to transfer enough energy from resonator to the wing.

IV. Flight control using resonance

First the level of control that is desirable has to be ascertained. The level of control needed in an indoor environment includes the ability to change altitude, the ability to change the heading and the ability to start and stop controlled forward or backward motion. When looking at the current setting of oscillating wings, there are certain limitations on the level of control. The response time of the system to a change in control signal will be significantly slower than in insects, since the ability to reconfigure the wingroot joint on a wingbeat-to-wingbeat basis is not available. The level of change in wing kinematics will also be limited. Due to the fact that the wing rotation is controlled passively by inertia, structural stiffness and aerodynamic forces. Knowing this, there are still a number of options to control the generation of aerodynamic forces in this setting of resonating wings.
The strive of this project is to design a truly integrated and insect-based wing actuation mechanism. This puts limitations on the options for control by other means than the control over the wing kinematics, i.e they are undesirable. There are various options to control an FMAV without influencing the wing kinematics. For example, a system that shifts the center-of-mass could be added to vectorize the aerodynamic forces, this option hinges on a high level of pendulum stability in the FMAV. Another option, is the addition of control surfaces, for example, a tail section. This option is a viable, but within the current setting the tail section will probably have negative effect on the total mass of the structure. The ability to perform take-off and landing maneuvers are not reviewed at this time.
The time dependent influencing of wing kinematics and the corresponding possibilities to control lift and drag generation by insect wings which, are well researched. A number of changes in wing kinematics have been identified and are, as such, candidates for the design of a control system for FMAV. These options are listed here: (Note that most of these methods are being used by insects.)

- Timing of wing rotation
- Magnitude of wing rotation (position dependent)
- Magnitude of wing stroke angle
- Frequency of wing stroke

- Center position of the wing stroke
- Time dependent wing driving

When looking at the scaling of FMAVs, the use of complex mechanisms at or close to the wing root is less desirable, as ,for example, in insects. The design and manufacture of these mechanisms, especially the actuation is very hard. It is therefore more attractive to search for methods of control that do not hinge on the real-time control of wing rotation. There are three options listed above that can be exploited when using a these are a resonant system. The magnitude of the wing stroke angle, the center position of the wing stroke and the time dependent wing driving. One major difficulty still persists, the wing rotation. It is assumed that a correct pattern of wing rotation can be accomplished by a combination of tailored stiffness in the wing and a wing root which has large rotational compliance.

Assuming that the resonating mechanism has been designed such that it incorporates a sort of steady state flight, either hovering or slow forward moving, the proposed control method is based on perturbing the steady state. This steady state is given in Fig. 4. This steady state represents wing motion which is fully symmetric w.r.t. the center position and parallel with the horizontal plane. Starting from this steady state the three control options will be reviewed.

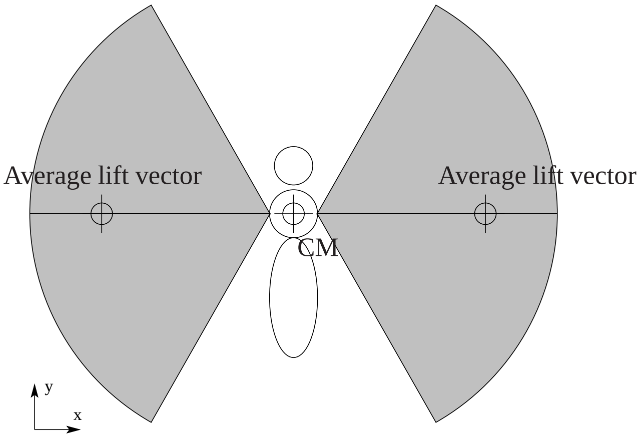
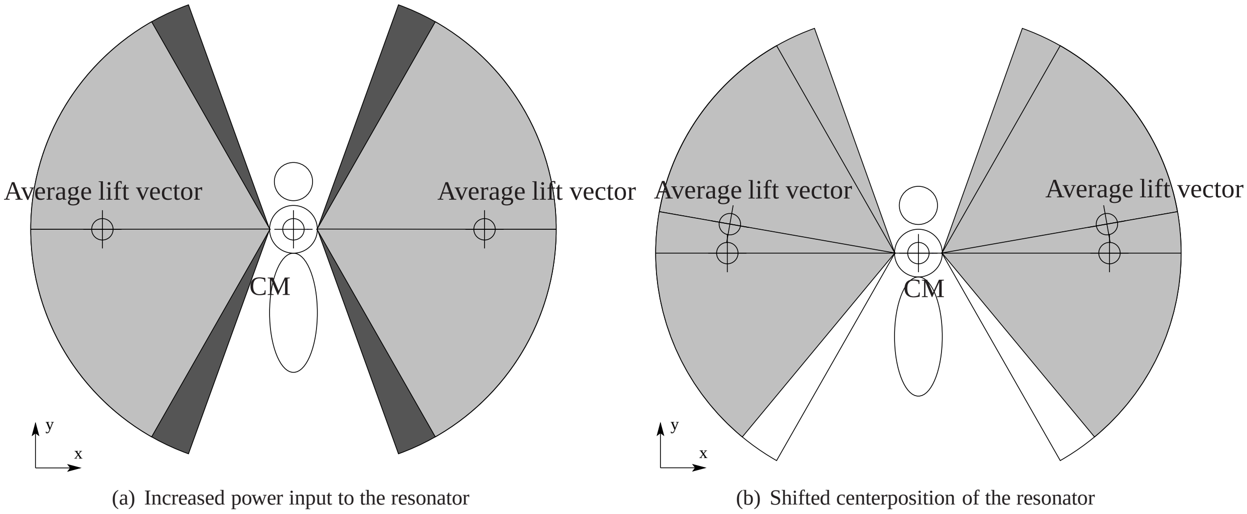


