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Some problems of micro air vehicles development

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Abstract. This paper is an overview of the application potential and design challenges of micro air vehicles (MAVs), defined as small enough to be practical for a single-person transport and use. Four types of MAVs are considered: 1) fixed-wing, 2) rotary-wing, 3) ornithopters (bird-like flapping) and 4) entomopters (insect-like flapping). In particular, advantages of a propeller-driven delta wing configuration for type 1 are discussed. Some detail is also given for type 4, the least understood of the four, including a new concept of manoeuvre control for such MAVs. The paper concludes with a brief prognostic of the future of each MAV type.

Key words: micro air vehicles, fixed-wing, rotary wing, ornithopter, entomopter.

1. Introduction

Micro Air Vehicle (MAV) is defined here as a small, portable flying vehicle which is designed for performing useful work. Its construction should enable a single person to operate it together with a complete ground station. Moreover, MAV should be safe and even collision with a human does not have any harmful consequences. In most cases, MAVs are envisaged to provide direct reconnaissance in various environments. These environments impose various requirements on the vehicle and hence there are different concepts of MAVs' design exhibiting different characteristics allowing them to match these requirements. However, all these concepts pose certain problems which have to be solved before MAVs can be utilized. This paper attempts to present these problems and show some possible solutions. It is organised as follows. Possible applications are discussed in the first section together with the resulting requirements. The most important problems of fixed wing, rotary and flapping wing MAVs are described in Section 2. Particular attention is paid to flapping wing MAVs, since they are the least developed so far and their characteristics are not widely known. A prognosis for each type concept of MAV is presented in Conclusions.

2. Examples of applications and requirements

In general, MAVs [1] are envisaged to perform any dirty, dull and dangerous reconnaissance missions in a direct neighbourhood of the operator. There are several typical missions:

– Outdoor NBC emergency reconnaissance
– Crowd control
– Suspect facilities
– Snap inspection of pollution
– Road accident documentation
– Urban traffic management
– Search for survivors
– Pipeline inspection
– High risk indoor inspection

In the case of NBC emergency reconnaissance, an MAV should fly into a toxic cloud and bring back a sample of contaminant for analysis. Since human operators do not want to stay close to the accident site, the long range of operation is required as well as the ability to fly against strong opposing winds. Crowd control is performed by police forces when there is to observe the crowd's behaviour with as little interference as possible from police. They do not want to stay too close to the crowd in order to avoid antagonizing the crowd or using a conspicuously large flying object.

Similar qualities are needed to observe the suspect facilities, since the presence of police forces and/or large flying objects would influence the suspects', behaviour thus frustrating police action.

An ability to sample industrial emissions released to the atmosphere would be useful, especially in the view of global warming. In this case, neither long range nor long endurance is required. Inspectors need just to stop relatively close to the site and take the sample as fast as possible (without being noticed by the inspected company staff). An ability to negotiate fast winds would be required, because of the need to fly to the high chimney tops. Also, an ability to take off vertically would be advantageous, since sufficient takeoff area may not be available. In the road accident documentation case, police would not be interested in long endurance nor long range since they have to reach the site personally anyway and prepare the

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documentation as quickly as possible not to cause excessive traffic jams. A stable hovering platform with VTOL capability would be required. Hover is necessary to obtain good quality pictures, while VTOL should enable MAV application in most circumstances.

In the case of urban traffic management, MAVs would supplement existing stationary surveillance systems. The greatest disadvantage of the stationary systems is that they provide partial information only and a large number of systems would be required to provide complete coverage even for a moderately sized city. The number of required systems could be significantly decreased if some of them were installed on-board of MAVs. Traffic problems could be located by stationary systems and solved with the help of mobile ones. After one problem is solved, mobile systems could fly to another site. Long range and long endurance would not be required because vehicles could be "refuelled" from existing electrical urban infrastructure. Moreover, they would not be required to fly all the time, but only during relocation.

A need for the system capable to find survivors became apparent after the World Trade Centre terrorist attack. Rescuers could have saved more lives if they had had a system designed to fly through the rubble, search for people and deliver necessary food and medications. Instead, they had to clear the rubble first which took several weeks and then they found no one alive. MAVs would be a good solution in this case. They could penetrate the rubble regardless of any "terrain" obstacles that could stop other vehicles. Ability to fly forward and hover efficiently and manoeuvre in confined spaces would be required here. On the other hand, high airspeed is not necessary and may be disadvantageous in some cases. This kind of system can be useful also in other disasters, e.g. earthquakes, hurricanes or tunnel roof fall in a mine.

