Meccanica
DOI 10.1007/s11012-016-0568-y

Methodologies for weight estimation of fixed and flapping wing micro air vehicles

M. Hassanalian · A. Abdelkefi

Received: 14 July 2016 / Accepted: 21 October 2016

Abstract One of the important steps in the sizing process of fixed and flapping wing micro air vehicles (MAVs) is weight estimation of the electrical and structural components. In order to enhance the flight performance and endurance of MAVs, it is required to carefully estimate their weight with a minimum error. In this study, methodologies to estimate the weight of fixed and flapping wing MAVs are proposed. After dividing the total weight of the MAV into weights of structural and electrical components, these two weights are separately identified. The weight of the MAV electrical components is estimated by using engineering design techniques and the weight of the structure is identified by using statistical and computational methods. The proposed methodology for structural weight estimation is based on calculating the percentage of the used material in the construction of different parts of MAVs and then presenting the weight of each part in terms of the wing surface. The proposed computational method gives the exact estimation for the weight of each structure component, such as wing, tail, fuselage, and etc. Based on the offered method for weight estimation of MAVs, the weight estimation of a fixed wing MAV with inverse Zimmerman planform and a flapping wing MAV named "Thunder I" are experimentally shown. This developed methodology gives guidelines for weight estimation and determination of the structural weight percentages in order to design and fabricate efficient fixed and flapping wing MAVs.

Keywords Fixed and flapping wing MAVs · Weight estimation · Statistical and computational methods · Structural components · Electrical components

M. Hassanalian · A. Abdelkefi (✉)
Department of Mechanical and Aerospace Engineering, New Mexico State University, Las Cruces, NM 88003, USA
e-mail: abdu@nmsu.edu

1 Introduction

Nowadays, there is a growing need for miniature flying drones with various capabilities including micro air vehicles (MAVs) and unmanned air vehicles (UAVs) for both civilian and military applications [1–3]. Micro air vehicles have received significant attention in the past few years. The broad spectra of applications of these drones include military surveillance, border patrol, air sampling, planetary exploration, and search-and-rescue [4–7]. In addition to that, these drones can carry visual, acoustic, chemical and biological sensors [8]. Because of their smaller sizes compared to UAVs, the broader performance of MAVs can be improved. These MAV drones are generally grouped into four categories, namely, fixed wings, flapping wings, vertical take-off and landing (VTOLs), and rotary wings [9, 10]. These types of drones and their remote control capability provide the

Published online: 31 October 2016

possibility to apply them in various conditions where the presence of humans is impossible, difficult, or dangerous. Considerable merits of MAVs have led to the publication of a myriad of studies aiming at optimizing and enhancing the endurance and ability of this group of air drone. Therefore, different types of micro air vehicles are these days active and well-integrated, attracting participation from a wide range of sciences [11].

MAVs are mainly flying at low altitudes for applications, such as monitoring of dangerous locations, target tracking, localization, and mapping. Flying of MAVs at low altitude places them within the atmospheric boundary layer, a particularly turbulent regime which makes them sensitive to these atmospheric disturbances [12]. Therefore, design and fabrication of these air drones should be done accurately. Conceptual design of micro air vehicles usually differs from that of conventional aircraft design due to nontraditional flight missions and required time for design, production, and evaluation of these drones [13]. For example, fixed wing MAVs usually consist of rigid wing, tails, and fuselage which use motor and propeller as their propulsion system while the flapping wing MAVs consist of the flexible and flapper wings which use an actuation mechanism for their flapping motion. Most of the flapping wing MAVs have flexible and light wings as observed in nature same as birds and insects which indicates that the flexibility and weight of wings have important role in their aerodynamic proficiency and flight stability [14–16].

Because of the utilized advanced sensors and new methods in fabrication, navigation, and power storage systems in MAVs, the development of these types of drones has become more and more expensive. Therefore, in order to reduce the development cost of MAVs, improvement of the conceptual design phase is needed. One of the important issues which should be estimated and determined accurately in conceptual design of MAVs and particularly in their sizing process is their total weight. In other words, weight estimation is one of the main challenges in the conceptual design of MAVs. There are different methods for weight estimation in conceptual design of the fixed and flapping wing MAVs which most of them are based on statistical or empirical methods [17]. In these approaches, usually the calculation of take-off weight can be performed with relatively use of empirical data which often extract values from similar MAVs or from historical trend [17, 18]. In weight estimation, usually all the components weights, such as motor, battery, servo motors, etc., are considered known, and the last item contributing to the weight is the airframe or structure of the MAVs where different approaches are available to estimate the weight of this part which consists of wing, fuselage, tails, and etc.

Some of the most common methods in weight estimation of every flying vehicle are empirical, classic plate theory (CBT), finite element, and three dimensional computer-aided design (3D CAD) [18, 19]. The empirical method in weight estimation is the simplest approach to obtain an estimate for structural mass based on the structures of previous test-bed air drones and weight analyses from similar existing MAVs [18]. The accuracy of this method is dependent on several factors including the quantity and quality of the available data on existing MAVs. This method which has been offered by Roskam [20], Torenbeek [21], and Raymer [22] can be often applied in early conceptual design of MAVs and other manned or unmanned air vehicles. Classic plate theory is a mathematical representation of the wing based on equivalent plate theory and combine Ritz analysis which is a direct method to find an approximate solution for boundary value problems, in order to study the structural response of the wing [18, 19]. According to the size and weight of MAVs, this method cannot be applied for these types of drones. The next one is finite element analysis which is the matrix method of solution of a discretized model of a structure [19]. The finite element method produces many simultaneous algebraic equations that are generated and solved using a computer. Obtained results are scarcely exact; however, errors decrease by processing more equations [18]. According to the used materials in the fabrication of fixed and flapping wings, this method is also not recommended for weight estimation of MAVs. The last methodology was offered by Jouannet et al. [18] for weight estimation. This method applies the CAD tool which is based on geometry and simple load analyses. The weight is determined from a 3D computer model. This method may be used for fixed wing MAVs but cannot be used for flapping wing MAVs. This is due to the unpredictable shape of some structural parts, such as actuation mechanism and fuselage before doing the whole design process.

In this work, we propose a methodology for weight estimation of fixed and flapping wing MAVs which separately divides the total weight of the MAV into the weights of components and structure. The weight of the electrical components, such as motor, battery, etc. is estimated by using the engineering designing and the weight of the structure is estimated by using statistical and computational methods. In this offered approach, we use the percentage of the used material in the fabrication of different parts of the fixed and flapping wing MAVs and then present the weight of each part in terms of the wing surface, for exact estimation of the structural weight of each component including wing, fuselage, and tail. The proposed method is a compromise between empirical methods and computational methods in order to determine the exact values of the weight and dimensions of each component. This method has been applied for weight estimation of a fixed wing MAV with inverse Zimmerman planform and a flapping wing MAV named “Thunder I”. The rest of this study is organized as follows: the placement of weight estimation in fixed and flapping wing sizing process is presented in Sect. 2. In Sect. 3, weight estimation of fixed and flapping wings MAVs and the weight components are presented and discussed. Estimation of the weight of the fixed and flapping wing MAVs electrical components and weight estimation of the flapping and fixed wing structure based on statistical method are, respectively, studied in Sects. 4 and 5. The computational method for estimation the weight of the fixed and flapping wing MAVs structure is offered in Sects. 6. In Sects. 7 and 8, the offered methods have been applied for weight estimation of a fixed wing MAV with inverse Zimmerman planform and a flapping wing MAV. Summary and conclusions are presented in Sect. 9.

2 Placement of weight estimation in fixed and flapping wing sizing process

Usually sizing of fixed and flapping wing MAVs is performed in five steps, namely, defining the flight mission, setting the flight mode, determining the planform and aspect ratio, constraint analysis, and weight estimation. In the mission definition, the analysis of the route is conducted resulting in the determination of the flight time, cruise speed, and turning speed. Based on the type of the mission, flight modes, planform and aspect ratio of the MAV are determined. Then, to determine the appropriate wing loading for fixed or flapping wing MAVs, a kind of constraint analysis is used. Along with the four mentioned steps, the offered method for weight estimation can be utilized. In Fig. 1, the placement of weight estimation in fixed and flapping wing MAV sizing process is shown.