Figure 4. The wing disk representation of the hovering insect

IV.A. Amplitude of wing deflection

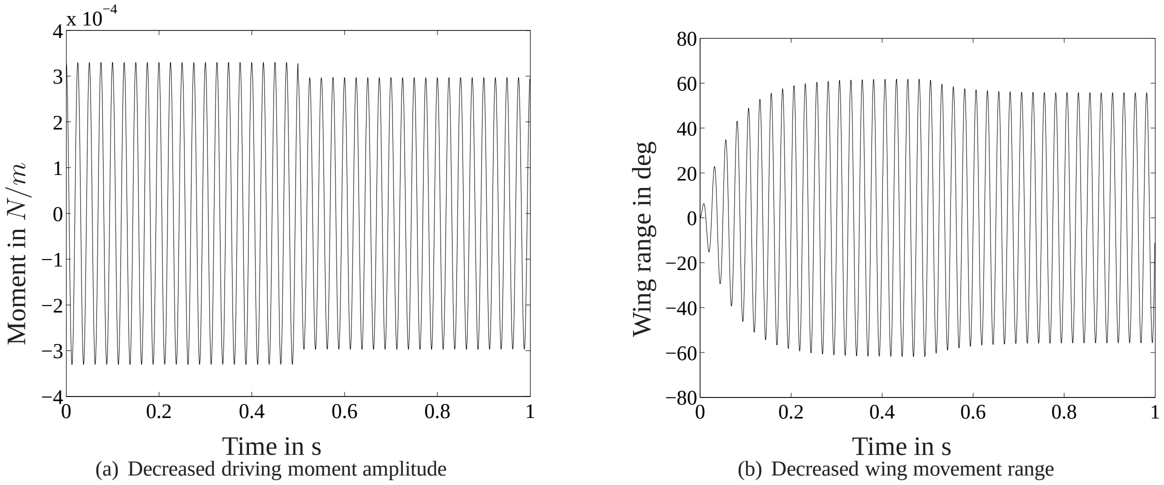
The wingbeat frequency is nearly constant due to the fact that the wings are part of the resonant system. When this system would be driven outside its natural frequency the deflections would rapidly deteriorate. Cox *et al.*[11] studied control systems that are based on the deterioration of flapping amplitude of the wings when the system is driven by frequencies which are not close to the natural frequency. They constructed a system where the left and right wings have resonance frequencies which are slightly different. By varying one actuator output an asymmetry in aerodynamic forces can be produced between left and right wing. Using this system one actuator can be used to get control in two degrees of freedom. One inherent drawback of this system is that in the steady state the system is not driven at optimal efficiency.

