Preliminary design of a small-sized flapping UAV.

I. Kinematic and structural aspects

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Keywords: flapping flight, kinematics aspects, structural design.

SUMMARY. The aim of the article is the kinematic and geometric design of a flapping wing UAV, in order to develop an Unmanned Aerial Vehicle, capable of executing reconnaissance and video-surveillance missions. To define the characteristic dimensions of the vehicle a biological study was initially carried out, analyzing, for example, the weight-wingspan ratio for the correct kinematics of the flight. On the other hand, several mechanisms capable to reproduce flapping flight were analyzed, searching for the best solution in terms of wings' articulation.

Then, an optimization of the length of the different parts of the mechanism was needed to reproduce the kinematic law, provided by CFD (computational fluid dynamics) simulations. The results of the optimization were the basis on which the design of the mechanism parts will be produced. In the related article the flight stability and the effects of flapping wing on the dynamics of flight are studied.

1 INTRODUCTION

The UAV is an aircraft with no pilot on board; it can be a remotely controlled aircraft or can fly autonomously based on pre-programmed flight plans or more complex dynamic automation systems. There is a wide variety of drone shapes, sizes, configurations and characteristics. UAVs are currently used for a number of missions, including reconnaissance and attack roles. They are predominantly deployed for military applications, but may be used for numerous indoor and outdoor civil applications, to monitor buildings, forests, cities, or to make possible an intervention in dangerous environments; moreover, for military applications, where discretion is important, the biomimetic aspect provides added value (spying and investigating).

The aim of the article is the development of a biomimetic flapping flight UAV; this vehicle must be able to fly over a range of 5÷15 m/s and must have a total wing span not superior to 2 m; furthermore it must be launched by hand. The mass of the UAV is supposed to be around 1 kg. To reach these targets the structure of the UAV was inspired to the birds anatomy, which have developed a skeletal system suitable for flying.

During the design phase fluid dynamics and structural aspects related to the wings have been considered. Wing should be long and slender to yield a proper aspect ratio, even if the cantilever present a large bending; for this reason a ribbed structure with a high moment of area is preferable. The structure of the mechanism is birds-based because they have optimal performance in terms of the ratio resistance/weight [1].

From a kinematic point of view, birds must produce lift and a negative resistance (the latter for propulsion). Both of these forces, lift and resistance, are generated from the movement of the wings; depending on the type of bird (dimension and weight) the first 50-60% of the wing semi-span generates the lift while the remaining 40-50% generates the thrust.

From a kinematic point of view the wing has four degrees of freedom:

- **flapping**: angular motion around the aircraft axis
- **lagging**: angular motion around a vertical axis permitting a back and forth wing motion
- **feathering**: angular motion permitting a variation of the wing angle of attack
- **spanning**: expansion and dilatation motion of the wing; it implies the articulation of the wing into parts.
Often, for propulsion and lift, model airplanes use only flapping, but also a passive feathering motion due to the fluid-structure interaction may be individuated. Utilizing only the flapping and feathering degrees of freedom, three parameters must be taken into account during the wing motion: the beat frequency, the beat amplitude and the wing angle of attack against its position. When properly coordinated, the three parameters may generate lift not only in the downstroke phase but also in the upstroke.

2 RELATED WORK

A pioneer on the studies on the feasibility of flapping flight has been De Laurier [2-4] who, in the eighties, started a long series of experiments on special airplanes called “ornithopters”; the goal of the research was to generate through the wings all the thrust and most of the lift force. Before him the name ornithopter was used to indicate aircrafts aesthetically similar to birds. The study was composed by both computer and wind tunnel experiments, leading to flight tests on a model with a 3 m wings span (1985-1991) and, finally, to a true airplane flight with a pilot on board (1999) [5].