3 Weight estimation of fixed and flapping wings MAVs

Weight estimation is one of the important steps in the design of fixed and flapping wing MAVs. Because of the low weight of these types of drones, the weight should be carefully estimated with a minimum error. For weight estimation of MAVs, the weights are first divided into the weight of the structural components and the weight of the electrical components. Then, the weight of each one is separately estimated [23–25]. If the weights of the structural and electrical components are, respectively, defined by W_{Str} and W_{Eq}, then the total weight of the MAV is given by:

$$W_{TO} = W_{Eq} + W_{Str} \tag{1}$$

The weight of the electrical components is equal to:

$$W_{Eq} = W_B + W_{PL} + W_{AV} + W_{pp} \tag{2}$$

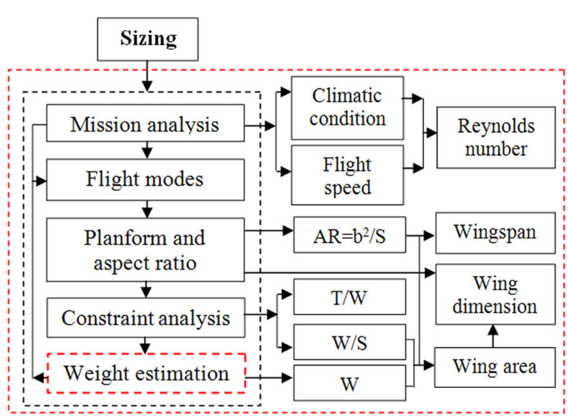

Fig. 1 The placement of weight estimation in the overall process of fixed and flapping wings' sizing. In this flowchart, *T*, *W*, *S*, *AR*, and *b*, respectively, denote the thrust, weight, wing area, aspect ratio, and wingspan

Since most of the used motors in fixed and flapping wing MAVs are of electric type and hence a battery is needed. Thus, W_B denotes the weight of battery. W_{PL} represents the sum of the loads, sensors, cameras, and other similar weights. W_{AV} is the sum of the servo motors, receivers, and navigation systems, such as autopilot. For flapping wing MAVs, W_{PP} denotes the weight of the motor and speed controller and for fixed wing MAVs, W_{PP} represents the weights of the motor, speed controller, and propeller. We should mention that the weight of the linking wires in electronic devices is measured along with the weight of the electrical components. For example, when we say the weight of the motor, actually we mean the weight of the motor as well as its wires. The other part of the weight of a fixed and flapping wing MAV is the weight of the structure, W_{Str}. For structure weight of fixed wing MAV, W_{Str} is obtained as follows:

$$W_{Str} = W_{Wing} + W_{Tail} + W_{Fuselage} + W_{Other} \tag{3}$$

where W_{Wing}, W_{Tail}, $W_{Fuselage}$, and W_{Other} are, respectively, the weight of the wing, tail, fuselage, and other weights.

To measure the structure weight of flapping wing MAV, we have:

$$W_{Str} = W_{Wing} + W_{Tail} + W_{Fuselage} + W_{Mechanism} + W_{Other} \tag{4}$$

The sum of the weights of the wing structure, the wing membrane, and their links represents the weight of the wing of flapping wing ($W_{Wing} = W_{wing\text{-}str} + W_{w\text{-}membrane} + W_{w\text{-}connections}$). The weight of the wing structure is the sum of the leading edge spars, diagonal spars, and ribs weights ($W_{wing\text{-}str} = W_{LE\text{-}spars} + W_{diagonal\text{-}spars} + W_{ribs}$). The weight of the tail includes the weights of the tails structure, tail membrane, and their links ($W_{Tail} = W_{tail\text{-}str} + W_{t\text{-}membrane} + W_{t\text{-}connections}$). 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 ($W_{Fuselage} = W_{fuselage\text{-}str} + W_{cape} + W_{f\text{-}connections}$). As for the weight of the actuation mechanism, it involves the weights of the gearbox system, linking bars, crankshaft, joints, and external parts linked to the flapping wing ($W_{Mechanism} = W_{gerabox} + W_{cranck} + W_{conrod} + \ldots$). Depending on its type, the weight of the actuation mechanism can vary. Furthermore, we should mention that the weights of other parts including landing gear, protective guards, etc. are not included. The used parts and components for designing and manufacturing flapping wing MAVs can be divided into five main categories including structures, propulsion, control, power, and endurable loads. 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. In Fig. 2, different sections comprising the components of the weight of a flapping wing MAV are schematically presented.

It should be mentioned that in designing and manufacturing fixed and flapping wing MAVs, all components should be of the least weight to endure unpredictable forces. The light-weighted materials used in the building of a fixed and flapping wing are foam, wood, composite materials, such as fiberglass and fiber carbon, and flexible membranes, such as mylar [26].

4 Electrical components weight estimation of the fixed and flapping wing MAVs

The electrical components of fixed and flapping wing MAVs include motor, battery, servo motors, speed controller (ESC), receiver, sensors, and navigation control system, as shown in Fig. 2. Among them, the motor and battery are the most important in the estimation of the weight of the fixed and flapping wings' components during the design of the MAV. As an example, in flapping wings, the motor selection is related to the kind of input data and mechanism, such as flapping frequency and, in fixed wing MAVs, the weight of motor can be estimated with considering the thrust loading (*T/W*) which is obtained from the constraint analysis. The selection of the battery is related to the flight endurance of the vehicle. 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. Thus, polymeric lithium batteries are usually used.

In the estimation of the weight of the applied devices in fixed and flapping wing MAVs, 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. In Tables 1 and 2, based on an engineering designing method [27], as an

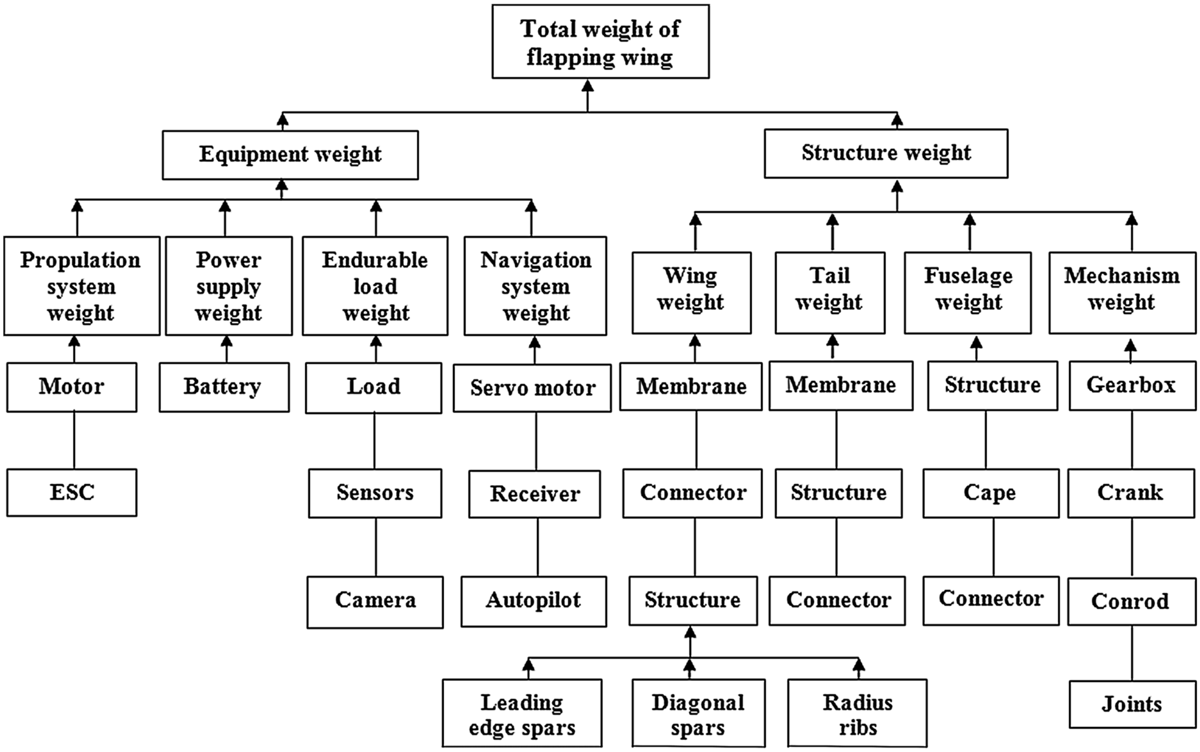

Fig. 2 Different components of the weight of a flapping wing MAV

Table 1 Technic servo motors features [27]

Manufacturer model	Technik LS2.0	Technik LS3.0	Technik LS2.4
Max deflection (mm)	14	14	14
Time to full deflection (s)	0.15	0.15	0.2
Max output force (N)	1.57	1.96	1.72
Operating voltage (V)	3–5	3–5	3–5
Dimensions (mm)	21 × 13 × 9	21 × 13 × 9	21 × 13 × 9
Load current (mA)	<100	<100	<100
Weight (g)	2	3	2.4

Table 2 Selection of Technic servo motors by engineering designing method [27]

Factors/candidates	Technik LS2.0	Technik LS3.0	Technik LS2.4
Max deflection	3	3	3
Time to full deflection	3	3	2
Max output force	3	5	4
Operating voltage	3	3	3
Dimensions	3	3	3
Load current	3	3	3
Weight	5	2	3
Mean score	3.3	3.1	3.0
Normalized score	100%	95.7%	91.3%

example, the way of selecting a Technik model of servo motors is shown.

