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Theoretical analysis and experimental verification for sizing of flapping wing micro air vehicles

Mostafa Hassanalian[1], Abdessattar Abdelkefi[1], Mingjun Wei[1] and Saeed Ziaei-Rad[2]

To design efficient flapping wing micro air vehicles (FWMAVs), a comprehensive sizing method based on theoretical and statistical analyses is proposed and experimentally verified. This method is composed of five steps including defining and analyzing the MAV mission, determining the flying modes, defining the wing shape and aspect ratio of the wing, applying the constraint analysis based on the defined mission, and estimating the weights of the electrical and structural components the bio-inspired flapping wing micro air vehicle. To define the vehicle mission and flight plan, path analysis is performed based on the defined mission, the speed of cruise and turning, the turning radius and climatic conditions in the flight area. Following the defined mission analysis, the appropriate modes of flying for the flapping wing bird are recognized. After that, the wing shape and the wing aspect ratio are determined based on the defined flight modes. To estimate the wing loading, a constraint analysis is exploited. Along with the four listed steps, statistical method is employed to estimate the FWMAV weight. Based on the proposed method for wing sizing of flapping wings, a FWMAV named Thunder I has been designed, fabricated, and tested. This developed methodology is very beneficial by giving guidelines for the design of efficient bio-inspired FWMAVs.

I. Introduction

The popularity of drones as their broad spectrum of applications, such as military surveillance, planetary exploration, and search-and-rescue has received most attention in the past few years[1,2]. Micro planes are usually divided into three classes, namely, Micro Air Vehicles (MAV), Nano Air Vehicles (NAV), and Pico Air Vehicles (PAV)[3]. MAV airplanes are those micro planes usually with a length smaller than 500 millimeters and a weight lower than 500 grams[4]. These MAVs can be grouped into four categories: fixed wings, vertical take-off and landing (VTOLs), flapping wings, and rotary wings[3]. Depending on the flight mission of the MAV, the size and the type of installed equipment are different. The smaller dimension of them, compared to UAVs, provides them with the broader performance range. According to the mentioned characteristics, MAV benefits from the potential to perform the variety of operations. In the past decade, due to the quick advances in microtechnology, MAVs have drawn a great deal of attention, as a result in subsequent years, several investigations have been carried out on the micro drones. Recently, few studies are aimed at inventing MAVs smaller than 15cm with the capability to perform reconnaissance and rescue missions[5,6]. In addition to their small sizes, these types of drones are capable to fly with low speeds[7].

The design of flapping wing MAVs are inspired from birds, PAV flapping wings are inspired from insects, and NAV flapping wings are inspired from organisms between very small birds and huge insects, such as hummingbirds and dragonflies. The research on flapping wings has shown that these types of air vehicles have more complexities compared with fixed and rotary wings mainly due to their complex aerodynamics[8]. As a result, there are few studies that are available in this field. Biologic inspiration indicates that flying through flapping wings presents unique maneuverability advantages[9]. There are fundamental challenges for fixed and rotary wings to fly reliably when their sizes are reduced. When the wing area is reduced, a flow transition to low Reynolds number occurs which reduces the aerodynamic wing efficiency. A flapping wing has the potential to benefit from the advantages of other MAV types and eliminates their disadvantages[1,10].

To design flapping wing drones, some methods have been used[11-22]. In general, these methods are based on empirical formulae. These formulae have been established based on allometrical data extracted from biological avian flight. The pioneers of these researches include Pennycuick[12,13], Rayner[14,15], Tucker[16,17], Lighthill[18,19], and

[1]Department of Mechanical and Aerospace Engineering, New Mexico State University, Las Cruces, NM 88003, USA.
[2]Department of Mechanical Engineering, Isfahan University of Technology, Isfahan 84156-83111, IRAN.

Spedding[20]. Their empirical formulae have related the sizing parameters of flapping wings, such as wing area, weight, and wing loading to the flapping frequency, flight speed, and required power for flight. In addition to that, these formulae have related the geometry of the wing including the area and wingspan to the weight of the FWMAV. These empirical formulae have been used for sizing of FWMAVs by some researchers, such as Beng[21] and Beasley[22]. In his design, Beasley[22] has utilized the biological mimicry for sizing the flapping wing. Indeed, by using the geometric scaling factors for Passeriformes[23], the fixed span, weight, flapping frequency, wing area, and aspect ratio of the MAV have been determined from the logarithmic relationships[22]. Other methods based on statistical and experimental sizing and testing have been applied. As an example, Gerard and Ward[24] have designed their flapping wing MAV based on existing FWMAVs, such as Luna and DelFly. Moreover, there are other methods which have been utilized for sizing of NAV and PAV flapping wings. For instance, Whitney and Wood[8] proposed a conceptual design process for insect-sized flapping wings, with a primary focus on hovering flight. Many assumptions have been considered in their method including linear and lumped representations to model the dynamics of the vehicle and blade-element method to model the aerodynamic forces. In their method, after developing a dynamic model for the flapping wings, they used energy methods to determine the fractions of the actuation mechanism and mass of the battery. Combining this sizing methodology with derived limits on wing structural-inertial efficiency, the range of feasible designs and the limits of performance of the flapping wing PAVs have been specified[8].