The most commonly used mechanism to create the motion of “flapping” is the four bar linkage, as in the studies of Madangopal et al. [6] and Malik et al. [7], where a simple oscillation of the output member is created. Kempf [8] patented a mechanism which produces a rigid beat with active twisting of the wing in a purely mechanical way, without use of servo-actuators. In particular the patent refers to an application of the mechanism to an aircraft using an elastic string as its engine. Essentially the beat is generated by a slider-crank linkage, with the slider connected to the wings. To generate the twist, the main mechanism has been replicated; the second slider-crank mechanism is given a different phase angle, equal to the desired torsion angle.

Recently a team or researchers of the Festo company developed a prototype of a robotic seagull called “Smartbird”. Although the results obtained by the Festo staff are impressive, some points remain unresolved and, in addition, many details of the project and of the control system have not yet been published. The relevant characteristics of the Festo prototype, as demonstrated for example in [9], are the flapping wing, composed by a number of parts, some rigid and some flexible, (the wing structure may be schematized as two rigid bodies connected through a revolute joint, and additional flexible secondary parts), where the motion of the mostly external part of the wing is not synchronized in an active way to the mechanism of the internal part of the wing, but only coupled to it. The twist motion is actively controlled to optimize lift and thrust during the beat cycle. Propulsion and lift are generated exclusively by the wings, without any additional lift generator; as in many birds the internal part of the wing produces the lift while the external part generates the thrust. Flight control is obtained through the tail and the fuselage. The tail is provided with two degrees of freedom to control roll and yaw. Roll is also controlled through the active torsion of the wings. Autonomous take-off and landing are possible [10].

3 SYNTHESIS OF THE KINEMATIC MODEL

For the definition of the mechanism it is necessary to consider the number of degrees of freedom to be given to the wings and the dimensions of the latter, as functions of the required forces for lift and thrust; this part is examined in detail in a related paper [11].

As anticipated, the task of the wings is to generate thrust and lift at the same time; the fluid dynamics study provided a parameterization of the motion of the wing and the corresponding optimal values.

The parameters of interest for the beat are:

- $\alpha_1$: angular stroke of the internal semi-wing,
- $\alpha_2$: relative angular stroke between the two semi-wings
- $S$: time extent of the up-stroke during the period.

Considering the angular ranges required and the beat frequency, the inertia of the wings should be low, to ensure a sufficient operation of the battery; therefore a solution was searched in order to permit to concentrate the mass related to the actuation, i.e. the electric motor, inside the aircraft body. On the other side the wings must be robust enough to carry the loads and to limit the deformations arising as a consequence of the beat. Each wing has been designed into two parts, having a relative motion, that will be indicated as “internal semi-wing” (the part nearer to the fuselage) and as “external semi-wing” (the portion including the final tip; its aerodynamic optimization has been
the object of a separated study). These preliminary considerations were followed by the synthesis of the mechanism. The goal of the kinematic synthesis is to isolate a single degree of freedom mechanism providing the required motion of each of the two semi-wings; the internal semi-wing oscillates with respect to the frame, while the external semi-wing makes a rotation with respect to the internal semi-wing.

To satisfy the required characteristics, the simplest system between the possible kinematic chains was adopted, i.e., four binary members. The four bar linkage provides form-coupling, good behavior at high speed and does not suffer of wear problems due to elevated contact forces. The articulated system is better also under the aspect of the weight; a cam in fact would require a spring having a high stiffness and would complicate the structure, rendering it heavier, with potential structural strength problems, due to additional load caused by the spring.

A four bar linkage was therefore adopted for each semi-wing. The configuration chosen for the four bar linkage driving the internal semi-wing is of the crank-rocker type, having at input the continuous rotational motion of the engine and at the output an oscillating arm; the mechanism was designed according to the Grashof rule; for the external semi-wing, on the contrary, a rocker-rocker configuration is adopted (non Grashof condition).

![Figure 1: Kinematic scheme of the mechanism proposed to generate the beat](image)

In summary, the choice was a kinematic chain consisting of two four bar linkages in series, where the conrod of the first four bar linkage is the input of the second.

The internal semi-wing is the rocker of the first four bar linkage, while the external semi-wing coincides with the rocker of the second four bar linkage.