It should be noted that the weights of other electrical components including motor, battery, ESC, and receiver can be estimated using the same engineering designing methodology. Using the engineering designing method and considering the required (T/W) according to the defined mission, the first component that its weight can be estimated is the motor. After estimating the weight of the motor, the weight of the battery, ESC, receiver and other electrical components can be estimated, respectively. After estimating the weight of the electrical components, the structural weights of the fixed and flapping wing MAV's are estimated using statistical and computational methods.

5 Structural components weight estimation of the flapping and fixed wing MAVs: statistical method

To estimate the weight of the structural components of the flapping and fixed wing MAVs, statistical or computational methods can be used. In general, as noted above, the total weight of a MAV includes W_{PP}, W_B, W_{PL}, W_{AV}, and W_{Str}. The weight of the used electrical components of the fixed and flapping wing MAVs can be estimated using engineering designing method, as shown above. The only remaining unknown is the weight of the structure which can be calculated by using statistical or computational methods. As for the statistical method, at first the weight parts (W_{PP}, W_{PL}, W_B, W_{AV}, W_{Str}, and W_{TO}) of many fixed and flapping wing MAVs have been extracted from different references. In Figs. 3, 4 and 5 and Tables 3, 4 and 5, the considered samples of flapping wings and the weights of their extracted components are presented. Three distinct categories are considered depending on the weight of the flapping wings ($m < 100$ g, 100 g $< m < 400$ g, and 400 g $< m <$ 800 g).

In Table 6, the approximate percentage of each constituent of the flapping wing for the three considered weight classes, which have been extracted from the given data in Tables 4, 5 and 6, is shown.

Based on this statistical method, it can be concluded that (1) the weight of the structural components (W_{Str}) have the highest percentage compared to the other weights; (2) with increasing the total weight of the flapping wing MAV, the percentages of the weights of the electrical components, such as W_{PP}, W_{PL}, W_{AV} and W_B are decreased; and (3) the weight of the avionic parts (W_{AV}) is smaller than W_{PP} and W_B. If we assume that the structural weight is x factor of the total weight of the MAV, by referring to the statistical data presented in Table 6, we can conclude that x is 38% for flapping wings weighing less than 100 g, 60% for flapping wings weighing between 100 and 400 g, and 72% for flapping wings weighing between 400 and 800 g.

To estimate the weight of the fixed wing MAV's structure, with statistical method, the structure weight of different fixed wing MAVs have been extracted as shown in Table 7.

With considering the statistical data presented in Table 7, it can be concluded that x is nearly 30% for fixed wing micro air vehicles. It should be noted that this percentage is independent of the total weight of the vehicle.

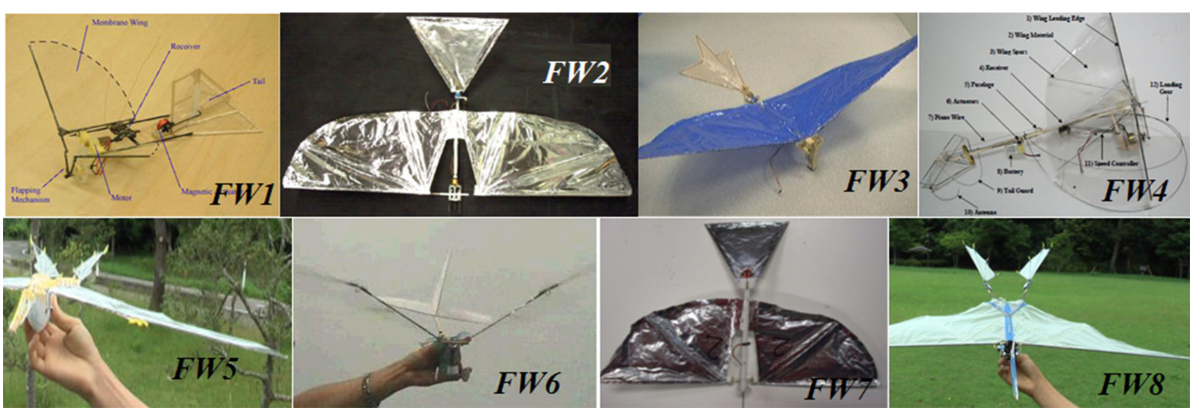

Fig. 3 Flapping wing with weight less than 100 g

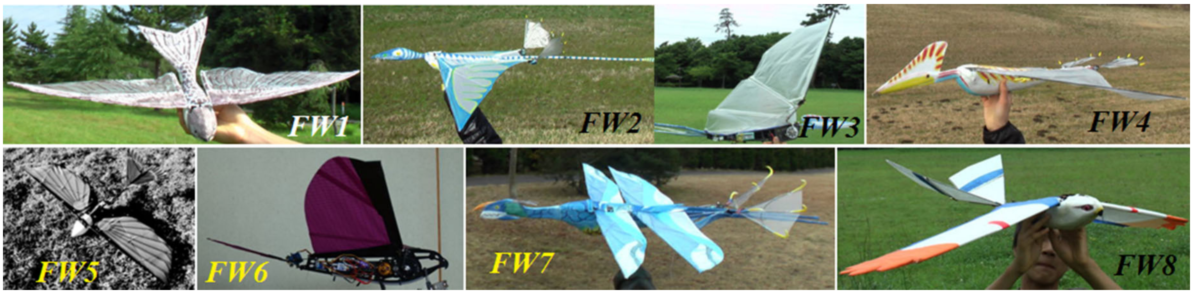

Fig. 4 Flapping wing with weight between 100 and 400 g

Fig. 5 Flapping wing with weight between 400 and 800 g

Table 3 Components weights of flapping wing with weight less than 100 g [28–31]

Weight (g)	FW1	FW2	FW3	FW4	FW5	FW6	FW7	FW8
W_{PP}	1.3	3.65	11.9	7.2	19.5	12.9	12	22
W_{PL}	0	0	0	7	0	0	0	0
W_B	3.18	4.8	8	4.7	13	16	21	20
W_{AV}	2.1	3.2	6.5	5.1	5.7	6.5	6	14.9
W_{STR}	4.27	5.83	12.36	15.6	17.8	24	23	43.1
W_{TO}	10.85	17.48	38.76	39.6	56	59.4	62	100

Table 4 Components weights of flapping wing with weight between 100 and 400 g [31, 32]

Weight (g)	FW1	FW2	FW3	FW4	FW5	FW6	FW7	FW8
W_{PP}	15.2	24	24	38	32	30.5	43	62
W_{PL}	0	0	0	0	10	0	0	0
W_B	18	17	22	42	46	35	21	50
W_{AV}	11.9	14.9	17.7	18.5	32	19.6	20	29
W_{STR}	56.9	63.1	73.3	79.5	128	169.9	221	247
W_{TO}	102	119	137	178	248	255	305	388

Table 5 Components weights of flapping wing with weight between 400 and 800 g [31]

Weight (g)	FW1	FW2	FW3	FW4	FW5	FW6	FW7	FW8
W_{PP}	93	65	65	58.7	62	58.7	58.7	58.7
W_{PL}	0	0	0	0	0	0	0	0
W_B	50	60	80	55	55	55	74	74
W_{AV}	27	20	20	20	29	20	29	29
W_{STR}	230	285	285	329.3	427	447.3	530.3	562.3
W_{TO}	400	430	450	463	573	581	692	724

Table 6 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 g	23	2	24	13	38
Between 100 and 400 g	16	1	14	9	60
Between 400 and 800 g	12	0	12	4	72

Table 7 Percentage of the structure weight to the total weight of the fixed wing MAVs

MAV name	W_{str}	W_{To}	W_{str}/W_{To}
RIT [27]	30	97.9	0.306
M.A.C 2006 [33]	76	240	0.316
Blacksqure [34]	84.45	263.6	0.320
Glotzer 2005 [35]	73	260	0.281
Dragonfly [36]	47	161	0.292
Bristol [37]	80	267	0.299
Hiledshiem [33]	65	220	0.295

6 Structural components weight estimation of the flapping and fixed wing MAVs: computational method

6.1 Fixed wing MAV

To exactly estimate the weight of the different structures forming a fixed wing MAV, such as wing, tail and fuselage, the weight of each parameter is first presented as a function of the wing surface. For fixed wing MAVs, the weight of the structural components can be written as given in Eq. (3). The weight of the wing and tails (horizontal and vertical) can be estimated by determining their geometric parameters including the planform, aspect ratio, and the types of the materials which are used in the fabrication. In Table 8, the used parameters to estimate the structure weight of the wing, fuselage and tails of a fixed wing MAV are presented.

To estimate the weight of the wing, we express their weights in term of the material density, surface, and thickness. For example, for the wing, we have;

$$W_{wing} = \rho_w \times S_{wing} \times t_{wing} \tag{5}$$

where t_{wing} is the thickness of the wing which can be determined according to the wing shape (planform) and airfoil.