Most of the mentioned sizing methods are based on allometric formulae extracted from natural birds and insects which have been applied directly for sizing of artificial flapping wings without taking into account the impacts of other parameters including the used materials for the wing membranes. Using the empirical formulae of natural birds and insects, non-optimized micro drones will be designed. Therefore, these empirical formulae should be revisited and probably some correction factors are needed. In this work, using theoretical, statistical, and revised allometrical methods, a comprehensive sizing methodology is proposed which finds solutions for the drawbacks of previous methods. This sizing process gives guidelines for the design of efficient bio-inspired FWMAVs.

II. Sizing of flapping wings

In this study, our proposed sizing methodology of flapping wings is composed of five steps: (1) defining the mission, (2) setting the flight mode, (3) determining the wing shape and aspect ratio, (4) constraint analysis, and (5) weight estimation. In the definition of the mission, the analysis of the route is conducted resulting in the determination of the flight time, cruise speed, and turning speed. After that, the determination of the flight modes, shape of the wing and its aspect ratio are determined based on the type of mission. Then, to determine the appropriate wing loading of the flapping wing, a constraint analysis is used in which the kinematic and dynamic equations of the flight are simulated. Along with the four mentioned steps, a statistical method for weight estimation is introduced and employed. The result of this process is the determination of the geometry and dimensions of the flapping wing MAVs and also the calculation of the parameters, such as frequency and angles of flapping.

A. Defining the flight mission and determining the flight modes

For executing a defined mission, at first, the kind of flight mission (indoor or outdoor) should be decided. Then based on this mission, the flight class of the flapping wing (MAV, NAV, or PAV) should be pinpointed. After determining the class of the flapping wing vehicle, the mission is analyzed including extracting the atmosphere features of the flight zone and preparing the plan. By preparing the flight plan, the distances and flight time should be determined. After that, by dividing these parameters, the estimated cruise speed can be calculated. Other parameters that need to be determined can be calculated using latitude and altitude values. The gravity acceleration and air density are the two most important environmental qualities for the flight calculations of the flapping wings. The effects of the altitude and latitude on gravity in this defined relationship are combined by Helmert. Helmert relationship[25,26] is a polynomial expression in which the acceleration of gravity (g) is stated based on a function of latitude (L_0) and altitude (h_0) which is given by:

$$g = 9.80616 - \left[0.025928\cos(2L_0)\right] + \left[0.000069\cos^2(2L_0)\right] - \left[(3.086\times10^{-6})h_0\right] \tag{1}$$

The air temperature (T_a), the air density (ρ), the kinematic viscosity (v), and the air pressure (p) are related through these expressions[25]:

$$T_a = 15 - 0.0065h_0 \tag{2}$$

$$\rho = 1.226(p/1013)\left[288/(T_a+273)\right] \tag{3}$$

$$\upsilon = 1.466 + 0.09507h_0 + 0.01047h_0^{\,2} \tag{4}$$

$$p = 1013\left[1-\left(2.26\times10^{-5}\right)h_0\right]^{5.256} \tag{5}$$

It should be mentioned that in Eqs. (1), (2) and (5) the unit of h_0 is meter and in Eq. (4) is kilometers, the unit of υ is $10^{-5}m^2s^{-1}$, and T_a is in degrees Celsius.

One of the important steps during sizing process is the determination of the flight modes (second step), which include flapping, gliding, hovering, soaring, and bounding[27]. Depending on the defined mission, the needed flight modes of the drone will be determined. As an example, flapping wing MAVs benefit from flapping and gliding[28] whereas PAVs benefit from flapping and hovering. Generally, the flight modes are composed of different steps including takeoff and landing, cruise, turning, climb, and descent.

B. Selecting the planform and aspect ratio

After defining the flight mission and determining the flight modes, the third step in the proposed sizing methodology can be achieved by selecting the best shape of the wing and its aspect ratio. The planform and aspect ratio for the flapping wing can be selected either by patterning the birds' wing shape or combining the geometric shapes. For instance, all birds follow one of the six basic shapes of flying[29]: (1) short, broad, and cupped wings for quick takeoff and fly for a short distance, (2) short and wide wings with cracked primary feathers for soaring, (3) high flat, thin, and triangular wings for flying with high speed and maneuverability, (4) large and arched wings for flapping flight, (5) tipped, flat, high, and thin wings for gliding and long distances, and (6) tipped and roll-back wings for hovering or motionless flights.