There is a need to inspect various types of pipelines. This task can be assigned to different types of robots, but only flapping wing MAVs will be able to perform such mission without minimal preparation even in complicated installations. Again high manoeuvrability would be necessary as well as good flight efficiency.

In the case of high risk indoor inspection flapping wing MAVs would provide more flexibility when inspecting dangerous laboratory or industrial facilities. Similarly to the traffic control example, the task can be also served by a fixed inspection system, but a greater number of systems would be necessary to provide complete coverage. Instead, flapping wing MAVs could provide the necessary coverage regardless of any changes made to the installations.

3. Outline characterization of MAV types

From the analysis in the previous section it can be seen that various applications require different MAV characteristics. In some cases these characteristics exclude each other. Therefore, it is reasonable to analyse various MAVs concepts for each type of mission. At the moment four configurations are considered: fixed wing, rotary wing, ornithopter (inspired by birds) and entomopter (inspired by insects). It seems reasonable to assign them to the missions as follows [1]:
– Fixed wing or ornithopter MAVs for long endurance outdoors missions
– Rotary MAVs for short endurance outdoor missions with hover
– Entomopter MAVs for indoors missions

3.1. Fixed wing MAVs. This is the best developed type of MAVs. There were several prototypes built and proposed to customers already. They exhibit quite good forward flight capabilities: gliding ratio in order of 8, maximum speed in order of 20 m/s and flight duration in order of 1 hour. They have power loading in order of 13 kg/kW for steady level flight. Figure 1 shows the power required for flight measured for the MAV built in the delta wing configuration with weight of 0.25 kg and span of 0.45 m.

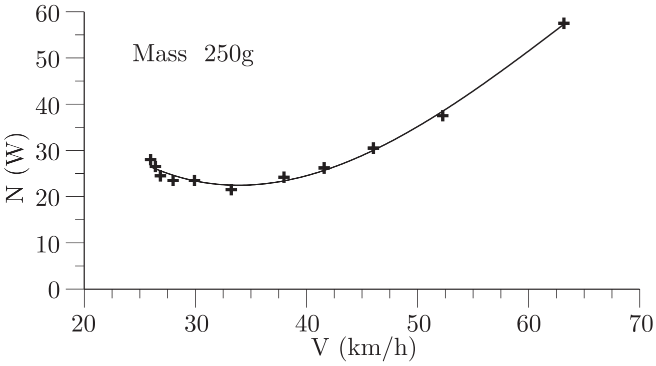


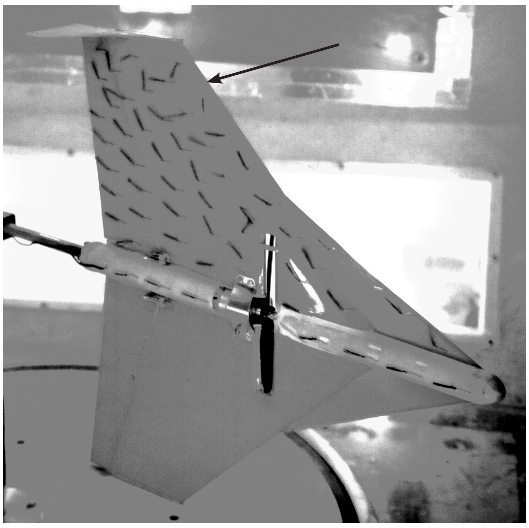
Fig. 1. Power required for flight of 250 g fixed wing MAV