Conventional fixed wing micro air vehicles usually use reflexed airfoils. In addition to that, in order to prevent laminar separation bubble formation and to reduce drag, their thickness must be as thin as possible [38, 39]. Usually, the maximum thickness of airfoils for fixed wing MAVs is between 8 and 11% of the chord [9]. The maximum thicknesses of some reflexed airfoils which are used in fixed wing MAVs have been shown in Fig. 6.

For weight estimation, the mean thickness should be considered. The calculated mean thicknesses for some reflexed airfoils are shown in Table 9.

According to the presented mean thickness values in Table 9, the mean thickness of the airfoil can be considered equal to 6% of the chord. A schematic of a delta planform has been shown in Fig. 7.

It should be mentioned that the thickness of the wing is dependent on the location of the chord. For example, for the considered wing in Fig. 7, the thickness of the wing in the root chord is larger than

Table 8 Main parameters for weight estimation of the wing, fuselage, and tails of the fixed wing MAVs

Structure part	Material	Main parameter
Wing	Foam, composite material, and etc.	ρ_w (density)
Horizontal tail	Foam, composite material, balsa wood	ρ_{ht} (density)
Vertical tail	Foam, composite material, balsa wood	ρ_{vt} (density)
Fuselage	Foam, composite material, balsa wood	ρ_f (density)

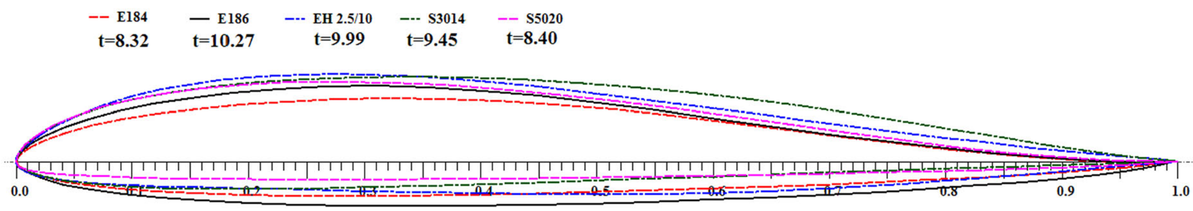

Fig. 6 Reflexed airfoils with different thickness

Table 9 Mean thickness of reflexed airfoils

Airfoil	E184	E186	EH2.5/10	S3014	S5020
Mean thickness	5.3	6.6	6.6	6.4	5.3

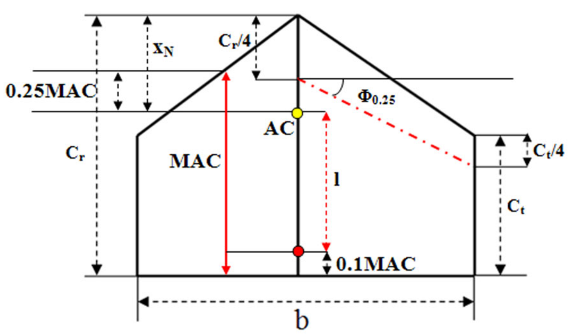

Fig. 7 Schematic view of a wing with delta planform

the thickness of wing in the tip chord. Therefore, we consider the thickness of the mean aerodynamic chord (MAC) for the whole wing, where the MAC is defined, for a delta wing, as follows [40]:

$$\bar{c} = MAC = \frac{2}{3} c_r \left(\frac{1 + \lambda + \lambda^2}{1 + \lambda} \right) \tag{6}$$

where c_r is the root chord, c_t is the tip chord, and λ is the taper ratio (c_t/c_r). The thickness of the wing in MAC for every planform can be written as follows equation:

$$t_{wing} = t_{MAC} = 0.06 MAC \tag{7}$$

The thickness of the wing in MAC, t_{MAC}, for a delta planform, can be written in terms of the wing surface as (see "Appendix"):

$$t_{MAC} = 0.08 \sqrt{\frac{S_{wing}}{AR}} \times \left(\frac{1 + \lambda + \lambda^2}{1 + 2\lambda + \lambda^2} \right) \tag{8}$$

Finally, according to Fig. 7, we can write the weight of wing in term of wing surface as below:

$$W_{wing} = 0.08 \rho_w \times S_{wing} \sqrt{\frac{S_{wing}}{AR}} \times \left(\frac{1 + \lambda + \lambda^2}{1 + 2\lambda + \lambda^2} \right) \tag{9}$$

As for the estimation of the weight of the tail, according to its type, its weight can be determined. Usually, in fixed wing MAVs, when using reflexed airfoil in wing, it is not necessary to use the horizontal tail as a stabilizer [9]. However, if the airfoils without reflex are used, horizontal tail should be designed. If a horizontal tail is placed near the wing and due to small tail arm, it will have a large surface. The tail will have the form of T and sometimes the MAV will look like a biplane MAV. In some of the MAVs having low horizontal tail surface, the arm is increased with adding boom which will increase the dimension of the MAV. For horizontal tail, the weight of the tail can be expressed as:

$$W_{ht} = \rho_{ht} \times S_{ht} \times t_{ht} \tag{10}$$

where W_{ht}, S_{ht}, and t_{ht} denote the horizontal tail weight, surface, and thickness, respectively. For a horizontal tail, we have [41, 42];

$$S_{ht} = \frac{S_{wing} \times \bar{c} \times V_h}{l} = \frac{V_h}{l} \times S_{wing} \times \frac{2\int_0^{b/2} c^2 dy}{S_{wing}} = \frac{2V_h}{l} \int_0^{\frac{\sqrt{AR \times S_{wing}}}{2}} c^2 dy \tag{11}$$

where V_h represents the horizontal volume coefficient and l is the tail arm which is the distance between the wing AC and the tail AC. In Eq. (11), V_h/l can be considered as known parameter and t_{ht} can be obtained using the same method which determined the thickness of the wing.

For some fixed wing MAVs, they can have one, two, or three vertical tails. The major parameter in designing the vertical tail is its surface which is the only unknown when designing the tail. Tail arm in fixed MAVs is equal to the distance between the point that is 0.1 (*MAC*) until wing AC which is described by l in Fig. 7 [9]. In designing the vertical tail, like horizontal tail, the volume coefficient (V_v) is defined. For vertical tail, the weight of the tail can be written as:

$$W_{vt} = \rho_{vt} \times S_{vt} \times t_{vt} \tag{12}$$

where W_{vt}, S_{vt}, and t_{vt} are the vertical tail weight, surface, and thickness, respectively. For a vertical tail, we have [41, 42]:

$$S_{vt} = \frac{S_{wing} \times b \times V_v}{l} = \frac{V_v}{l} \times bS_{wing} = \frac{V_v}{l} \times S_{wing}\sqrt{S_{wing} \times AR} \tag{13}$$

where V_v can be considered as known parameter. Concerning l, it can be written in terms of the wing surface if the wing shape is specified. For example, for a delta planform, the position of the wing AC (x_N) is given by [43]:

$$x_N = \frac{c_r}{4} + \frac{2b}{3\pi}\tan_{\Phi_{0.25}} \quad if\ \lambda < 0.375 \tag{14}$$

$$x_N = \frac{c_r}{4} + \frac{b}{6}\frac{1+2\lambda}{1+\lambda}\tan_{\Phi_{0.25}} \quad if\ \lambda > 0.375 \tag{15}$$

where $\Phi_{0.25}$ is the angle between the horizontal line and the line which connect 0.25 root chord to 0.25 tip chord of wing, as shown in Fig. 7.

For a delta planform, according to Fig. 7 and Eqs. (16) and (17), l can be written as follows:

$$l = c_r - x_N - 0.1\bar{c} \tag{16}$$

For a delta planform, with $\lambda > 0.375$, the tail arm is equal to (see "Appendix"):

$$l = \left[\frac{2.6(1+\lambda+\lambda^2)}{3(1+\lambda)^2\sqrt{AR}}\right]\sqrt{S_{wing}} \tag{17}$$

Finally, the weight of the vertical tail can be expressed as:

$$W_{vt} = \rho_{vt} t_{vt} V_v \times AR \frac{3(\lambda+1)^2}{2.6\left(1+\lambda+\lambda^2\right)} S_{wing} \tag{18}$$

t_{vt} which is the thickness of vertical tail can be calculated and written in term of the wing surface and other tail geometric parameters, but usually in fabrication of the vertical tails, a sheet of balsa wood, that its thickness is 5 or 7 mm is used.

As for the weight of the fuselage, its estimation depends on its shape; however, an approximate estimation of its dimension based on the wing shape can be determined. If the fuselage is considered as a hollow cube with a length (l_f), width (w_f), and height (h_f)and its length, width, and height are assumed equal to the wing root chord ($l_f = c_r$) and 15% of the wingspan ($h_f = w_f = 0.15b$), the weight of the fuselage can be expressed as:

$$W_f = \rho_f \times \left[2h_f\left(l_f + w_f\right) + l_f \times w_f\right] \times t_f = 0.45\rho_f t_f (c_r + 0.1b)b \tag{19}$$

where t_f is the thickness of the body.