C. Determining the parameter of wing loading

The fourth step in sizing of flapping wings is the determination of the wing loading (W/S) parameter. To this end, a constraint analysis is carried out. Regarding a flapping wing at the state of flying, the inserted forces are lift, drag, thrust, and weight. Based on the energy balance equation, a relation between these existing forces is given by[30]:

$$\frac{T-D}{W}=\frac{1}{U}\frac{d}{dt}\left(h+\frac{U^2}{2g}\right) \tag{6}$$

where T stands for thrust, D for drag, U for flight speed, W for weight of FWMAV, and h for flight height. In Eq. (6), the sum of the potential energy and kinetic energy is called the head of the energy.

Generally, in any aerial vehicle, the momentarily thrust and sea level thrust relationship is given by the following relation $T=\alpha T_{SL}$. The relationship between the momentarily weight and the weight at the time of takeoff is defined by $W=\beta W_{TO}$. However, since the driving force of flapping wing is obtained from battery, the weight during flying does not change and β is equal to 1. Considering the above relations, Eq. (6) can be rewritten as:

$$\frac{T_{SL}}{W_{TO}}=\frac{1}{\alpha}\left\{\frac{D}{W_{TO}}+\frac{1}{U}\frac{dZ}{dt}\right\} \tag{7}$$

where $Z=h+U^2/(2g)$, and α is defined by[31]:

$$\alpha=\frac{T_a+273.16}{T_a+273.16-0.001981h_0}\left\{1-\frac{0.001981h_0}{288.16}\right\}^{5.256} \tag{8}$$

To make sure that the designed FWMAV tolerates its weight, the lift force should be always larger than the weight of the MAV. Generally, the lift force is constantly equal to a coefficient (n) of the weight of the flapping wing ($L=nW$). Furthermore, the lift force for any flying object is given by:

$$L=0.5\rho U^2 SC_L \tag{9}$$

where ρ and C_L denote, respectively, the air density and lift coefficient. Since the lift force is changing in flapping wings due to flapping up and down, a mean lift can be considered.

The total drag force on a bird instrument is equal to the sum of the induced and parasite drag in the way that parasite drag includes the two drags of profile and shape. The induced drag for an elliptical lift distribution for flapping wings is determined by[32,33]:

$$D_i=\frac{2L^2}{e\pi b^2\rho U_{ref}^2}=\frac{2(Wn)^2}{e\pi b^2\rho U_{ref}^2} \tag{10}$$

where e is the Oswald number. The parasite drag is determined by using Tucker method. This method starts with determining the coefficient of the frictional drag (C_f) of a flat sheet during turbulence by applying Prandtl equation[32]:

$$C_f=0.455\left(\log_{10}\mathrm{Re}_{ref}\right)^{-2.58} \tag{11}$$

where Re denotes the Reynolds number. Next, we define $\Psi=C_{DP}/Cf$ which is the ratio of the parasite drag coefficient of flapping wing (C_{DP}) to the frictional drag coefficient (C_f) for a flat sheet. This coefficient (Ψ) is changing from 2 to 4.4 for most birds[32]. The parasite drag is calculated by utilizing Ψ and the drag coefficient for a wet sheet which is given by:

$$D_p = \frac{\rho U_{ref}^2 S_{wet} C_{DP}}{2} = \frac{\rho U_{ref}^2 S_{wet} \Psi C_f}{2} \tag{12}$$

where S_{wet} is the sum of the wings' wet surfaces. Considering $S_{wet}=2S$, the total drag force can be expressed as:

$$D_{tot} = \frac{2(Wn)^2}{e\pi AR\, \rho U_{ref}^2 S} + \frac{2\rho U_{ref}^2 S \Psi C_f}{2} = qS\left\{k_1\left(\frac{n}{q}\frac{W}{S}\right)^2 + 2\psi C_f\right\} \tag{13}$$

where $k_1 = 1/\pi eAR$ and $q = 0.5\rho U_{ref}^2$. Substituting Eq. (13) into Eq. (7), one obtains:

$$\frac{T_{SL}}{W} = \frac{1}{\alpha}\left\{\frac{qS}{W}\left\{k_1\left(\frac{n}{q}\frac{W}{S}\right)^2 + 2\psi C_f\right\} + \frac{1}{U}\frac{dZ}{dt}\right\} \tag{14}$$

Eq. (14) states the relationship between the wing loading and thrust loading. This equation is simulated for any flapping wings MAVs with electric engine in constant cruise speed, constant climb speed, constant turning altitude/speed, horizontal acceleration, accelerated climb and flapping wing launching situations. In the six mentioned flight scenarios, Eq. (14) of the thrust loading (T/W) has been represented as a function of wing loading (W/S). Therefore, with drawing the related curves of the six corresponding equations, a bounden space for determination of a design point (W/S, T/W) can be obtained. The bounden space is specified by the drawn curves. It should be mentioned that the selected point in the bounden space should satisfy all of the constraints regarding to the defined mission.