Assume that the FMAV is hovering with a horizontal stroke plane. As depicted in Fig. 4 looked from above. To create significantly more lift in a system where the wing motion is only controlled by the resonator input signal, it is necessary to increase the power input to the resonant system, see Pålsson.[27] This is done by providing a larger amplitude force to the actuator. One can create more lift because the wings get a larger stroke-angle and therefore higher speed in the center position. Note that the power increase is realized by increasing the amplitude of the control signal and not the frequency. The effects can be seen in Fig. 5(a). Hence, altitude control is achieved controlling the amplitude of the wing stroke. The same reasoning can be used to decrease the amplitude of the control signal and so decrease the effective wing stroke-angle. The results of the simulation using the resonator depicted in Fig. 2 are shown in Fig. 6(a) and 6(b). In these graphs a decrease in the driving moment results in a decrease in wing flapping angle. The response time of the resonator to adjust to the new energy state can be controlled by changing the Q factor of the system. It is possible in the setting of these oscillating systems to construct a system in which the increase or decrease in power input can be applied asymmetrically. This can be done, for example, by two weakly coupled resonators driven by two actuators. The effect would be that the possibility arises to generate more lift with one wing than the other, resulting in an rolling moment. When controlled this can be used to maneuver the FMAV not only in the up-down direction but also left to right.



(a) Increased power input to the resonator
(b) Shifted centerposition of the resonator

Figure 5. Examples of control by influencing a resonating motion



(a) Decreased driving moment amplitude
(b) Decreased wing movement range

Figure 6. Examples of control by influencing a resonating motion

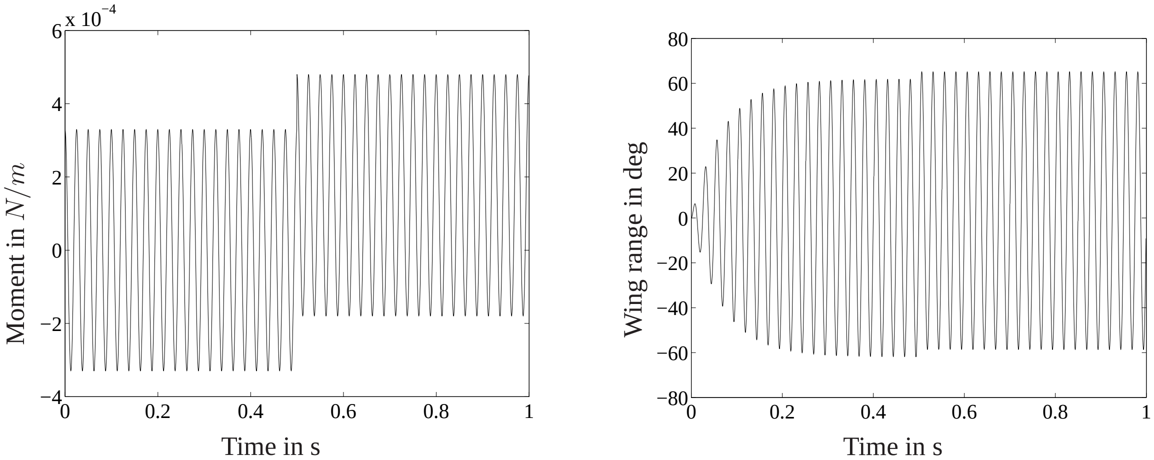
IV.B. Center position of the wing stroke

The same resonator can also be used to generate a pitching moment. When shifting the center position of the resonator, the position of the average lift vector with respect to the center of mass, a forward or backward pitching moment can be generated, see Fig. 5(b). This can be accomplished by providing a asymmetric control signal to the resonator. In the current setting influencing the center-position of the resonator can be done by applying an constant offset signal in addition to the time-varying signal. This is shown in Fig. 7(a) where a constant force is added to the resonator of Fig. 2 after the simulation reached a steady state. The result is shown in Fig. 7(b) which shows the resulting offset in the wing stroke-angle.

Note that the off-set is large compared to the amplitude om the total signal. The source of this effect is the Q factor of the resonator, a high Q factor in this sense means that the stiffness of the spring is large. Any offset force will therefore also have to be large. This has as a side-effect that the force range of the actuator has to be significant. In order to apply this in a real system the force range of the actuator has to be significantly large. Another option is to use an extra actuator which is able to slightly reconfigure the mechanism. Although more complex from a constructional viewpoint it is simpler from the viewpoint of control.