Fig. 2. Possible design of gust resistant fixed wing MAV

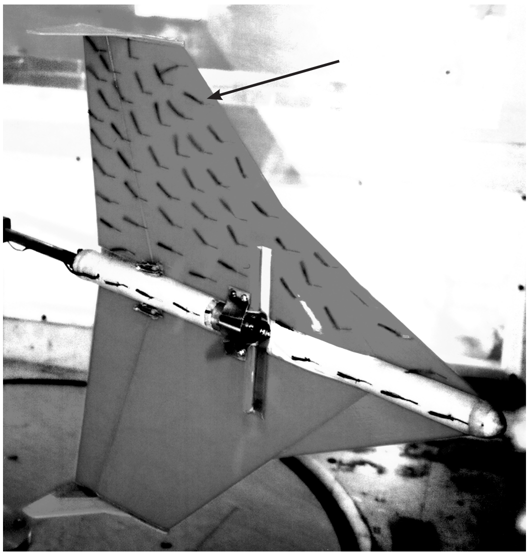
The most important problem encountered so far is the quality of images taken from onboard TV equipment. The problem is caused by the necessity to fly in the Earth boundary layer that is turbulent [2]. Near Earth turbulence is particularly difficult for MAVs because of their small sizes. This problem can be solved by application of advanced control system combined with a highly manoeuvrable aerodynamic configuration [3]. Figure 2 shows one possible design. The non-standard propeller location helps to keep the flow attached to the control surfaces even for quite high angles of attack which provides controllability even in strong gusts. Figures 3 and 4 show the effect of the propeller on the flow and resulting lift coefficient.

Quite well organised flow can be observed when propulsion is active Fig. 3(b), whereas large regions of separation are present when propeller does not rotate Fig. 3(a). This is true not only in the propeller stream, but also close to the wing tip. Of particular interest are three outboard tufts close to the leading edge. They indicate no flow at all without propulsion and organised flow with propulsion.

This effect can be probably explained by unsteady effects similar to these described in [4–7], but created by propeller rotating in the slot. Similar result can be probably obtained by application of flapping propulsion for fixed wing aircraft [8]. The results presented here were confirmed by flight testing [9].



(a)



(b)

Fig. 3. Comparison of the flow over the MAV without (a) and with (b) active propulsion for AoA = 25°

3.2. Rotary MAVs. Rotary MAVs have been also quite successful recently. A few designs reached the flight tests phase. Unfortunately, similarly to their larger originals they are not particularly efficient. The most advanced design presented by SEIKO EPSON [10–12] is capable to fly controllably with payload only for 3 minutes. So even if its efficiency was doubled and propulsion efficiency tripled, it would not fly longer than ca. 20 minutes. This conclusion can be supported by DARPA requirements concerning Organic Unmaned Air Vehicles (OAV) [13]. OAV are a new class of UAVs devoted for urban warfare with takeoff weight in range between 10 to 35 kg.