D. Estimating the electrical and structural weights of flapping wing MAVs

The fifth step in the process of sizing of FWMAVs is the weight estimation. Since FWMAVs have low and reasonable weight, it is required to carefully estimate the weight with a minimum error. Various methods have been used to estimate the weight of MAVs before their construction which are mostly based on guessing or statistical data[34]. The used one in this study divides the weights into the weight of the structure and the weight of the components and then estimates the weight of each one separately. Defining the weight of the structure by W_{Str} and the weight of the electrical components by W_{Eq}, the total weight of the flapping wing MAV can be expressed as:

$$W_{TO} = W_{Eq} + W_{Str} \tag{15}$$

The weight of the electrical components can be written as follows:

$$W_{Eq} = W_B + W_{PL} + W_{AV} + W_{pp} \tag{16}$$

where W_B denotes the weight of the battery, W_{PL} represents the weight of the loads, sensors, cameras, and other similar weights, W_{AV} is the weight of the servo motors, receivers, and navigation systems, such as autopilot, and W_{PP} denotes the weight of the motor and speed controller. Among these electrical components, the motor and battery are the most useful in the estimation of the weight of the flapping wings' components. It should be noted that the main criterion in the selection of the motor is low weight and high torque. The main criterion for battery selection is low weight and high capacity. In the estimation of the weight of the applied devices in flapping wings, a list of different types of them should be made and then score them based on the less weight, features, and links in order to select the best ones.

The other part of the weight of a FWMAV is the weight of the structure, W_{Str} which can be expressed as:

$$W_{Str} = W_{Wing} + W_{Tail} + W_{Fuselage} + W_{Mechanism} + W_{Other} \tag{17}$$

The sum of the weights of the wing structure, the wing membrane, and their links represents the weight of the wing (W_{Wing}). The weight of the wing structure is the sum of the leading edge spars, diagonal spars, and ribs weights. The weight of the tail (W_{Tail}) includes the weights of the tails structure, tail membrane, and their links. It should be noted that the weight of the tail varies according to the type of the used tail. $W_{Fuselage}$ is the sum of the flapping wing's body, flapping wing's cape, and their links weights. As for the weight of the mechanism ($W_{Mechanism}$), it involves the weights of the gearbox system, linking bars, crankshaft, joints, and external parts linked to the flapping wing. Depending on its type, the weight of the mechanisms can vary. Furthermore, it should be mentioned that the weights of other parts including landing gear, protective guards, etc. are not included. The total mass of each complex and the sum of the separate components masses are determined and expressed as a percentage of the total mass.

To estimate the flapping wing structures, in our proposed sizing methodology, a statistical method is utilized. In general, as noted above, the total weight of a FWMAV includes W_{PP}, W_B, W_{PL}, W_{AV}, and W_{Str}. The weight of the used electrical components in the flapping wing can be estimated and the only remaining unknown is the weight of the structure which can be calculated by using statistical data. In this method, the weight parts (W_{PP}, W_{PL}, W_B, W_{AV}, and W_{Str}) of many flapping wings have been extracted from different references[35-37]. Three distinct categories are considered depending on the weight of the FWMAV (m<100grams, 100grams<m<400grams, and 400grams<m<800grams), as shown in Table 1. In this table, the approximate percentage of each constituent of the flapping wing for these three considered weight classes, is presented.

Table 1. Percentage of the weight of the constituents of flapping wings for the three weight classes.

Weight range	W_{PP}	W_{PL}	W_B	W_{AV}	W_{Str}
Less than 100 grams	23%	2%	24%	13%	38%
Between 100 and 400 grams	16%	1%	14%	9%	60%
Between 400 and 800 grams	12%	0%	12%	4%	72%

By referring to the statistical data presented in Table 1, it can be concluded that x ($x=W_{Str}/W_{TO}$) is 38% for flapping wings weighing less than 100 grams, 60% for flapping wings weighing between 100 and 400 grams, and 72% for flapping wings weighing between 400 and 800 grams. These percentages will be considered when fabricating our prototype Thunder I.