IV.C. Time dependent wing driving

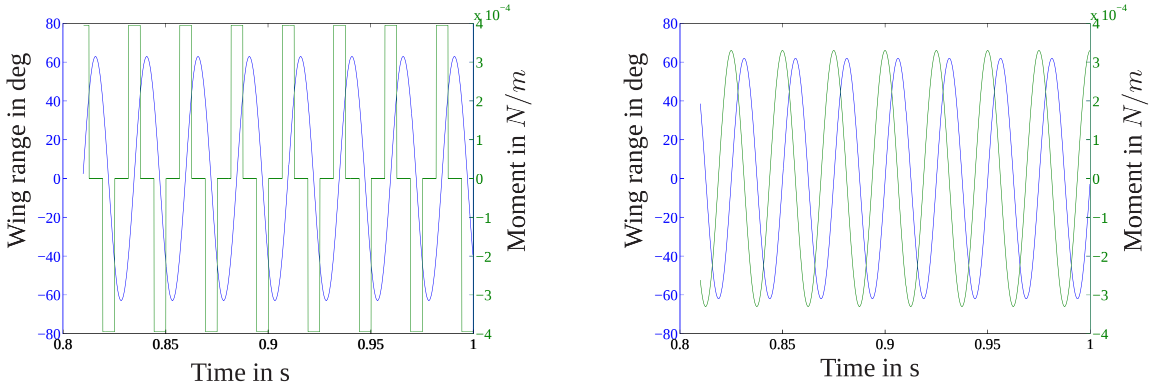
In all previous control mechanisms the force generated by the actuator is assumed to be sinusoidal in origin. However, it is possible to use other types of signals, for example, square waves, sawtooth waves or a combination of both, see, for example, Fig. 8(a) and 8(b) in which a the resonator from Fig. 2 is driven using two different control signals. Using this type of control it is feasible to distribute the power-input to the resonator in such a way that it is possible to influence the velocity profile of the wing stroke. Using this setup, the passive wing



(a) Offset in driving moment

(b) Offset in wing movement range

Figure 7. Examples of control by influencing a resonating motion



(a) Square wave driving

(b) Sine wave driving

Figure 8. Effects of different driving signals

rotation could be exploited to generate lift and drag forces which are different in the forward moving stroke and the backward moving stroke. The effect would a rowing effect in the wing stroke, causing forward or backward oriented forces.

Note that this system does not work for resonators which have high Q factors since they are insensitive to the type of force input. Systems with lower Q factors are more susceptible to this kind of control. And again the actuator has to be able to generate time variant forces as a response to time variant control signals.

V. Actuating the FMAV

The topology and morphology of the structure highly dictate the type of actuators used. The opposite is also true since a specific type of actuators might highly influence the morphology and topology of the mechanism. The choice of actuators is also influenced by other factors such as the actuator stiffness, the driving voltage, specific power, among others. Implicitly assumed here is the choice for electric power, since electric power is needed for control electronics and sensors anyway. The ease of application and the increasing energy density in electric storage are the other factors. Focus is here on actuators which are in the thorax structure, distributed actuators in the wings seem very promising but currently make wings unnecessarily heavy. The actuator technologies looked at are Shape Memory Alloys (SMAs), Piezoelectric, electromagnetic and Electro Active Polymers (EAPs). The different actuators perform different when exposed to the boundary conditions posed by an insect inspired FMAV. In Table 1, these actuator principles are compared on properties which are important for application in FMAVs. These properties include the energy density, which is important for vehicle mass. The maximum strain, in order to create mechanisms without the need for extensive mechanical amplification, should be considerable. Wing flapping angle is inherently large. The response speed for a full cycle, at the intended size range the flapping frequency is around 40 Hz so the response speed should be able to cover this range. The control complexity, is highly linked to linearity and hysteresis of the actuators. If the actuator is nonlinear in the control signal and exhibits hysteresis the control electronics need to be complex, and thus heavy. High voltages are not convenient in FMAV since they

Actuator type	Energy density $[J/g]$	Max. strain [%]	Response speed $fullcycle$	Control $Complexity$	Maximum efficiency [%]
Piezoelectric (PZT)	0.013	~ 0.2	Fast	High	$> 90\%$
Dielectric EAP	0.75	$1 - 300$	Fast	High	90%
Ionic EAP	0.001	2	Slow	High	$< 1\%$
E. motor rot.	0.005	NA	Fast	Low	$> 90\%$
Voice coil(electromagnetic)	0.003	50	Fast	Low	$> 90\%$
Shape memory alloy	15	1-100	Slow	High	$< 1\%$
Muscle mammal	0.07	40-50	Slow	NA	$> 35\%$
Muscle insect	0.10	∼5	Med	NA	$> 35\%$