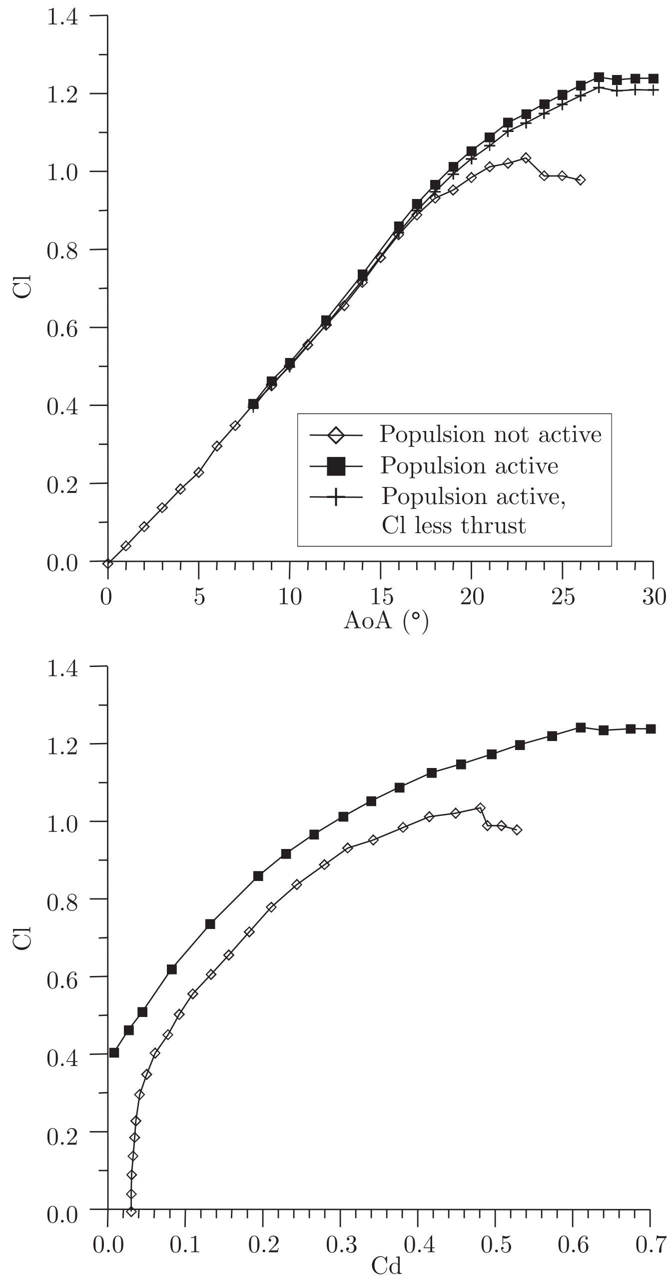


Fig. 4. Lift coefficients of the MAV with and without active propulsion. The propeller slot was sealed in the case of measurement without active propulsion

They are envisaged to operate in "urban canyons" for 15–25 minutes. On the other hand, rotary MAV configurations are the only configurations capable to combine acceptable high and low speed characteristics including hovering. They are also the only controllably hovering flying objects at the moment.

3.3. Ornithopters. Ornitopters attempt to imitate bird wing kinematics. Birds flap up and down with small variation in angle of wing incidence. This allows to generate the thrust while maintaining small variation in angle of attack. However, thrust generated this way is quite small. Moreover, this method of thrust generation requires forward speed similarly to fixed wing aeroplanes. Therefore, birds cannot hover, except for hummingbirds but hummingbirds apply insects' kinematics rather than birds'. As a result, birds need some initial airspeed to take off. This airspeed can be obtained by jumping or running. In flight, birds can apply wing shape morphing thanks to multi-hinged skeleton and active flow control thanks to feathers controlled by separate muscles [14]. Both of these features are very important, since they allow to optimize the flow around the wing to certain flight conditions which allows to climb even with relatively small thrust generated. Moreover, birds can increase their flight range thanks to their high gliding ratio which enables them to utilize thermal atmospheric streams. They can also exploit the ground effect, particularly in the case of flying over water.

Wing shape morphing and flow control are particularly difficult to obtain in the ornithopter. In an engineering implementation bird-like wing morphing would require multi-spar and multi-actuator design which would be very complicated, heavy, and not reliable or advanced intelligent materials [15], not available at the moment. Bird-like flow control could be imitated by application of MEMS actuators over the whole wing [16]. This solution would require significant progress in the area of MEMS technology. As a result typical ornithopters are seriously simplified, thus not allowing to utilize advantages bird flight. Designs equipped with only one hinge are usually not effective, as they can only increase their gliding ratio with constrained ability to climb. DeLaurier's ornithopter [17,18] is probably the most advanced ornithopter at the moment. Its wing design allows constrained wing morphing and wing incidence variation during flapping. This enables a reasonable climb rate, but was obtained with a very complicated wing structure.

3.4. Entomopters. This is the least developed group of MAVs. Entomopters attempt to imitate insect wing kinematics. The major difference between birds and insects lies in variation of wings' angle of incidence. Birds generally flap up and down with only minor angle of incidence variation (in order of a few degrees), maintaining quite small angles of attack. Insects' kinematics utilizes large and rapid change in wing angle of incidence (in order of 100 degrees) at the end of each stroke. Therefore, it is often called as a "pitch reversal" since the wing is almost flipped over at the stroke end (Fig. 6). This allows to generate much stronger vortical system in the flow including leading edge vortex since high angles of attack are typically applied. As a result lift force peaks are generated which should allow enthomopters to hover and take off vertically like insects do. Despite progress in fundamental analysis of insect-like hover [19,20], understanding of insect flight aerodynamics and flight dynamics [21] is still elusive. Therefore only flapping test rigs have been built for aerodynamic experiments so far, rather than ready MAVs. The only "flying" prototype [22] is not controllable and too small to carry useful payloads, since it weights only 1g. Designs suitable for future application with wing span of ca. 0,2 m and flapping mechanism in the 0.025×0.025×0.025 m box are just emerging Fig. 5 [23,24].