III. Specifying other parameters in sizing of flapping wings

There are various parameters which can determine the geometry and physics of flapping wings MAVs. Among them, we can point to the flapping frequency, angles of upward and downward flapping, aspect ratio, wing surface, wingspan, root chord length of the wing, wing loading parameter, dynamic twist angle, angle of attack, wing dihedral angle, etc. With the implementation of the five-fold process of sizing, the initial values of parameters of wing loading, weight, planform, and aspect ratio are determined. Thus, the surface of the wing and its span can be calculated as:

$$W/S\,,\; W \to S \quad \text{and} \quad AR = b^2/S \to b = \sqrt{AR \times S} \tag{18}$$

The mean chord which has a unique value for the wing of a FWMAV is equal to the ratio of the wing surface to the wingspan: (C_m=S/b). In the next subsections, a particular focus is paid in determining the flapping frequency, time fractions, and flapping angles of downstroke and upstrokes.

A. Calculating the flapping frequency of a FWMAV

For birds, the flapping frequency is the complete cycles of flapping per second which varies according to the type of the birds. The flapping frequency should be sufficient to allow the birds to provide the required lift and thrust to make their takeoff and propulsion. Pennycuick[38] performed many observations for various samples with low frequencies (<13Hz). Using 47 samples of low frequency birds[38], a formula which introduces estimation for the flapping frequency is then developed:

$$f = m^{\frac{3}{8}} g^{\frac{1}{2}} b^{-\frac{23}{24}} S^{-\frac{1}{3}} \rho^{-\frac{3}{8}} \tag{19}$$

The commercial flapping wing Park Hawk[21] has a wingspan of 120cm and weight of 425g with 6Hz frequency. If Eq. (19) is used, the estimated frequency will be 2.7Hz while this flapping wing should flap 2.2 times more than birds' wing due to the membrane wing. Indeed, the membrane wings are often made from flexible and flat materials. These materials can either be thin plastic film or thin cloth. Nowadays, because of their lightweight, they become so popular especially for small flapping wing applications. However, the disadvantage of these materials is their poor efficiencies. Thus, the obtained frequency should be multiplied by a correction factor. Determining the ratio between the commercial and estimated frequencies of most of the used flapping wings in the literature[21,24,39,40-42], it is demonstrated that the ratio between these frequencies should be ranged between 1.2 and 4.7. To this end, in our proposed methodology, Eq. (19) is adjusted as follows:

$$f = \xi m^{\frac{3}{8}} g^{\frac{1}{2}} b^{-\frac{23}{24}} S^{-\frac{1}{3}} \rho^{-\frac{3}{8}} \tag{20}$$

where ξ is the correction factor which depends on the type of the FWMAV.

B. Determining the upstroke and downstroke angles

Any flapping wing has a cycle of alternative flapping including downstroke flapping to produce lift force and upstroke flapping to produce thrust force[43]. The sum of the upstroke and downstroke flapping angles is called flapping angle, as shown in Fig. 1.

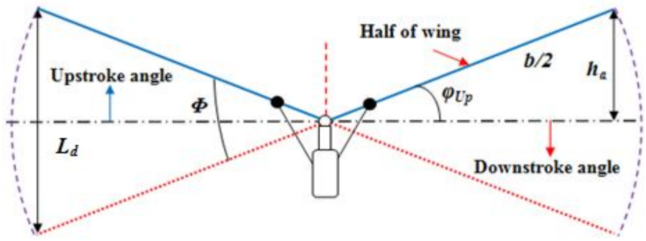

Figure 1. Upstroke and downstroke angles. *Φ* is the total flapping angle of a FWMAV.

Upstroke and downstroke angles are among those cases that should be considered in the design of the flapping wing mechanism. For estimating the initial values of the flapping angle, we can benefit from upward and downward movements of the wing. From Fig. 1, for flapping angles calculation, we have:

$$\sin\varphi_{Up} = \frac{2h_a}{b} \rightarrow \varphi_{Up} = \sin^{-1}(\frac{2h_a}{b}) \tag{21}$$

where h_a is the domain of upstroke of the flapping wing. For estimating the value of h_a, the Strouhal number can be used, which is one of the important non-dimensional parameters and can be obtained by dividing the flapping frequency (f) and the vertical domain of the wing tip (L_d) by the forward speed (U) of the FWMAV as[28]:

$$St = \frac{fL_d}{U} = \frac{2fh_a}{U} \tag{22}$$

It was demonstrated that high propulsive efficiencies (almost 70%) are obtained when the Strouhal number is in the range of 0.2-0.4. It was demonstrated that a peak efficiency is achieved when the Strouhal number is set equal to 0.3[44,45]. Considering this value, h_a can be estimated by having the values of the frequencies and forward speeds.