Table 1. Comparison of different actuator technologies

require voltage converters. The efficiency has is repercussions on the endurance of the FMAV. High efficiency is very attractive. Data is collected from JPL,[28] Langelaar[29] and Bar-Cohen.[30] At the moment electromagnetic actuators are considered for practical reasons. Their energy density is less than other mentioned technologies but they provide a large freedom in the design space. A small electromagnetic actuator that meets the requirements will have to be designed. It is here that many challenges lie, since the topology for such an actuator is influenced by more constraints than maximum force and response speed. The main issue in FMAV design is vehicle weight. It is therefore expected that some efficiency and force generation will be lost due to the fact that actuator mass is also a stringent requirement.

For the application of electromagnetic actuators in the setting of a resonating wing actuation mechanisms a few aspects have to be taken into account. First is the place of the actuator in the resonant structure. These actuators do not have mechanical stiffness, they can be tailored to yield stiffness by electromagnetic means. For effective power transfer to the structure the actuator should be able to provide its largest force at the moment its strain rate is highest. The morphology of the actuator is a major design variable, subsequent studies are needed to design and optimize the electromechanical actuator to effectively fit within the setting of light-weight resonating structures.

The linear actuator technologies mentioned here, including the chosen electromagnetic types, exhibit frequency dependent power output. In this application the actuators share their actuation frequency with the wings. Consequently, for a higher power density the operating frequency will have to go up. To support a given mass larger wings with lower frequency are more efficient. Therefore an optimum has to be found between wing size and flapping frequency.

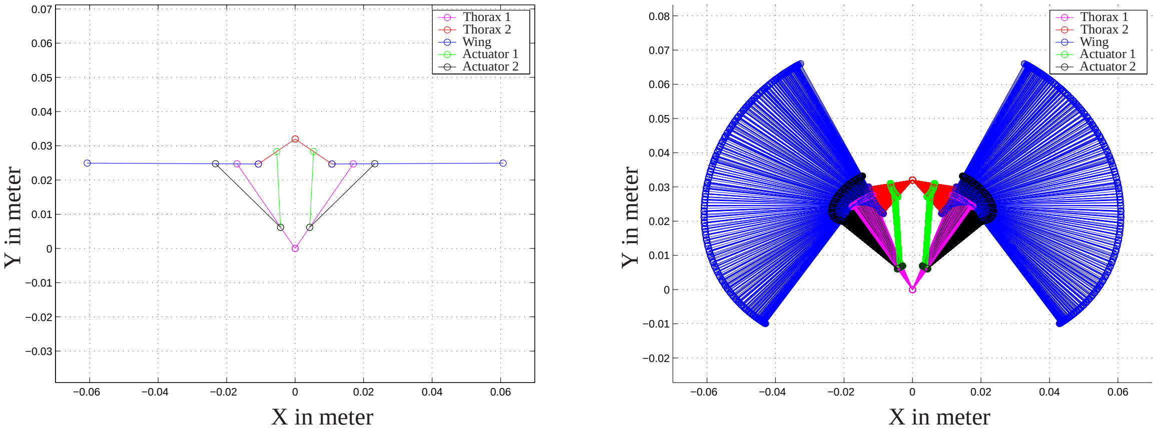
In the future EAP technology might come to such a level that is can be used in FMAVs. EAPs exhibit excellent properties for application in FMAVs, for example stiffness and power density. They are, however, currently not at a level that they can be used effectively in the current setting. Future developments will certainly produce highly effective materials and actuator topologies, in the field of EAPs. The prospect is that this type of technology will, when ready, bring large opportunities to the field of FMAVs.

VI. Prototypes and Testing

The configuration of FMAVs is usually inspired by nature. This leads to configurations which have two, four or more wings attached to a single thorax structure. It is possible to have a more distributed setup in which four wings are on the four corner points of a square, see Pålsson[27] and Kornbluh.[31] Although non-natural looking, this type of setup introduces natural flight stability. The mechanism depends greatly on the role the FMAV will have. The role intended for the FMAV within this project is mainly a hovering and slow moving mode, as described in the Introduction.

