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Resonance Based Flapping Wing Micro Air Vehicle.

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Abstract

Flapping wing micro air vehicles have many possible applications and have therefore been the subject of extensive research. The Atalanta project aims to develop a fully autonomous, 10 cm wingspan, flapping wing sensor platform. The structure is based on a fully compliant resonating structure with passive wing pitching. Several design improvements have taken place since the last report. Introduction of non-linear springs result in a more effective wing kinematic and extensive simulation and optimization was done to improve the wing design. Lighter electromagnetic actuators were designed while the possibilities of a chemical micro engine are investigated. Control experiments are underway using piezoelectric elements to locally change the structure stiffness thereby changing the kinematics of the system and thus the lift. To be able to efficiently design such a flight control, a framework was developed for the control of resonant compliant systems. Finally a sensor system for flight stabilization and object avoidance is suggested and under investigation.

1 Introduction

Flapping wing micro air vehicles (FWMAV) have been under development for some time as a mobile platform for sensing and surveillance for applications such a search and rescue, measurement and mapping of dangerous or inaccessible places, and as mobile communication nodes. The flapping wing method of flight is particularly promising for indoor applications and small scale vehicles [1],[2], but it presents a number of unique challenges. Therefore, such a vehicle presents a fascinating research subject as many problems need to be solved before an autonomous flying FWMAV can be realized.

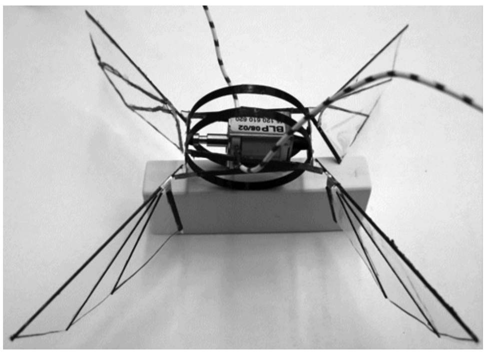

Figure 1: The first incarnation of the Atalanta FWMAV.

The Atalanta project was initiated as such a research vehicle by the industrial partners and aims at the development of a fully autonomous flapping wing flying sensor platform capable of hovering and slow flight with a wingspan of 10 cm. This size was chosen as it exhibits all the major problems without taking experiments and prototypes beyond normal manufacturing capabilities. However, all design decisions are made keeping further miniaturization in mind. Although the programme includes all issues from aerodynamics and flight kinematics, to control and navigation, most of the effort has been on the mechanical aspects, in particular wing flapping and kinematics. Figure 1 shows the design that was reported on previously [3]. Its four wings are driven by bringing the structure into resonance. The figure also shows the solenoid used in previous experiments to drive the structure.

2 Flight Kinematics

When looking at the performance of the MAV, the motion of the wings is the most important, next to weight. It is this wing motion that creates the aerodynamic forces and thus the lift and steering forces needed for flight. When considering the kinematics we can distinguish the basic sweeping motion of the wings and the pitching and deformation of each individual wing. Many papers have been published on the wing kinematics of insects [4][5][6], simulations of flapping wing motions using analytical models [7][8] and CFD [9][10], and experimental investigations [11][12]. However, the simulations and experiments usually simplify the problem to harmonic motions and the wing is assumed to be a plate. When looking at the flight of insects and hummingbirds we see quite different kinematics, which presents us with the question what kinematics would be desirable for a FWMAV and how to achieve this.

2.1 Wing Shape and Kinematics

The main consideration in the kinematic design is the motion of the wings. When we look at insects with a wingspan similar to the desired design, such as the hawkmoth (Manduca sexta), we see wing flapping that is not sinusoidal and includes an out of plane motion known as the heaving motion. Also torsion of the wing is apparent, resulting in varying angles of attack along the wing span as well as camber. These factors are usually not included in the design of FWMAVs, but their influence on wing performance is worth considering. To this end, an extensive investigation has been started on the optimization of wing shape and kinematics. The first results, using a quasi-steady aerodynamic model [13] and harmonic motions, show that many wing planforms have almost the same performance when considering lift production and efficiency [14][15]. A graph of the lift versus power performance of many optimized wings is shown in Figure 2 with four examples of corresponding wing shapes. In addition, this optimization shows the importance of wing torsion for efficient lift production and how this relates to wing shape. Preliminary investigation of wing performance with respect to heaving and torsion show the influence of both in particular for passive wing pitching, and further optimization will result in a more optimal wing shape, along with the corresponding kinematic. Investigation of insect wing kinematics often shows a distinctly non-sinusoidal wing stroke kinematic [14][6], and simulations with both the quasi-steady model and CFD have shown that a more constant wing translation and quick reversal at the end of the stroke increases lift over the sinusoidal kinematic [16].