IV. Sizing a FWMAV: Thunder I prototype and experiments

Based on the aforementioned procedures and techniques, a FWMAV called Thunder I is designed and constructed. As mentioned in section II. A, the first step in sizing of a FWMAV is the mission analysis and the preparation of the flight plan. In Fig. 2, the flight route of this fabricated MAV is depicted. In place (1), the FWMAV should be hand launched and after flying over route (1), it should detect the first black square. With flying over route (2), the MAV should arrive to the start point and after that it should detect two other black squares when crossing the route (3). Starting the flight performance, the flapping wing should fly as many laps as possible in the mission around 2 poles (red circles) in route (4). After doing the flight performance mission, the MAV should detect the other two black squares when crossing route (5) and then fly between two aligned arches (route (6)) without going out of the corridor landing. Finally, the flapping wing should land when crossing route (7). The estimated flight route of the fabricated MAV is considered 6000m. The flight endurance of Thunder I is considered almost equal to 10 minutes. Hence, the approximate cruise speed for this MAV is 10m/s.

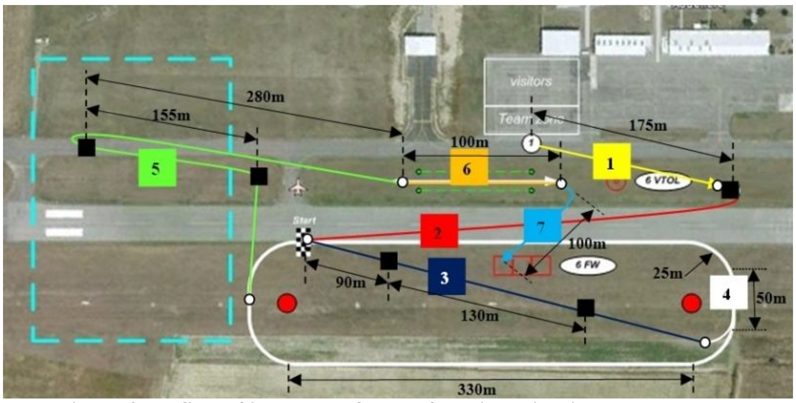

Figure 2. Defined flight route for the flapping wing in outdoor place.

Since this flapping wing's flight tests are carried out in Isfahan, the latitude (L_0) and altitude (h_0) are, respectively, considered equal to 32.42 degrees and 1631m. Then, regarding these values and considering Eqs. (1-5) given in section II. A, the air pressure, density, temperature, and viscosity as well as gravity acceleration are determined.

The designed flapping wing should be able to execute different flight modes including takeoff (launch), landing, cruise, turning, climbing, and descending. According to what was discussed in section II. A and based on the defined mission, the flight of the FWMAV is only composed of flapping and gliding modes. It should be mentioned that the hovering mode is often used for flapping wings with small size (NAV and PAV). Based on what was mentioned in section II. B, it is better to consider a short wing with low aspect ratio. In addition to that, it is better that the fabricated flapping wing could takeoff rapidly in order to consume less energy. Consequently, the selected planform and aspect ratio for Thunder I is imitated from the northern mockingbird wing shape, as presented in Fig. 3(a) and (b).

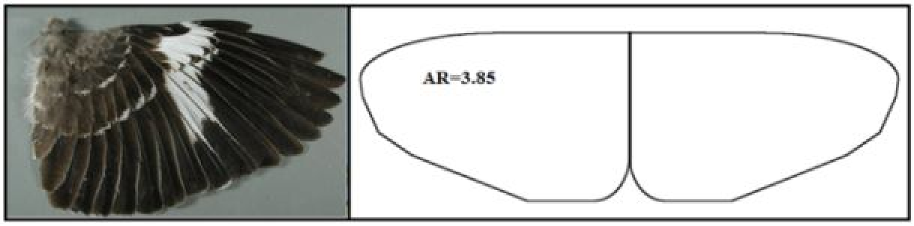

Figure 3. (a) Wing shape of northern mockingbird and (b) extracted planform of Thunder I from northern mockingbird.

Based on what was discussed in section II. C, for an estimation of the wing loading parameter, the constraint analysis process is used. The input data for such an analysis are shown in Table 2.

Table 2. Used input data to carry out the constraint analysis.

Parameter	Symbol	Value	Parameter	Symbol	value
Aspect ratio	AR	3.85	Climbing speed	U_C	7m/s
Oswald numbers[46]	e	0.8	Horizontal acceleration	a_H	1m/s^2
Cruise speed	U	10m/s	Turning radius	R_c	10m
Climbing rate	C_R	1m/s	Launch speed	V_{HL}	6m/s
Climbing acceleration	a_C	0.5m/s^2	Turning speed	V_T	7m/s

One of the parameters that should be estimated when applying the constraint analysis for the prototype flapping wing is the maximum lift coefficient (C_{Lmax}). According to the Reynolds number of artificial flapping wings, which usually is in the order of 10^5 [47], it can be concluded that the proper range for estimating this coefficient (C_{Lmax}) is between 1.4 and 1.9 [48]. For this prototype, the maximum lift coefficient is considered equal to 1.8 which is in the defined range and is verified with other flapping wings[49-51]. It should be noted that the determination of an accurate value of C_{Lmax} requires experimental tests, which should be done in a wind tunnel after fabrication. The parasite drag coefficient (C_{DP}) is considered equal to 0.03 for this prototype flapping wing. In Fig. 4, the obtained results from the simulations of the constraint analysis are presented. It follows from these plots that the maximum possible wing loading value that should be considered for this prototype is 26N/m^2.