The topology and morphology of the wing actuation mechanism are being developed within a framework guided by numerical studies on insects as well as generating own concepts. This is done by using both multi-body representations of insect inspired mechanisms, as well as finite element models. A very useful source of inspiration and progress is the use of simple prototypes. It is these prototypes which usually provide best insight into the viability of different ideas. A start was made to model the thorax structure present in insects. Using 2-dimensional models. As an example, a model of the thorax of an dragonfly is shown in rest position, see Fig. 9(a). The actuated model is shown in Fig. 9(b), using simple aerodynamic damping. Note that the dragonfly has a thorax of the type shown in Fig. 1(a). The kinematics of this thorax can be represented by 2 dimensional models, when looking at the indirect driven insects the need for 3-dimensional modelling rises.

As discussed a ring-type structure was chosen to function as the main spring and thus energy storage for the resonating systems. A first prototype was build using the wing-coupling depicted in Fig. 3(a), the use of a spring to transfer energy from the ring to the wings. Note that the analogy in this case is not 100 percent, since the

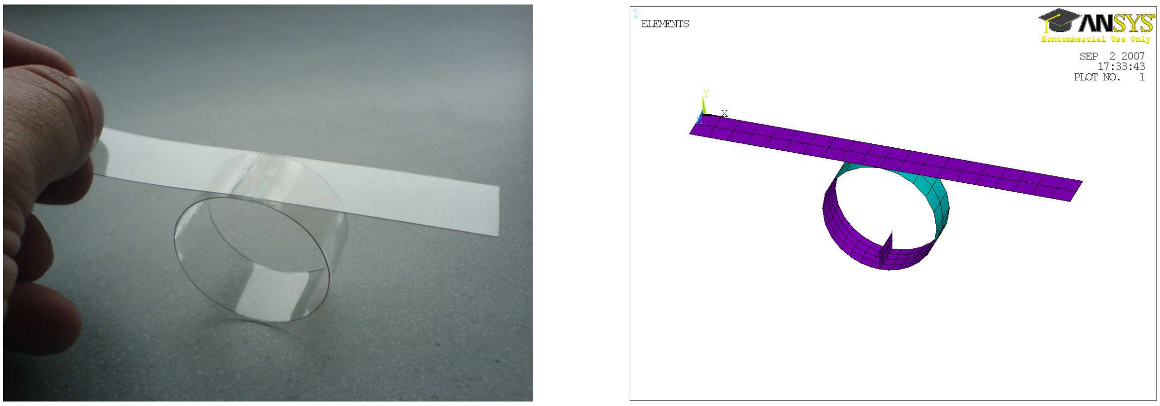


(a) Thorax model (b) Movement range

Figure 9. Insect inspired thorax models

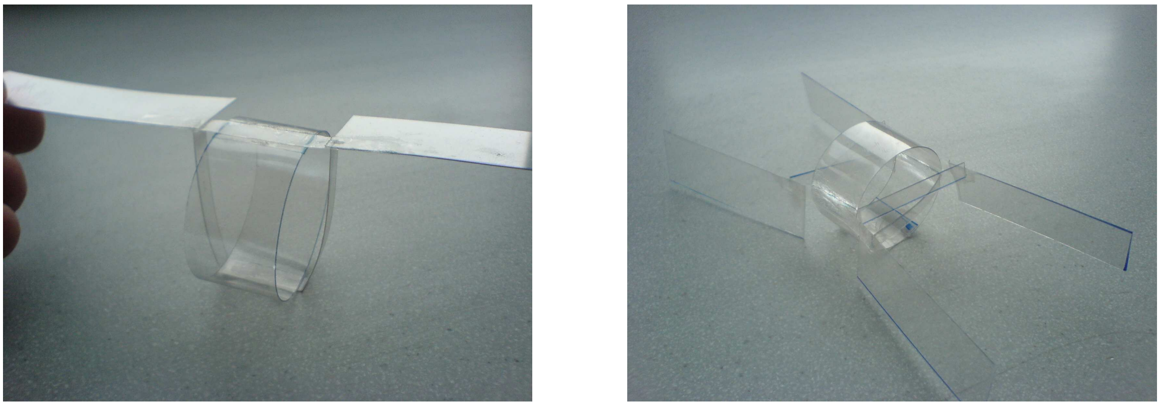
intended structure is not discrete but fully compliant. The structure was actuated by an electromagnetic motor as an exciter. The structure is depicted in Fig. 10(a) and the FE model in Fig. 10(b). The FE model was used to validate and natural frequencies and study influences of parameter changes. From this model early conclusions led to the fact that although wing deflection is very significant, the amount of power transfer from resonating ring to the aerodynamics is not enough to sustain flapping flight.