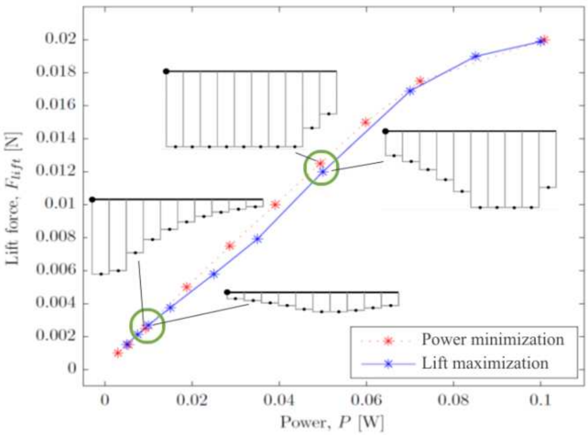

Figure 2: Optimized wing planforms for different lift and power requirements showing very different wing shapes with almost identical performance.

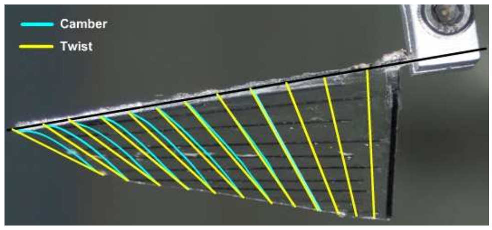

Figure 3: Front view of an experimental wing at midstroke showing pitching, twist and camber.

Practical implementation of this kinematic in a FWMAV is not trivial as full control of all degrees of freedom would require complex mechanics and several actuators per wing. However, insects manage to create their wing kinematic using passive wing pitching and deformation. A similar approach would do away with the need for full control over all kinematic parameters and use just one or two [16]. Simulations show that passive pitching and torsion can achieve efficient results that approach the optimal kinematic but require a heaving motion. Implementation of such performance in a wing is difficult, but experimental results are promising and have shown the desired pitching and twist. Figure 3 clearly shows the pitching and twist in a the front view of a wing in motion. It is also clear that this wing shows considerable camber which has not been included in the simulations. Wing design and the influence of camber is the subject of further research.

2.2 Resonance Based Flapping

An issue often discussed in insect inspired flight is that of resonance based kinematics for the wing flapping motion. Most insects seem to make use of resonance to drive the main flapping motion [18][19]. Although the advantages, such as the cancellation of losses due to inertia and the decoupling of aerodynamic loading and actuation are clear, hardly any of the current FWMAV designs use resonance. The advantages of such a system are countered by several difficulties.

- Actuation. A resonant system requires an actuator that is force coupled to the system instead of the more common displacement coupling. The most obvious solution is a linear electromagnetic actuator, but this limits the actuation frequency to the resonance (flapping) frequency, which introduces problems with the power needed per cycle.
- Flight control. Changing the flapping frequency, which is an effective way of controlling lift is not an option. Varying the drive frequency has a negative impact on the flapping amplitude and therefore the lift production of the wings.
- Weight. In order to have any resonance, a quality factor of more than 2 is needed which requires considerable energy storage in such a highly damped system. For this we need a more stiff spring structure, which will add weight to the FWMAV.

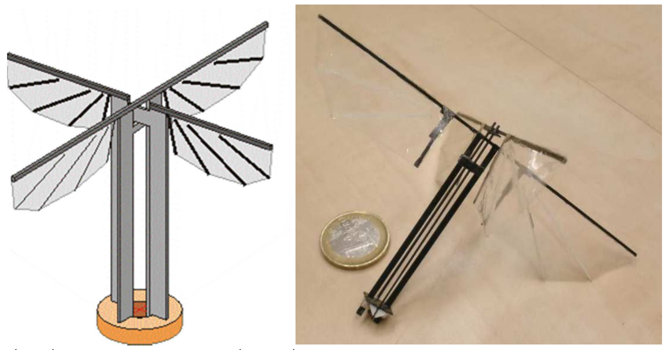

Figure 4: Schematic (left) and realization (right) of the four wing vibrating design using torsion springs for non-linear spring stiffness, resulting in better flapping kinematics.