In terms of the wing surface, the weight of the fuselage can be rewritten as:

$$W_f = 0.45\rho_f t_f\left(c_r + 0.1\sqrt{AR \times S_{wing}}\right)\sqrt{AR \times S_{wing}} \tag{20}$$

In Eq. (20), c_r can be expressed in terms of the wing surface which depends on the wing's planform. As an example, for a delta planform, the weight of the fuselage can be expressed as (see "Appendix"):

$$W_f = 0.45\rho_f t_f\left(\frac{2S_{wing}}{(\lambda+1)} + 0.1\left(AR \times S_{wing}\right)\right) \tag{21}$$

The weight of the structural components of a fixed wing MAV can be the sum of all structural parts including wing, fuselage, horizontal, and vertical tail. For instance, for a fixed wing MAV with delta planform without horizontal tail, the weight of the structural components is given by:

$$W_{Str} = \begin{bmatrix} 0.08\rho_w S_{wing}\sqrt{\frac{S_{wing}}{AR}}\left(\frac{1+\lambda+\lambda^2}{1+2\lambda+\lambda^2}\right) + \rho_{vt}t_{vt}V_v\frac{3(\lambda+1)^2}{2.6(1+\lambda+\lambda^2)}AR \times S_{wing}+ \\ 0.45\rho_f t_f\left(\frac{2S_w}{(\lambda+1)}+0.1(AR \times S_w)\right) \end{bmatrix} \tag{22}$$

After expressing the weight of each component (wing, tail, and fuselage) in terms of the wing surface, it is clear that the total weight of the structural components can only be expressed as a function of the wing surface. Considering the extracted value for wing loading from sizing process and considering the estimated weight for the structural components of fixed wing MAV from statistical method, the weight of each component can be determined.

6.2 Flapping wing MAV

As performed for fixed wing MAVs, the weight of all structural components of a flapping wing MAV are first expressed as a function of the wing surface. The only structural component that its weight should be estimated based on statistical method is the mechanism weight. The weight of the actuation mechanism along with other unpredictable weights (such as linking) is nearly 30% of the structural weight of a flapping wing MAV. This percentage is determined by performing a statistical process for various fabricated flapping wing MAVs as the presented one in Tables 3, 4 and 5 [28–33]. It should be noted that these parts of the structure are unpredictable for weight estimation because it is very difficult to estimate the size and material of the actuation mechanism parts before designing and fabricating the MAV. Therefore, the weights of the structural components are related as:

$$W_{Str} = W_{Wing}\left(S_{wing}\right) + W_{Tail}\left(S_{wing}\right) + W_{Fuselage}\left(S_{wing}\right) + W_{Mechanism} + W_{Other}$$

Concerning the estimation of the wing weight, first of all, the geometric parameters of the wing including the planform, aspect ratio, wingspan, and the types of materials that are used to fabricate the wing are determined. In Table 10, the used parameters to estimate the weight of the wing are shown. The placements of the wing structure parameters are shown in Fig. 8.

Table 10 Main parameters for wing weight estimation

Parameter	Material	Main parameter
Wing membrane	Mylar, textile	ρ_w (surface density)
Leading edge spars	Carbon rod	D_{Ls} (diameter) ρ_{Ls} (density)
Diagonal spars	Carbon rod	D_{ds} (diameter) ρ_{ds} (density)
Radius ribs	Carbon rod	D_{rr} (diameter) ρ_{rr} (density)
Root chord rib	Carbon rod	D_{cr} (diameter) ρ_{cr} (density)

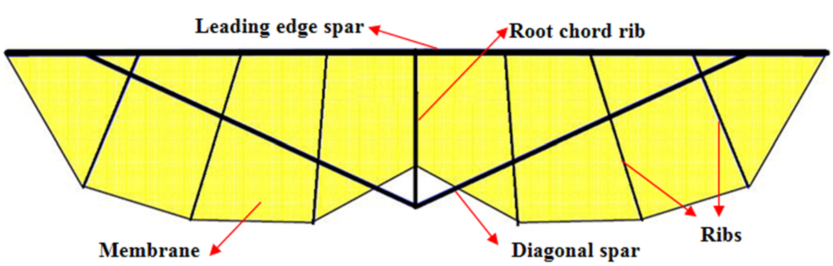

Fig. 8 Schematic view of the wing structure

In Table 11, the general formulas for the estimation of the weight of the wing's parts and an example of the weight estimation for a half elliptical wing shape, as the one shown in Fig. 9, are presented.

In Table 11, S_{wing} denotes the wing area and c_r represents the root chord. In equations presented in Table 11 when considering general wing, it is assumed that the diagonal spars are extended from the wing tips in leading edge until the end of the wing root chord. In addition, depending on the wing shape, the root chord can be expressed as a function of the aspect ratio and wing surface. For instance, for a half elliptical planform, as shown in Fig. 9, the root chord c_r can be expressed as follows:

$$S_{wing} = \frac{\pi}{4} c_r b \rightarrow c_r = \frac{4S_{wing}}{\pi b} = \frac{4}{\pi}\sqrt{\frac{S_{wing}}{AR}} \tag{24}$$

It should be noted that the weights of the radius ribs are different based on the numbers and their positions on the wing. It can be assumed that the sum of radius ribs lengths is equal to 0.75% of the sum of diagonal spars, leading edge spars, and root chord lengths. Generally, it is very difficult to have an accurate estimation of the radius ribs because their weights change according to their numbers and the position angle. However, with having these parameters, this part of the wing structure can be estimated. We should also mention that the diameter of the carbon rods which are used as spars is greater than the radius ribs. Finally, the weight of the wing of a flapping wing MAV can be estimated as:

$$W_{Wing} = \left[\begin{array}{c} \rho_w S_{wing} + \frac{\pi}{4}\rho_{Ls} D_{Ls}^2 \sqrt{AR \times S_{wing}} + \frac{\pi}{2}\rho_{ds} D_{ds}^2 \sqrt{\frac{AR \times S_{wing}}{4} + c_r^2} + \\ \frac{\pi}{2}\rho_{cr} D_{cr}^2 c_r + 0.75 \left[\begin{array}{c} \frac{\pi}{4}\rho_{rr} D_{rr}^2 \sqrt{AR \times S_{wing}} + \\ \frac{\pi}{2}\rho_{rr} D_{rr}^2 \sqrt{\frac{AR \times S_{wing}}{4} + c_r^2} + \frac{\pi}{2}\rho_{rr} D_{rr}^2 c_r \end{array} \right] \end{array} \right] = f_{wing}\left(S_{wing}\right) \tag{25}$$

As for the estimation of the tails weight, in general, the tails of flapping wing MAVs have similar structural shapes to the wing of a flapping wing MAV. In addition to that, the materials which are used in the fabrication of the tails are usually similar to the ones of the wing. However, tails can be fabricated with different materials, such as foam or balsa wood. In Table 12, the used parameters to estimate the structural weight of tails of the flapping wing MAVs are presented.

The physical and geometric parameters of the tails can be defined same as vertical and horizontal tails for fixed wing MAVs. According to Table 12 and the geometric parameters of the tail, the weight of each part of the tail can be written in terms of the wing surface as:

$$W_{T-Membrane} = \rho_t \times (S_{ht} + S_{vt}) \tag{26}$$

S_{ht} and S_{vt} can be expressed as:

$$S_{ht} = \frac{S_{wing} \times \bar{c} \times V_h}{l} = \frac{V_h}{l} \times S_{wing} \times \frac{2\int_0^{b/2} c^2 dy}{S_{wing}} = \frac{V_h}{l} 2 \int_0^{\frac{\sqrt{AR \times S_{wing}}}{2}} c^2 dy \tag{27}$$

where the mentioned integral can be calculated easily if the shape of wing is specified. For instance, if the shape of the wing is a half elliptical, we have:

$$\bar{c} = \frac{2\int_0^{b/2} c^2 dy}{S_{wing}} = \frac{2}{S_{wing}} c_r^2 \int_0^{b/2} \left(1 - \frac{4y^2}{b^2}\right) dy = \frac{2c_r^2 \times b}{3S_{wing}} = \frac{32}{3\pi^2}\sqrt{\frac{S_{wing}}{AR}} \tag{28}$$