There are also three large-scale mechanisms designed for aerodynamic testing, rather than real flight [25–27]. They allowed measuring time histories of the lift during flapping. One of them is presented in the Fig. 6 according to [28]. Note that advanced pitch reversal means that pitch reversal occurred before the wing stroke end and delayed pitch reversal means that pitch reversal occurred after wing stroke end.

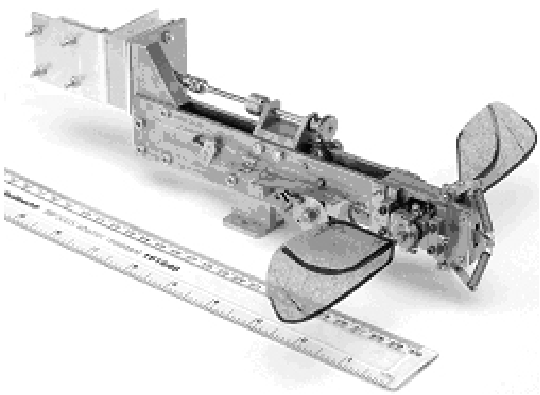


Fig. 5. Flapping test rig in the size of future MAV (after Ref. 23)

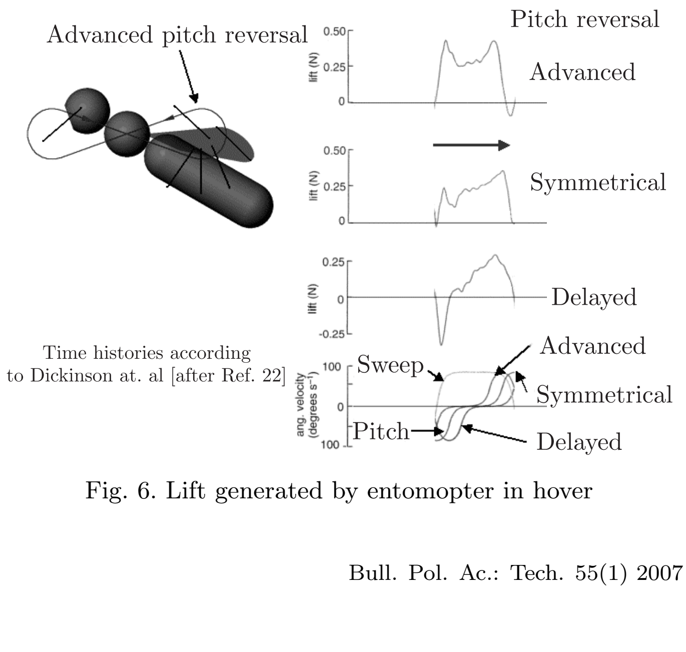


Fig. 6. Lift generated by entomopter in hover

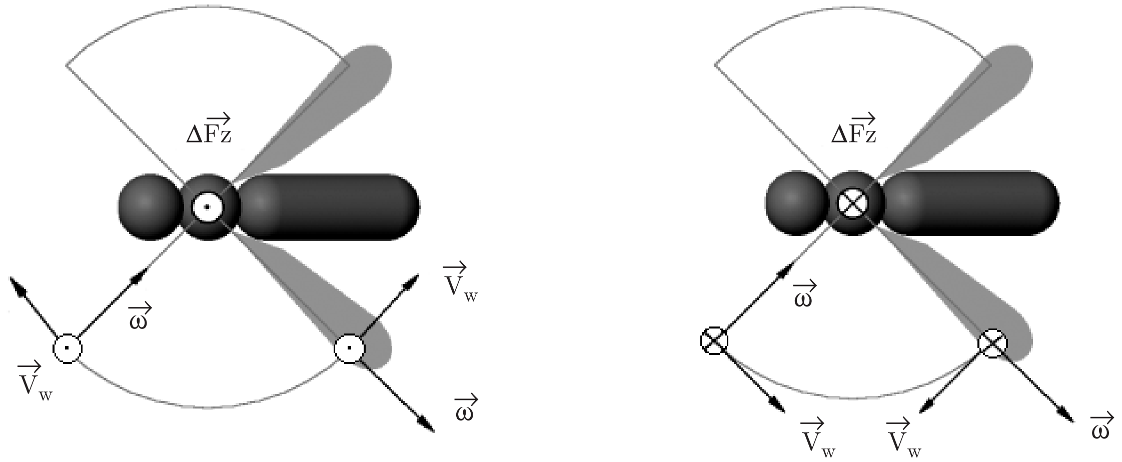


Fig. 7. Lift peaks senses

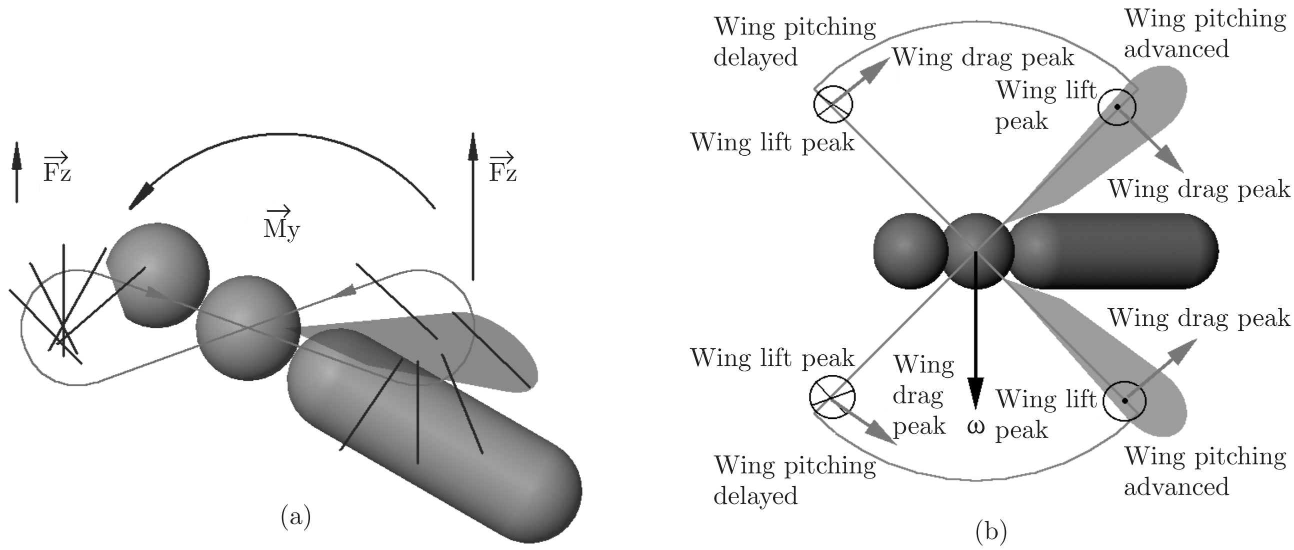


Fig. 8. Global pitching moment generated by different wing pitch reversals on both stroke ends