To further investigate the possibilities of resonance, the Atalanta was designed as a resonant compliant structure [3]. The previously reported configuration consists of a ring shaped spring connected to a compliant mechanism to transform the linear motion into the required wing rotation. The overall system is designed with a resonance frequency of approximately 30 Hz, which is reported to be the most efficient for the 5 cm wings [20], and a quality factor of approximately 2.5 in air. Due to the linear spring behaviour of the rings the flapping motion of the wings is sinusoidal. As was discussed earlier, non-sinusoidal motion seems preferable and can be achieved in a resonant system using non-linear or bi-stable mechanisms. The use of non-linear springs or pre-tension can be used to convert the sinusoidal displacement into a more triangular motion. Although this allows for a more advantageous kinematic it can complicate the structure and has the disadvantage that the vibration frequency of such a system becomes amplitude dependent. To experiment with this non-linear behaviour a different structure was designed that also simplifies manufacture and makes the structure more robust. The new design is shown in Figure 4 and makes use of two counter rotating torsional springs. The rotation allows for a direct connection between the wing and the spring and does away with the conversion mechanism. The configuration of the torsion springs in combination with the large rotation results in the non-linear response and a more constant wing translation velocity and faster wing reversal. Further optimization of this non-linear spring is underway, as is the use of both pre-tension and bi-stability to achieve an optimal wing sweeping kinematic. For more efficient flight when using passive pitching a heaving motion is desired resulting in the figure eight motion of the wingtip. Like the pitching, we would like to achieve this in a passive manner without the need for actuators or control. The first design introduces some torsion flexibility close to the root of the flat spar, which, with the moment caused by the passive pitching results in a torsion and out of plane bending of the wing spar, which gives the desired heaving motion.

3 Actuation

Actuation is one of the biggest challenges of FWMAVs. Driving a resonant based structure is difficult as the design requires reciprocal motions which are limited to the vibration frequency of the design. Two options have been under investigation. First, electromagnetic actuators, as these are easy to control and make. Although, the energy density of such actuators is relatively low [21] when taking into account their efficiency and additional requirements with respect to drive circuitry and comparing them to other options at actuation frequencies of 30 Hz, they compare quite favourably. Two electromagnetic actuators were designed. The first linear design consists of a simple coil and two permanent magnets, which is used to drive the ring shaped spring of the original design. This design outperforms more sophisticated Lorenz force actuators due to the low volume of the relatively heavy core material for the magnetic circuit. The strong asymmetry of the force output of the actuator is compensated partially by modification of the spring but additional non-linearity is of little importance due to the resonant nature of the system. The second actuator uses a permanent magnet that can rotate in a coil and thus will try to align itself with the field. This actuator is used to drive the torsional spring of the new design.

As an alternative, the feasibility of a chemical engine is under investigation. Such an engine can take advantage of the high energy density of a chemical fuel and the reduction in weight as the fuel is used. Previous research on a suitable fuel and reaction for such an engine showed the potential of the pulsed catalytic decomposition of hydrogen peroxide. However, the engine at the scale required does not exist. In order to design such an engine, an extensive thermodynamic investigation of the primary methods for converting a chemical reaction into mechanical work was done, taking the problems of miniaturization into account. When considering the application, which requires a reciprocal motion, the Otto engine principle was found to be the most promising. Research is underway on the design of such a miniature chemical engine for FWMAV applications.

4 Flight control

In order to stabilize and steer the FWMAV, control is required. In a resonating structure with passive wing pitching, no direct handles are available for the control of the vehicle as structures such as a tail and rudder exclusively for control purposes are undesirable due to their weight. In order to control the vehicle, the basic symmetry of lift production of the four wings must be broken in order to create a rolling motion which is required for stabilizing hover and through a tilt in the thrust vector allows for sideway motion. As the whole structure can be considered a resonating system, the kinematic of the system is determined by the stiffness and mass distribution in this system. The lift production of each wing during flight is determined by this kinematic, and any changes in this distribution will result in a change of kinematics and therefore in lift production. In order to determine where to change the structure to achieve the desired kinematic response with the least amount of energy, a general design framework was developed based on using the modal description of the structure, required modification and results of actuation [22][23]. This allows for an optimization of the placement of control actuators to achieve the needed controls.