Therefore, the surface of horizontal and vertical tails can be obtained as follows:

$$S_{ht} = \frac{32V_h}{3\pi^2 l} S_{wing} \sqrt{\frac{S_{wing}}{AR}} \tag{29}$$

Table 11 General formulas for the estimation of the weight of the wing's parts

Part of wing	General formula	For half elliptical wing
Membrane	$W_{W-Membrane} = \rho_w \times S_{wing}$	$W_{W-Membrane} = \rho_w \times S_{wing}$
Leading edge spars	$W_{LE-Spars} = \frac{\pi}{4}\rho_{Ls}D_{Ls}^2 b = \frac{\pi}{4}\rho_{Ls}D_{Ls}^2\sqrt{AR \times S_{wing}}$	$W_{LE-Spars} = \frac{\pi}{4}\rho_{Ls}D_{Ls}^2\sqrt{AR \times S_{wing}}$
Diagonal spars	$W_{Diagonal-Spars} = \frac{\pi}{2}\rho_{ds}D_{ds}^2\sqrt{\left(\frac{b}{2}\right)^2 + c_r^2} = \frac{\pi}{2}\rho_{ds}D_{ds}^2\sqrt{\frac{AR \times S_{wing}}{4} + c_r^2}$	$W_{Diagonal-Spars} = \frac{\pi}{2}\rho_{ds}D_{ds}^2\sqrt{\frac{AR \times S_{wing}}{4} + \frac{16}{\pi^2}\frac{S_{wing}}{AR}}$
Root chord ribs	$W_{Chord-ribs} = \frac{\pi}{2}\rho_{cr} \times D_{cr}^2 \times c_r$	$W_{Chord-ribs} = 2\rho_{cr}D_{cr}^2\sqrt{\frac{S_{wing}}{AR}}$
Ribs	$W_{Ribs} = 0.75\left[\frac{\pi}{4}\rho_{rr}D_{rr}^2\sqrt{AR \times S_{wing}} + \frac{\pi}{2}\rho_{rr}D_{rr}^2\sqrt{\frac{AR \times S_{wing}}{4} + c_r^2} + \frac{\pi}{2}\rho_{rr}D_{rr}^2 c_r\right]$	$W_{Ribs} = 0.75\left[\frac{\pi}{4}\rho_{rr}D_{rr}^2\sqrt{AR \times S_{wing}} + \frac{\pi}{2}\rho_{rr}D_{rr}^2\sqrt{\frac{AR \times S_{wing}}{4} + \frac{16}{\pi^2}\frac{S_{wing}}{AR}} + 2\rho_{rr}D_{rr}^2\sqrt{\frac{S_{wing}}{AR}}\right]$
Wing structure	$W_{Wing-Str} = W_{W-Membrane} + W_{LE-Spars} + W_{Diagonal-Spars} + W_{Chord-ribs} + W_{Ribs}$	

$$S_{vt} = \frac{S_{wing} \times b \times V_v}{l} = \frac{V_v}{l} \times bS_{wing} = \frac{V_v}{l} S_{wing}\sqrt{S_{wing} \times AR} \tag{30}$$

According to the above equations, the weight of the tail membrane can be written as follows:

$$W_{T-Membrane} = \rho_t \times \left(\frac{V_H}{l} 2 \int_0^{\frac{\sqrt{AR \times S_{wing}}}{2}} c^2 dy + \frac{V_v}{l} \times S_{wing}\sqrt{S_{wing} \times AR} \right) \tag{31}$$

Clearly, the only unknown parameter in Eq. (31) is the tail arm (l) which can be estimated according to the flapping wing type, fuselage, and stability issues. If the tails are fabricated from balsa wood or foam, the formula shown in Eq. (31) can be used for weight estimation of the whole tails. However, if the tails are consisted of the perimeter structure and ribs, their weight should be estimated. For example, if the shape of the tail is similar to the birds' tails, as shown in Fig. 10, we have:

$$W_{T-Membrane} = 2\rho_t \times \left(\frac{V_h}{l} \int_0^{\frac{\sqrt{AR \times S_{wing}}}{2}} c^2 dy \right) \tag{32}$$

The weight of the tail structure (tail perimeter) can be calculated as follows:

$$W_{Tail-Str} = \frac{\pi}{4}\rho_{st} \times D_{st}^2 \times k \tag{33}$$

where k is the sum of the bars which constitute the perimeter of the tail and is calculated as:

$$k = 2d_{ht} + b_{ht} \tag{34}$$

In Fig. 10, a schematic view of the bird-like tail is shown.

To determine the expression of k as a function of the wing surface, we first express the span of the tail b_{ht} as:

$$b_{ht} = \sqrt{AR_{ht} \times S_{ht}} = \sqrt{\frac{2V_h \times AR_{ht}}{l} \int_0^{\frac{\sqrt{AR \times S_{wing}}}{2}} c^2 dy} \tag{35}$$

where AR_{ht} denotes the horizontal tail aspect ratio. According to Fig. 10, c_{ht} and d_{ht} can be determined using the following relations:

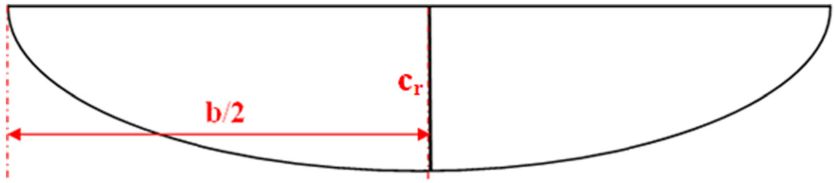

Fig. 9 Half elliptical wing shape

Table 12 Main parameters for tail weight estimation

Parameter	Material	Main parameter
Tail membrane	Mylar, textile, foam, balsa	ρ_t (surface density)
Tail perimeter structure	Carbon rod, wood	D_{st} (diameter) ρ_{st} (density)
Radius ribs	Carbon rod	D_{rt} (diameter) ρ_{rt} (density)

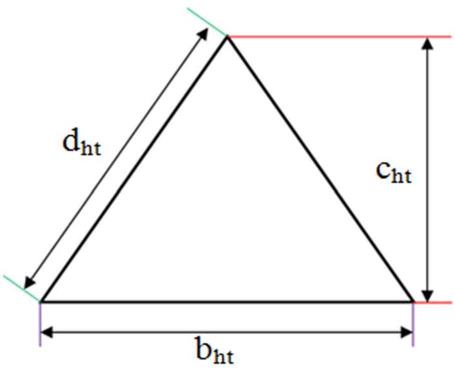

Fig. 10 A schematic view of a bird-like tail

$$AR_{ht} = \frac{b_{ht}^2}{S_{ht}} = \frac{2b_{ht}}{c_{ht}} \rightarrow c_{ht} = \frac{2b_{ht}}{AR_{ht}} \tag{36}$$

$$d_{ht}^2 = c_{ht}^2 + \frac{b_{ht}^2}{4} = \left(\frac{2b_{ht}}{AR_{ht}}\right)^2 + \frac{b_{ht}^2}{4} = b_{ht}^2\left(\frac{4}{AR_{ht}^2} + \frac{1}{4}\right)$$
$$\rightarrow d_{ht} = \sqrt{\frac{2V_h \times AR_{ht}}{l}\left(\frac{4}{AR_{ht}^2} + \frac{1}{4}\right)\int_0^{\frac{\sqrt{AR \times S_{wing}}}{2}} c^2 dy} \tag{37}$$

Substituting Eqs. (35)–(37) into Eq. (34), one obtains:

$$k = 2d_{ht} + b_{ht}$$
$$= 2\sqrt{\left(\frac{4}{AR_{ht}^2} + \frac{1}{4}\right)\frac{2V_h \times AR_{ht}}{l}\int_0^{\frac{\sqrt{AR \times S_{wing}}}{2}} c^2 dy}$$
$$+ \sqrt{\frac{2V_h \times AR_{ht}}{l}\int_0^{\frac{\sqrt{AR \times S_{wing}}}{2}} c^2 dy} \tag{38}$$

Substituting Eq. (38) into Eq. (33), the weight of the tail perimeter can be expressed as:

$$W_{Tail-Str} = \frac{\pi}{4}\rho_{st} \times D_{st}^2 \times \left(2\sqrt{\left(\frac{4}{AR_{ht}^2} + \frac{1}{4}\right)} + 1\right)$$
$$\times \sqrt{\frac{2V_h \times AR_{ht}}{l}\int_0^{\frac{\sqrt{AR \times S_{wing}}}{2}} c^2 dy} \tag{39}$$

Considering Eqs. (32) and (39), the weight of tail is then given by:

$$W_{Tail} = \rho_t \times \left(\frac{V_h}{l} 2\int_0^{\frac{\sqrt{AR \times S_{wing}}}{2}} c^2 dy\right) + \frac{\pi}{4}\rho_{st} \times D_{st}^2$$
$$\times \left(2\sqrt{\left(\frac{4}{AR_{ht}^2} + \frac{1}{4}\right)} + 1\right)$$
$$\times \sqrt{\frac{2V_h \times AR_{ht}}{l}\int_0^{\frac{\sqrt{AR \times S_{wing}}}{2}} c^2 dy} \tag{40}$$

Concerning the weight estimation of the fuselage, it is strongly dependent on its type. In fact, in general, there are three types of fuselage in flapping wings, namely, bar-shape, planer, and solid ones. In Table 13, the used parameters to estimate the structure weight of fuselage of flapping wing MAVs are presented.