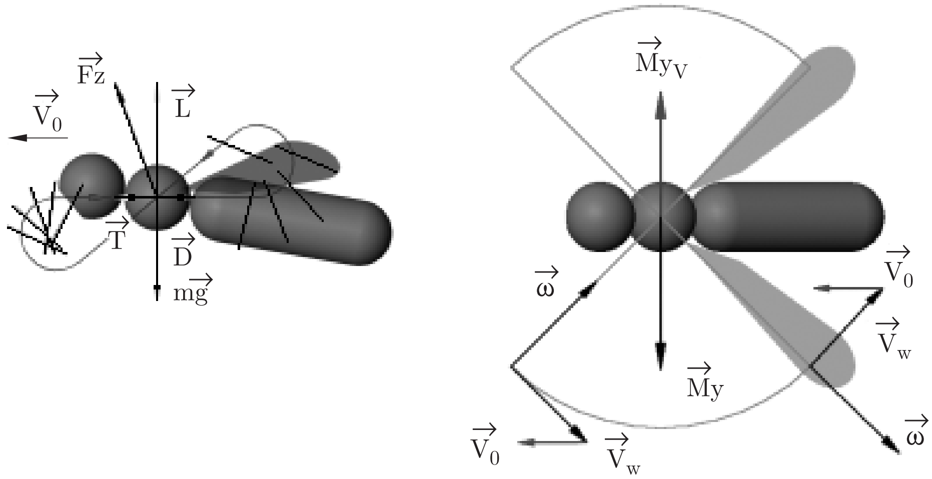


Fig. 9. Forces and moments balance for the forward flying flapping MAV

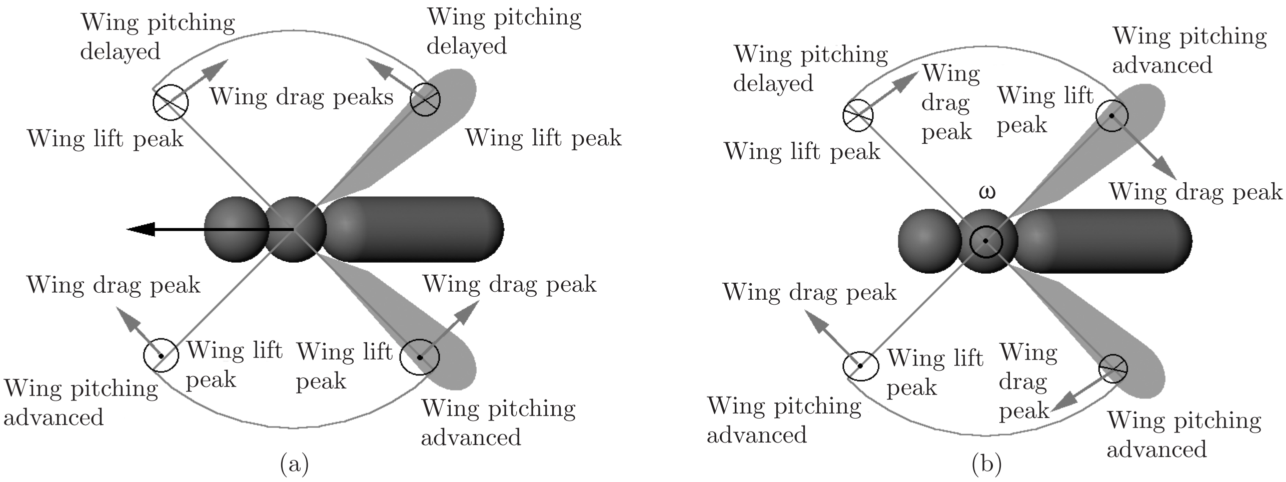


Fig. 10. Entomopter control in roll (a) and in yaw (b)

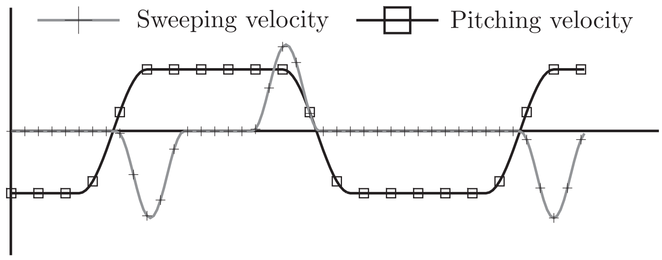


Fig. 11. The most advanced and the most delayed pitch reversal

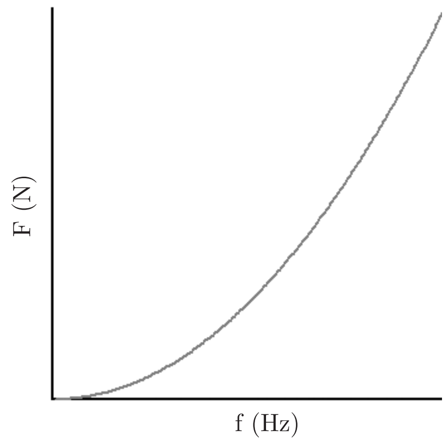


Fig. 12. The character of the flapping wing loading

As can be seen from Fig. 6, the lift is not uniform during the stroke. There are two lift peaks at the beginning and at the end of each stroke. It is worth noting that both lift peaks have the same sense as the product $\boldsymbol{\omega} \times \mathbf{V}_w$. Both are directed simultaneously upwards or downwards (Fig. 7), but never in opposite directions.

Hence it is possible to hypothesize that lift peaks are proportional to this product. This observation allows analysing transient state of the entomopter between hovering and forward flight. Let us assume that because of control command pitch reversal becomes advanced on one stroke end and delayed on the opposite. This will generate the opposite lift peaks on both stroke ends (Fig. 8) and the resulting global pitching moment in the direction of negative lift peak (delayed wing pitch reversal).