Based on the more deterministic model depicted in Fig. 3(b) another idea was realized. It is in essence a more complex variety of the first resonating prototype. Two struts were added to increase wing flapping angle. The wing root flexibility has been changed by adding two more compliant sections. The structure is shown in Fig. 11(a). An extension of this structure is the addition of 2 wings. As discussed earlier such a system is able to provide more stability, but will make some of the described control methods harder to implement. The four winged concept is shown in Fig. 11(b). To study performance, results of parameter changes and eigen-frequencies, FE-models of the proposed structures have been made. These are shown in Fig. 12(a) and Fig. 12(b) The added value of the current FE-models is not very large, as opposed to the value of simple and more complex experimental structures. Current research will be extended to maximize the usage of the spring-like function of the ring-type structure which serves as the basis.



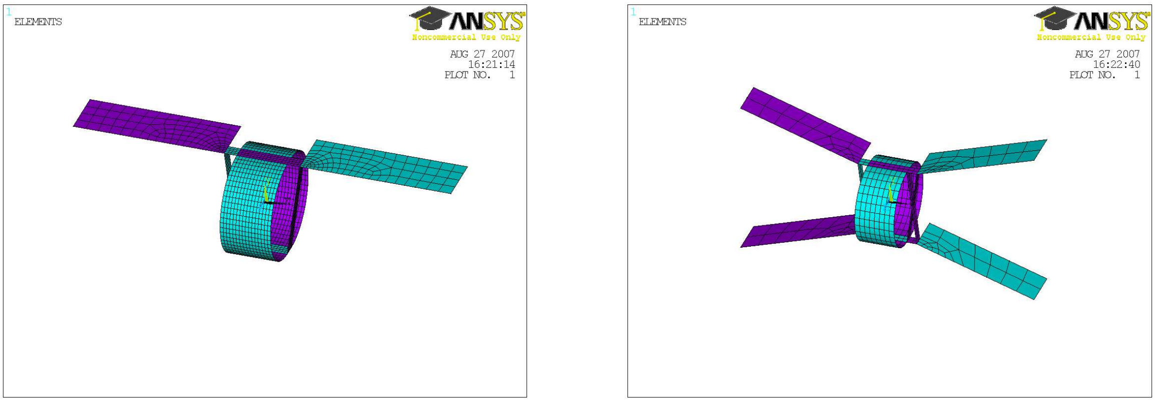
(a) Ring-based resonator (b) FE-model of ring based resonator

Figure 10. Ring-based resonator



(a) Thorax model 2 wings (b) Thorax model 4wings

Figure 11. Resonant thorax models



(a) Thorax model 2 wings (b) Thorax model 4wings

Figure 12. Resonant thorax models

VII. Conclusions and Outlook

The use of resonant elastic structures is very promising for application in FMAV. The design process is slightly more involved but can yield solutions which can be scaled down. The choice of using a ring-type elastic structure is very promising for the use as a basis for a FMAV. When using the ring as basis, a number of different wing configurations can be used. The wings can be coupled to the elastic structure in a variety of ways, with two extremes, fully compliant coupling and fully stiff coupling. The prototypes use intermediate forms.

The control of the FMAV by influencing the resonant state of the mechanism seems possible within this framework. The adjustment of the wing kinematics makes control over the of the aerodynamic forces possible. These forces can then be used to change heading and speed of the FMAV. Altering the resonant state of the system by altering the main wing actuation signal can be used to reduce the complexity of the wing root mechanism.

Although many actuators exist, for these dimensions linear electromagnetic actuators are a reasonable actuator candidate, however, for increasingly smaller designs magnetic actuation becomes less feasible due to unfavorable scaling laws and other actuator technologies have to be considered.

These are the first preliminary conclusions and are dominantly based on literature study and computational modeling. Functional models of different resonant mechanisms, both with and without actuators and wings, have been built. These mechanisms will function as testbeds for ideas as well as for validation of computational models.

Future developments include the construction of a more advanced testbed structure of a resonant wing actuation mechanism and wing structures. The first goal is to achieve enough lift and correct kinematic wing patterns to sustain hovering flight. Control over up an down movement has to be incorporated. These experiments will use an external power supply in the beginning. Later a move will be made towards onboard power.

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