As for the bar-shape fuselage weight estimation, it is first assumed that its length is twice of the wing root chord. Hence, the weight of the fuselage can be expressed as:

$$W_{Fuselage} = \frac{\pi}{2}\rho_{bf} \times D_{bf}^2 \times c_r \tag{41}$$

Table 13 Main parameters for fuselage weight estimation

Type of fuselage	Material	Main parameter
Bar-shape	Carbon rod, balsa wood	D_{bf} (diameter)ρ_{bf} (density)
Planer	Wood, carbon sheet	D_{pf} (diameter) ρ_{pf} (surface density)
Solid-shape	Foam, composite	D_{sf} (diameter) ρ_{sf} (surface density)

In Eq. (41), with knowing the planform, the wing root chord can be written in terms of the wing surface. As an example, for a half elliptical wing, the estimated weight of a bar-shape fuselage is given by:

$$W_{Fuselage} = 2\rho_{bf} \times D_{bf} \times \sqrt{\frac{S_{wing}}{AR}} \tag{42}$$

Concerning the planer-shape fuselage weight estimation, it is first considered that the length and height of the fuselage are, respectively almost equal to the (1.5) wing root chord and (1/6) root chord [28–32]. To reduce the weight of the fuselage, it is usually considered hollow. Consequently, the weight of the planer-shape fuselage is expressed as:

$$W_{Fuselage} = \rho_{pf} \times \frac{c_r^2}{4} \tag{43}$$

For a half elliptical planform, the estimated weight of planer-shape fuselage is:

$$W_{Fuselage} = \frac{4\rho_{pf}}{\pi^2}\frac{S_{wing}}{AR} \tag{44}$$

Concerning the solid-shape fuselage weight estimation, it is considered as thin wall cylinder with length equal to the (1.5) wing root chord and with diameter almost equal to (1/6) root chord length [28–32]. Therefore, its weight expression is given by:

$$W_{Fuselage} = \rho_{sf} \times \frac{\pi c_r^2}{4} \tag{45}$$

The estimated weight of the solid-shape fuselage for a half elliptical planform is expressed as follows:

$$W_{Fuselage} = \frac{4\rho_{sf}}{\pi}\frac{S_{wing}}{AR} \tag{46}$$

Assuming y is the ratio of the actuation mechanism and other unpredictable weights to the total weight of the structure as:

$$W_{Mechanism} + W_{Other} = yW_{Str} \tag{47}$$

Hence,

$$\begin{aligned} W_{Str} = {} & W_{Wing}\left(S_{wing}\right) + W_{Tail}\left(S_{wing}\right) \\ & + W_{Fuselage}\left(S_{wing}\right) + yW_{Str} \end{aligned} \tag{48}$$

$$(1-y)W_{Str} = f\left(S_{wing}\right) \rightarrow W_{Str} = \frac{f\left(S_{wing}\right)}{(1-y)} \tag{49}$$

The overall weight of the flapping wing MAV is then estimated as follows:

$$\frac{W_{TO}}{S_{wing}} = \frac{W_{Str} + W_{Eq}}{S_{wing}} = \frac{f\left(S_{wing}\right) + (1-y)W_{Eq}}{(1-y)S_{wing}} \tag{50}$$

Consequently, the weight of the flapping wing MAV can be easily calculated with the parameter of the wing loading which can be obtained by solving the constraint analysis process [44]. By solving Eq. (50), the value of S_{wing} is pinpointed and then the total weight is estimated. Considering the extracted value of the wing surface and the estimated weight for structural parts of the flapping wing MAV from statistical method (Table 6), the weight of each component (wing, tail, and fuselage) can be determined.

7 Weight estimation of a fixed wing MAV: inverse Zimmerman planform prototype

The statistical and computational methods for weight estimation of a fixed wing MAV with inverse Zimmerman planform are applied. The estimated electrical components weight, W_{Eq} for a fixed wing MAV is equal to 315 g. Using statistical method presented in Sect. 5, the total weight of the fixed wing MAV is equal to 450 g. Using the computational method, the weight of the structural components can be determined by calculating the percentage of the used materials in the construction of these parts. To estimate the weight of the different structure forming the inverse Zimmerman MAV, the weight of each component, such as wing, tail, and fuselage should be presented in term of the wing surface. It should be mentioned that P20 foam is used for the fabrication of the wing and two balsa wood sheets to cover the wing surface. The densities of the P20 foam and balsa wood materials are, respectively, equal to 20 and 125 kg/m^3. According to the inverse Zimmerman shape of the wing, the weight of the wing (W_{wing}) as a function of the wing surface can be written as:

$$W_{wing} = \rho_{foam} \times S_{wing} \times t_{MAC} + 2\rho_{balsa} \times S_{wing} \quad (51)$$

If we consider the mean thickness of wing equal to $0.06MAC$, for inverse Zimmerman planform, we have:

$$\begin{aligned} t_{MAC} &= 0.06MAC = 0.06 \times \frac{8c_{root}}{3\pi} \\ &= 0.06 \times \frac{8}{3\pi} \times \frac{4}{\pi}\sqrt{\frac{S_{wing}}{AR}} = 0.065\sqrt{\frac{S_{wing}}{AR}} \end{aligned} \quad (52)$$

Considering $AR = 1.45$, the weight of the wing can be expressed as:

$$W_{wing} = 1.08 \times S_{wing} \times \sqrt{S_{wing}} + 0.25 \times S_{wing} \quad (53)$$

As for the vertical tail of this fixed wing MAV, considering balsa wood sheet with thickness equal to 5 mm and density equal to 125 kg/m^3 and considering the vertical tail volume coefficient equal to 0.07, the weight of the vertical tail is given by:

$$\begin{aligned} W_{vt} &= \rho_{vt} \times S_{vt} \times t_{vt} \\ &= 1.2\rho_{vt} \times t_{vt} \times V_v \times S_{wing} \times AR = 0.76S_{wing} \end{aligned} \quad (54)$$

Concerning the weight of the fuselage, considering balsa wood as the material which is used in fabrication with thickness equal to 7 mm and density equal to 125 kg/dm^3, the fuselage weight can be expressed as:

$$\begin{aligned} W_f &= 0.45\rho_f t_f \left(c_r + 0.1\sqrt{AR \times S_{wing}}\right)\sqrt{AR \times S_{wing}} \\ &= 5.58S_{wing} \end{aligned} \quad (55)$$

Considering Eqs. (53)–(55), the weight of the structural components can be related to the surface of the wing by:

$$\begin{aligned} W_{STR} &= W_{wing} + W_{vt} + W_f \\ &= 1.08S_{wing}\sqrt{S_{wing}} + 6.6S_{wing} \end{aligned} \quad (56)$$

Dividing the total weight by the wing surface and using the results of the constraint analysis, one obtains:

$$\begin{aligned} \frac{W_{TO}}{S_{wing}} &= \frac{W_{Str} + W_{Eq}}{S_{wing}} \\ &= \frac{1.08S_{wing}\sqrt{S_{wing}} + 6.6S_{wing} + 315}{S_{wing}} = 35\,\frac{\mathrm{g}}{\mathrm{dm}^2} \end{aligned} \quad (57)$$

Thus,

$$1.08S_{wing}\sqrt{S_{wing}} - 28.4S_{wing} + 315 = 0 \quad (58)$$

Solving numerically Eq. (58) and using $W_{TO} = 35S_{wing}$ (wing loading = 35 N/m^2) [9], the total weight is almost equal to 450 g which is in excellent agreement with the statistical data. Using Eqs. (53)–(55), the computational method gives us the exact estimation for the weight of the wing, tail, and fuselage, which are almost equal to 55, 10, and 70 g, respectively. In Fig. 11, two views of the fabricated fixed wing MAV are shown. It should be mentioned that this fabricated MAV is successfully tested for well-defined mission.

8 Weight estimation of a flapping wing MAV: Thunder I prototype

Based on what was mentioned in Sect. 5 for the weight estimation of a flapping wing MAV, its total weight is divided into two parts, namely, structural and electrical components weights. The weight of the electrical components is first estimated by using the engineering designing method and the weight of the structural components is estimated by using both statistical and computational methods. The results of the estimated weights of the electrical components are shown in Table 14.

It follows from Table 14 that the weight of the electrical components is about 135 g. Based on Table 11 and the estimated weight of the electrical components, the weight range of the flapping wing is from 100 to 400 g. Thus, the weight of the structural components comprises about 60% of the total weight. Based on the statistical method, the total weight is calculated which is almost equal to 340 g. Next, the weights of different structural components of a flapping wing MAV named Thunder I are estimated by using the computational method. The material characteristics of this MAV are described in Table 15.