For the preliminary sizing, the lengths of the first four bar mechanisms were determined (Fig.1), to obtain the variables of interest:

\[ \alpha_1 = f(l_2, l_3) \]
\[ \alpha_2 = f(l_2, l_3) \]

The length \( l_1 \) is assumed as the scale parameter of the mechanism. An optimization was then performed to obtain the lengths of the different parts of the mechanism so as to reproduce with the minimum error the law of motion obtained from the fluid dynamics simulations.

4 OPTIMIZATION OF THE KINEMATIC MODEL

The numerical optimization has been performed through the LMS Virtual-lab\textsuperscript{®} software and has been verified through Matlab\textsuperscript{®}. To that purpose a parametric model has been created representing only the lengths of the members and the constraints imposed by the kinematic chains (cf. Fig. 1). Due to symmetry, it has been possible to study only half of the complete mechanism, i.e. only one wing. The problem is totally decoupled since the variables of each semi-wing are independent, so it was possible to perform the optimization in two phases, separately for each four bar mechanism. With reference to fig. 2, the driver of the motion is the crank (2), the angles of the wings are those between the links 4-1 (\( \alpha_1 \)) and 4-6 (\( \alpha_2 \)).

As far as the fluid dynamics simulations and the determination of the optimal values of the various parameters defining the beats (angular stroke of the internal semi-wing, angular stroke between the two semi-wings, time length of the upstroke) are concerned, refer to the paper [11]; The four bar linkages characteristic equations expressing such quantities have been translated into objective functions within the program.
For the study of the internal semi-wing, the lengths of the four links could be chosen as the free variables, but it was preferred to fix the frame length ($l_1$); this means adding a condition to the problem, to state the dimension of the four bar linkage, i.e., $l_1$ represents the scale parameter of the mechanism. Fig. 2 reports the names assigned to each member; $\theta_2$ is the angle between $l_2$ and the frame $l_1$ and $\theta_4$ the angle between $l_4$ and $l_1$.

To satisfy the imposed conditions, observations of geometrical nature have been done; in particular the dependence of the four bar linkage output angle ($\alpha_1$) from the links lengths has been defined locating the two extreme positions ($\alpha'_1, \alpha''_1$) of the stroke as the intersection between two circles.

$$\alpha_1 = \alpha'_1 - \alpha''_1$$

The first equation for the optimization was

$$(\alpha_1 - 60^\circ)^2 = \varepsilon_1 \quad (1)$$

As far as the second condition is concerned, a correlation exists between the length of the period and the phases of the crank positions corresponding to the extreme positions $\theta'_{2}$ e $\theta''_{2}$ of the output; therefore with a procedure analogous to the one of the $\alpha_1$ case, $\theta_2$ has been defined.

To obtain different angular speeds during the upstroke and the downstroke, it has been imposed that the extreme positions of the rocker corresponded to two positions of the crank having phases so to have an upstroke corresponding to $65\%$ of the period (T) and a faster downstroke. The second equation for the optimization was therefore

$$(\Delta\theta_2 - 0.65 T)^2 = \varepsilon_2 \quad (2)$$

After having studied the sensitivity to the various parameters, a multi-objective optimization was performed searching for the condition:

$$\varepsilon_1 + \varepsilon_2 \rightarrow 0$$
The optimization is therefore the search for a minimum with constraints. Referring to the external semi-wing, the condition for a third optimization refers to the relative angle between the two semi-wings ($\alpha_2$). The variables are $l_5$, $l_6$ and the position, in ($r,\theta$) polar coordinates, of the third kinematic pair corresponding to the conrod of the first four bar (shown in red in Fig. 2).

Considering the encumbrances, since the mechanism has to be inserted inside the wing section, the best four bar linkage would be the parallelogram, since its couples of bars remain parallel during the entire stroke; but in this mode the relative angle is fixed and by scaling the dimensions the value of $\alpha_2$ does not vary. On the contrary, considering a four bar linkage the parameters $r$ and $\theta$ have an influence on the objective function; therefore this solution was adopted, assuming as free variables $r$ ($=l_6$), $\theta$ and $l_5$. The remaining lengths were chosen in such a way as to reduce as much as possible the encumbrances.