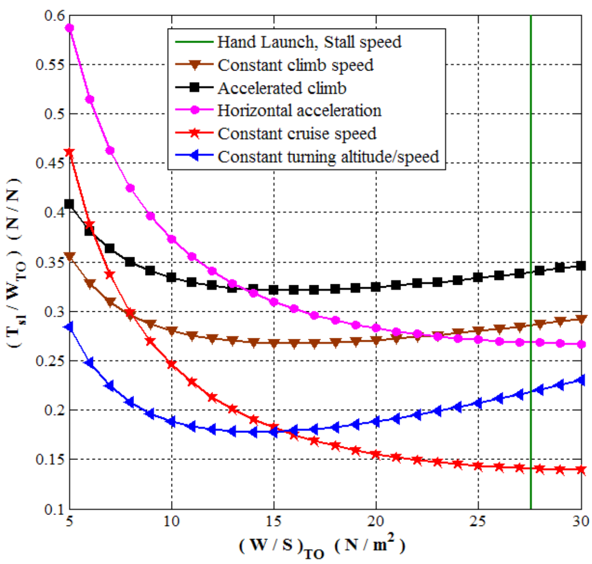

Figure 4. Results of the constraint analysis.

Based on what was mentioned in section II. D, for the estimation of the weight of the FWMAV, its total weight is divided into two parts, namely, structure and equipment weights. Considering the maximum thrust loading (T_{SL}/W) shown in Fig. 4, the weights of the electrical components are estimated using engineering designing[22,52] and presented in Table 3.

Table 3. The estimated weights of the electrical components.

Equipment	Estimated weight
Motor + linking wire	30g
Speed controller + linking wire	15g
Servo motors + two linking wires	20g
Receiver + linking wire	10g
Battery + linking wire	60g
Total weight	135g

It follows from Table 3 that the weight of the equipment is about 135 grams. Based on Table 1 and the estimated weight of the electrical components, the weight range of the flapping wing is from 100 to 400 grams. Thus, the weight of the structural components comprises about 60% of the total weight. Using the proposed statistical method, W_{TO} is estimated to be equal to 337.5g. For the fabricated prototype, the total weight is considered 350g.

By specifying the types of the planform, aspect ratio, flapping wing weight, and wing loading parameter, the flapping wing micro air vehicle's dimensions are calculated as follows:

$$\frac{W}{S}=\frac{0.35g}{S}=26N/m^2 \rightarrow S=0.132m^2 \tag{23}$$

$$AR=\frac{b^2}{S} \rightarrow b=\sqrt{3.85\times 0.132}=0.713\approx 70cm \tag{24}$$

Using a scaling procedure for the chosen planform, the final dimensions of Thunder I are presented in details in Fig. 5.

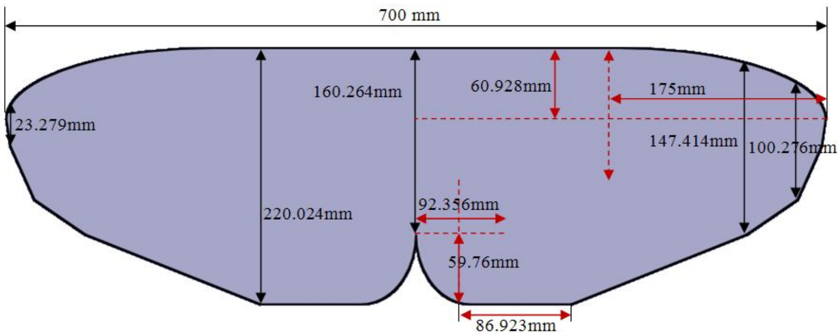

Figure 5. Dimensions of Thunder I wing with northern mockingbird planform.

Then, Eq. (20) is used to estimate the flapping frequency of this MAV. Based on what was discussed in section III. A, the calculated frequency which is obtained from the Pennycuick formula, should be multiplied by a correction factor which is between 1.2 and 4.7 depending on the type of the FWMAV. According to the fabricated FWMAV, the correction factor is considered equal to 1.53 in order to get a flapping frequency of 9Hz. This correction factor is estimated by averaging the correction factors of two flapping wings (UA-74 and Tadbir) with similar wingspan to our prototype. In fact, according to Greenwalt formula[53], the flapping frequency is directly related to the wingspan of the MAV.