As a result, forward thrust, forward speed and the drag will be generated Fig. 9. However, forward speed generates its own product $\boldsymbol{\omega} \times \mathbf{V}_w$ with the opposite sense to the previous one. Therefore the opposite global pitching moment is generated as well. Finally, the new balance state is established when both moments become equal to Fig. 9.

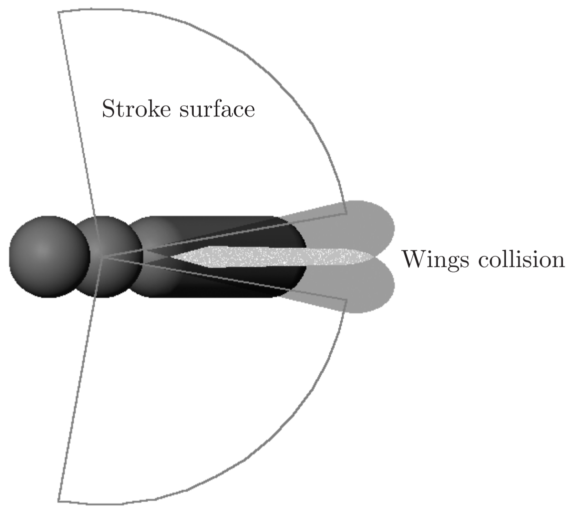


Fig. 13. Shifting the whole stroke surface backwards

Roll control can be obtained similarly by application of advanced pitch reversal for one wing and delayed pitch reversal for the opposite wing (Fig. 10a). Yaw control will utilize the fact that resistance against the wing motions behaves similarly to the lift [27,29]. Therefore antisymmetric application of the advanced and delayed pitch reversal like at the Fig. 11b should provide required yawing moment. This mechanism would explain not only the method of change between hovering and forward flight but would also suggest a main constraint of the entomopter.

Pitch reversal advance and delay cannot be increased indefinitely. Figure 11 shows the most advanced and the most delayed pitch reversal. The most advanced pitch reversal occurs if a pitch reversal ends at the same time as a stroke ends. The most delayed pitch reversal occurs if pitch reversal begins at the stroke end. Further advancing and delaying will not increase the speed since lift peaks will occur on shorter arms thus decreasing the pitching moment generated.

There are also three other methods to increase forward speed, but all of them are of limited applicability.

First of all, it is possible to increase wing linear and/or rotational velocity during pitch reversal. This should increase the value of the lift peak, but also the wing loading. Figure 12 shows how the wing rot loading changes with the flapping frequency.

As it is seen, a small change of the frequency results in a quite high increase of the loading for higher frequencies. Therefore, it is reasonable to assume that this method will not allow to increase the speed too much, taking into consideration that currently existing mechanisms are at the material limits even for pure hovering.

The second method of airspeed increase would require the whole stroke surface to be shifted backwards. This method is quite difficult to implement mechanically, and constrained by simple geometry. The wings cannot hit each other or any other aircraft components. Therefore the airspeed increase is also constrained in this case.

The third method assumes control by CG position like in the case of hang glider [30,31]. It is assumed here that entomopter will be equipped with insectlike abdomen. This abdomen will be rotated forward and backward for forward speed control. However, application of this concept is quite complicated since abdomen has to be relatively heavy. This means it will contain at least batteries supplying onboard equipment and propulsion. Wires delivering the current will have to go through the hinge. This will require a powerful (and thus heavy) actuator, since power wires are usually quite thick and rigid. Moreover, frequent wire bending will cause fatigue problems, possible wires damages and short circuits. Among these drawbacks no hinge will allow for abdomen incidence variation greater than 0–90° if abdomen size is realistic. Also yaw control is not possible in this case.

The conclusion can be drawn on the basis of mentioned above reasons that entomopters will not fly too fast, a limiting factor, despite projected high performance in hovering and slow flight.

4. Conclusions

The solution of fixed wing MAV technology seems to be almost ready for applications requiring high airspeed and long endurance. Microhelicopters can supplement fixed wing designs if hovering is required, but more work has to be done to increase their endurance. Among other concepts entomopters seem to be the most promising, because their successful application would provide high manoeuvrability and efficiency in hover. This potential justifies significant efforts necessary to understand insects' aerodynamic and develop controllable flapping mechanisms. Among control concepts application of the variable sweeping – pitching phase shift looks the most interesting at the moment.

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