The structural changes caused by the control actuators can include variations in stiffness, damping or redistribution of mass. Of these, changes in stiffness and damping are the simplest to achieve through the use of piezoelectric patches. Passive control through the opening or closing of the contact between the electrodes will result in a change of apparent stiffness of the patch without the need for additional energy. Simulations have shown that local stiffness changes up to 20% are possible, which is sufficient to achieve the kinematic changes and therefore the control required for flight stabilization and steering. Experiments are underway to determine the change in kinematic that can be achieved using such a system.

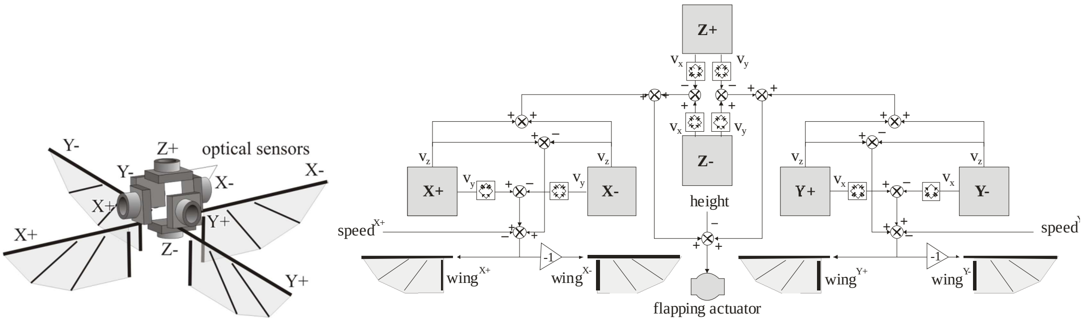

Figure 5: Stabilization and object avoidance system for hovering and forward flight. Placement of the optical sensors (left) and a possible analogue control system (right).

Apart from the changes that can be achieved this way, the initial kinematics and how this produces lift is of great importance to the control. The wings shape and kinematic determine where the resultant force is with respect to the centre of mass and therefore will have great influence on how a change of lift production relates to a control moment. Consider the two top wings in Figure 2. Both produce virtually identical lift and require the same power in hovering flight. However, this resulting lift acts closer to the wing root for the wing on the left than for the wing on the right, resulting in a different moment around the centre of mass. This shows that de control requirements should be taken into account when designing the wings.

5 Sensors and Control Systems

For the stabilization of the FWMAV and autonomous flight, sensors are of the utmost importance as the time constants for rolls and disturbances are so small that a pilot can not correct them. In addition, the possibility of autonomous flight must be kept in mind as the ultimate goal. The requirements of weight and power limit the possible sensor and control systems that can be used. Inspired by insects senses, a sensor and control system is under investigation that uses image flow sensors and a simple control circuit. Similar systems have been shown to be effective for stabilization and obstacle avoidance in fixed wing MAVs [24],[25] but have not been applied successfully to hovering vehicles. However, these system are attractive in that they used simple analogue control systems and can be designed to show object avoidance behaviour without the need for complex image processing. A flow sensor based control system for flight stabilization and object avoidance was designed (see Figure 5) [26], and is now under investigation.

6 Conclusions

The FWMAV developed within the Atalanta project has shown the possibilities of using resonant systems for the basic wing sweeping and passive pitching of the wings. The investigation of the wing design space has shown that considerable advances in lift and efficiency can be realized by using the proper wing shape and wing kinematic. This includes the passive pitching, twisting and heaving of the wing. It also shows that control considerations play a role in most aspects of the design. Electromagnetic actuators where designed to drive the two FWMAVs but actuation and power storage are still the main challenge in the development of a usable FWMAV. Further research will continue in the design of chemical micro engines. To control the FWMAV, piezoelectric patches placed around the structure can be used without the need for additional power, high voltages and at a minimal additional weight. However, the sensor and control systems required for stabilization and autonomous flight have not been realized and require further research.

The design of FWMAVs cannot be broken down in the design of separate subsystems. An overall design approach is necessary for achieving autonomous flight and unconventional solutions, such as resonant compliant structures, non-linear mechanics and analogue controls systems must be considered and developed further.

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