Based on section III. B, the time fraction for downstroke to upstroke ratio of this prototype is considered one and hence symmetric flapping movements are considered. As reported in section III. C, the Strouhal number should be considered equal to 0.3. Having the values of the frequency and cruise speed, the domain of upstroke and downstroke movements of the wing (h_a) will be 16.66cm. To obtain the upstroke and downstroke angles, we use Eq. (21) as:

$$\sin\varphi=\frac{2h_a}{b}=\frac{2\times 0.166}{0.70}=0.476 \rightarrow \varphi=\sin^{-1}(0.476)=28.42^\circ \approx 30^\circ \tag{25}$$

Thus, the upstroke and downstroke angles are considered equal to 30 degrees. The final designs of Thunder I flapping wing and its wing are given in Figs. 6(a) and 6(b).

(a) (b)

Figure 6. (a) Thunder I FWMAV and (b) wing of the Thunder I FWMAV.

After designing and fabricating the Thunder I FWMAV, various flight tests are then performed. In Table 4, the used equipment are presented.

Table 4. Thunder I flapping equipment.

Equipment	Model
Battery	Lipo-3 Cell-800mAh
Motor	DualSky XM300ES
Receiver	Spektrum-DX6
Servo motors	Futaba-S3114
Speed controller	DualSky XC1210BA

The first test of Thunder I is performed to check the launching and safe takeoff. The second test is to check that an adequate thrust can be produced from the wing. Then, a turning test when using a constant altitude is performed. After that, a gliding test is investigated. The tests of the launching and safe takeoff are presented in Table 5.

Table 5. Launching tests of Thunder I FWMAV.

Number	Wind speed	Result	Estimated problem	Correction
1	≈ 1m/s	Crashing	Nose up fly	Moving the center of gravity forward about 1cm with battery relocation
2	≈ 0m/s	Crashing	Below launch speed	Launching with more speed
3	≈ 2m/s	Takeoff	---	----
4	≈ 1m/s	Takeoff	---	---

In the launching process of the flapping wing, four tests are performed. As presented in Table 5, the second test is unsuccessful. In this launching process, Thunder I does a nose up flight, which means that the flapping wing has not been stabilized longitudinally. It is concluded from these performed tests that there are some important parameters which significantly impact the vehicle takeoff. These parameters are the wind speed, wind direction, place of the center of gravity, throttle, launching angle, launching speed, etc. It should be mentioned that in these launching tests, the associated launch speed values are not exactly determined. In the takeoff cases, the launch speed is higher than the stall speed. Some pictures of the launching tests are given in Fig. 7.

Figure 7. Thunder I FWMAV takeoff.

After successful takeoff, Thunder I undergoes a thorough flight testing. With doing necessary adjustments for the center of gravity (CG) position which is obtained with relocation of the battery position, Thunder I is then able to fly at a cruise speed of 10m/s. The results of the powered flight tests are satisfactory after a number of attempts where the center of gravity and flapping frequency are varied during the tests. It is found that a flapping frequency of approximately 8 to 9Hz is sufficient for the Thunder I to achieve powered flight, as estimated by our developed methodology. We should mention that during flight, Thunder I is stable and not perturbed. During these tests, our fabricated FWMAV can withstand against a wind disturbance up to 2m/s and can perform a series of turns while maintaining its altitude. The flight endurance of this flapping wing is between 11 and 13 minutes at a moderate throttle setting without any payload. It should be noted that by making batteries with higher energy density, endurance can be further improved.
In the final test, we try to measure the gliding ability of this flapping wing in ceiling almost equal to 50m, which is also satisfactory. It should be mentioned that all of these flight tests are done in heights below 50m. In general, in the design and fabrication of any FWMAV, one of the most vital components which has important role in flight performance is the wing. With considering this point, it is concluded that sizing of wing is one of the most important parts in the design of FWMAVs.

V. Conclusions

A new sizing strategy based on theoretical and statistical analyses for designing efficient flapping wings MAVs has been introduced and tested. The sizing of these MAVs was composed of five main steps including (1) defining and analyzing the mission, (2) determining the flight modes, (3) determining the planform and aspect ratio of the wing, (4) conducting constraint analysis based on the defined mission, and (5) estimating the weight. In defining the mission, the analysis of the flight mission as well as the calculation of the atmosphere parameters were performed. After completing these two steps, the wing shape (planform) and aspect ratio of the designed FWMAV were determined. The constraint analysis and the weight estimation steps were then performed. It was demonstrated that these two steps are related through the wing loading and surface of the wing. After working on all these steps, all wing dimensions and its flapping frequency were easily determined. To check the accuracy of our proposed method, a wing sizing procedure was performed for a FWMAV named Thunder I. Several flight tests were successfully performed to determine the impact of different parameters on the efficiency of Thunder I. The proposed methodology in this study can open new horizons for designing efficient bio-inspired flapping wings micro air vehicles.

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