The objective function “relative angle between the two semi-wings” was defined by inserting virtual velocity sensors on the members under consideration ($l_4$ and $l_6$) and integrating over the period the expression of the relative angular speed so obtained. The range of acceptability of the maximum relative angle between the two semi-wings is the result of a compromise between the aerodynamic need of maximizing the lift coefficient and the structural strength of the real components. For the first two objective functions a DOE (design of experiment) was initially performed, with the following parameters, to explore their variability range:

- Gradient method
- 450 computation points

The lower limits have been defined in terms of structural strength, while for the other numerical values the choice has been dictated by minimum encumbrance criteria. Fig.3 reports the Pareto diagram, whose abscissae and ordinates are the first and the second objective function. It is possible to note that only a part of the results is acceptable since for other results the error of the objective functions is too large. The two objective functions are competitive, i.e. many values optimizing the first generate a large error in the second; the opposite phenomenon is more limited. As a consequence the best results have been obtained giving a higher weight to the second objective function.

![Figure 3: Pareto diagram of the results of the first multi-objective optimization](image)

Passing to consider the optimization for the internal semi-wing, the parameters used are:

- Gradient method
- 100 computation points

Fig.4 shows the results of the second optimization; the abscissa reports the second objective function, the ordinate is the first one. The chosen optimal solution is the result representing the best compromise between the two objective functions.
As far as the external semi-wing is concerned, as previously seen the variables of the problem are \( r, \theta \) and \( l_5 \); the last assumes a fundamental role since it strongly influences the third objective function. Since in the parallelogram configuration the relative angle does not vary, a four bar linkage must be used, trying to keep it close to a parallelogram, in order not to lose the advantage of minimal encumbrance.

The third objective function (which expresses the relative angle between the two semi-wings), when applied to a four bar mechanism, is proportional to the radius \( r \) and inversely proportional to the angle \( \theta \). The parameter \( l_5 \) has been chosen so that the relative angle lays in the desired range; making a compromise between the effect of such value and the effect of \( r \) and \( \theta \), it was possible to obtain an acceptable result. The choice of \( r \) was done on the basis of a reasonable encumbrance of the second four bar linkage, that must fit into the wing section.

### 5 RESULTS

The solution of the objective functions has not presented particular problems, the starting configuration being already quasi-optimal, requiring only corrections of the initial values; in the same way also the configuration of the overall mechanism is not altered.

The values have been selected according to the criteria previously reported between the results of the multi-objective optimization. Tab.1 summarizes the results obtained through the optimization. Another confirmation of the results obtained through LMS.Virtual-lab® has been obtained via an analytic procedure developed in Matlab®.

<table>
<thead>
<tr>
<th>Objective function</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \alpha_1 )</td>
<td>0.036%</td>
</tr>
<tr>
<td>( S )</td>
<td>0.005%</td>
</tr>
<tr>
<td>( \alpha_2 )</td>
<td>---</td>
</tr>
</tbody>
</table>

Table 1: Comparison between the initially specified design goals and the values obtained through the optimization

### 6 CONCLUSION

The work presented here is the object of a multi-disciplinary research effort aimed at a preliminary design of a model UAV under the mechanical and fluid dynamics constraints.

To reach this result required a large documentation phase on birds’ anatomy, on the kinematics of flight, and on the mechanisms apt to obtain an efficient wing beat. At the conclusion of the preliminary phase tracing the guidelines for the design, the shape and the mass of the moving parts will be decided, therefore creating a structural
sizing apt to the operating loads and the flight dynamics will be analyzed in detail. For example the material is expected to be a composite material, being efficient and light at the same time.

In conclusion it is necessary to design a structure suitable to be resistant to the load and a fuselage having the only role of provide the aircraft with the correct aerodynamic properties.

Based on these results it will be possible to build the first prototype of a biomimetic aircraft having flapping articulated wings and to perform wind tunnel tests to validate the fluid dynamics results; specific flight tests will also be performed to test the model’s maneuverability.

References