Fig. 11 Views of fixed wing MAV with inverse Zimmerman planform

Table 14 The estimated weights of the electrical components

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

According to Table 15, the weight of the Thunder I wing with $AR = 3.85$ is estimated. A schematic view of the planform of Thunder I is presented in Fig. 12. It should be noted that this planform is determined though a sizing analysis as performed by Hassanalian et al. [44]

Considering the Table 14, the weight of the membrane is given by:

$$W_{W-Membrane} = 0.16 S_{wing} \tag{59}$$

According to the wing planform, it is clear that the leading edge spar length is not equal to the wingspan and almost is equal to 0.66 of its length. Therefore, the weight of leading edge spars is estimated to be equal to (see "Appendix"):

$$W_{LE-Spars} \approx 0.04 \sqrt{S_{wing}} \tag{60}$$

As for the weight of diagonal spars, it is given by (see "Appendix"):

Table 15 Material characteristics of the flapping wing MAV

Parameter	Material	Characteristic parameter	Value
Wing membrane	Textile	ρ_w (surface density)	0.16 kg/m^2
Leading edge spars	Carbon rod	D_{Ls} (diameter) ρ_{Ls} (density)	5 mm, 1400 kg/m^3
Diagonal spars	Carbon rod	D_{ds} (diameter) ρ_{ds} (density)	2.5 mm, 1400 kg/m^3
Radius ribs	Carbon rod	D_{rr} (diameter) ρ_{rr} (density)	1.5 mm, 1400 kg/m^3
Root chord rib	Carbon rod	D_{cr} (diameter) ρ_{cr} (density)	2 mm, 1400 kg/m^3

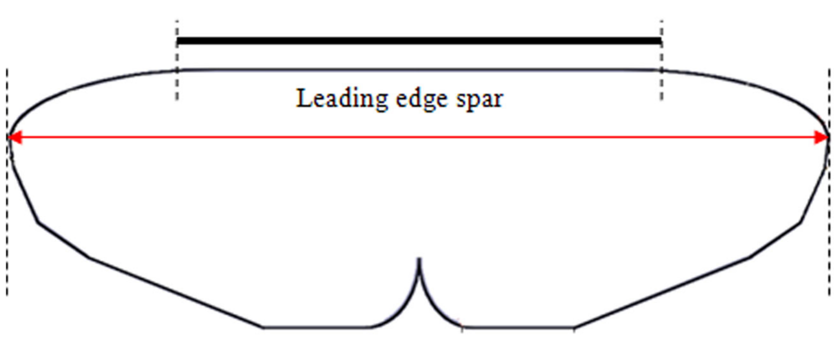

Fig. 12 A schematic view of planform for flapping wing MAV named Thunder I

$$W_{Diagonal-Spars} \approx 0.014\sqrt{0.96S_{wing} + c_r^2} \tag{61}$$

According to the wing shape, the wing root chord can be expressed as a function of the wing surface as:

$$c_r \approx 0.35 \times b = 0.35\sqrt{AR \times S_{wing}} \approx 0.7\sqrt{S_{wing}} \tag{62}$$

Thus,

$$\begin{aligned} W_{Diagonal-Spars} &\approx 0.014\sqrt{0.96S_{wing} + 0.49S_{wing}} \\ &\approx 0.02\sqrt{S_{wing}} \end{aligned} \tag{63}$$

The weight of the root chord rib can be obtained as follows:

$$W_{Chord-rib} = 2 \times \frac{\pi}{4}\rho_{cr} \times D_{cr}^2 \times c_r \approx 0.01\sqrt{S_{wing}} \tag{64}$$

The weight estimation of radius ribs cannot be accurate, since it can be changed according to their numbers and positions. According to the shape of the wing, we can have estimation from the number and position of the radius ribs and according to Table 11, their weights can be calculated as:

$$W_{Ribs} \approx 0.02\sqrt{S_{wing}} \tag{65}$$

Considering Eqs. (59)–(65), the weight of the wing can be expressed in term of the wing surface, as:

$$\begin{aligned} W_{Wing} &= 0.16S_w + 0.03\sqrt{S_{wing}} + 0.017\sqrt{S_{wing}} \\ &\quad + 0.006\sqrt{S_{wing}} + 0.015\sqrt{S_{wing}} \\ &\approx 0.16S_{wing} + 0.09\sqrt{S_{wing}} \end{aligned} \tag{66}$$

Using the material characteristics given in Table 16 and considering the tail volume coefficient and its aspect ratio are equal, respectively, to 0.37 and 4, the weight of the tail is then expressed as:

$$W_{Tail} \approx 0.02\sqrt{S_{wing}} + 0.04S_{wing} \tag{67}$$

As for the weight of the fuselage, a planer shape fuselage is considered for Thunder I. Considering a carbon sheet with surface density and thickness are, respectively, equal to 4.7 kg/m^2 and 3 mm, its weight can be then estimated as:

$$W_{Fuselage} = \rho_{pf} \times \frac{c_r^2}{4} \approx 0.6S_{wing} \tag{68}$$

Considering the weight of the actuation mechanism equals to 30% of the flapping wing structure [45], one obtains:

$$W_{Str} \approx 1.143S_{wing} + 0.16\sqrt{S_{wing}} \tag{69}$$

According to the computational estimation of the structure weight and the weight of the electrical components which was estimated equal to 135 g, and the extracted wing loading parameter for flapping wing MAV which is equal to 2.65 kg/m^2 [44], one obtains:

$$\frac{W_{TO}}{S_{wing}} = \frac{1.143S_{wing} + 0.16\sqrt{S_{wing}} + 0.135}{S_{wing}} = 2.65\,\frac{\text{kg}}{\text{m}^2} \tag{70}$$

Therefore, the total weight of the prototype can be easily calculated by having the wing loading parameter which is determined through a constraint analysis [44]. Solving Eq. (70), the value of S_{wing} can be determined which is equal to 0.13 m^2. Substituting this obtained value for S_{wing} in Eq. (70), it is determined that the total weight of Flapping wing is equal to 345 g. Subtracting the weight of the electrical components from the total weight that is estimated by the computational method, the weight of the structure is then equal to 210 g which represents 61% of the total weight of the MAV which is almost equal to the given statistical ratio in Table 7. Using Eqs. (66)–(68), and the mentioned percent for mechanism weight, the computational method gives us the exact estimation for the weights of the wing, tail, fuselage, and actuation mechanism which are almost equal to

Table 16 Material characteristics which are considered for tail structure

Parameter	Material	Characteristic parameter	Value
Tail membrane	Textile	ρ_t (surface density)	0.16 kg/m^2
Tail perimeter structure	Carbon rod	D_{st} (diameter) ρ_{st} (density)	2.5 mm, 1400 kg/m^3
Radius ribs	Carbon rod	D_{rt} (diameter) ρ_{rt} (density)	2 mm, 1400 kg/m^3

Fig. 13 A view of "Thunder I" flapping wing MAV

53, 12, 78, and 67 g, respectively. In Fig. 13, two views of the fabricated flapping wing MAV Thunder I are shown.

9 Conclusions

Different methods for weight estimation of fixed and flapping wing micro air vehicles were proposed. To accurately estimate the weight of a MAV, its total weight is divided into two parts, namely, electrical components weight and structural components weight. The electrical components weight is estimated by using the engineering designing method. As for the estimation of the structural components weight, two methods were proposed for both fixed and flapping wing MAVs. The first one was based on statistical data of previous fabricated similar MAVs. For flapping wing MAVs, it was shown that the ratio of the structure weight to the total weight is 38, 60, and 72% for flapping wings weighting less than 100 g, between 100 and 400 g, and between 400 and 800 g, respectively. Concerning fixed wing MAVs, it was indicated that this ratio is independent of the total weight of the MAV and it was determined to be equal to 30%. The second method was based on computational calculations of different parts of the structure including wing, tail, and fuselage. In this offered method, the weight of each part of fixed and flapping wing MAVs was presented in terms of the wing surface and then the total weight was easily calculated by having the wing loading parameter. Based on these proposed statistical and computational methods, the weights of a fixed wing MAV with inverse Zimmerman planform and a flapping wing MAV named "Thunder I" were estimated. It was demonstrated that the computational method is very beneficial to accurately estimate the weight of each component of the structural part.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Appendix

Substituting Eq. (6) into Eq. (7), one obtains:

$$t_{wing} = t_{MAC} = 0.06MAC = 0.06 \times \frac{2}{3} c_r \left(\frac{1+\lambda+\lambda^2}{1+\lambda} \right)$$

The parameter c_r can be written as a function of the wing surface as follows:

$$S_{Wing} = (c_r + c_t)\frac{b}{2} = c_r(1+\lambda)\frac{\sqrt{AR \times S_{wing}}}{2} \to c_r = \frac{2}{(1+\lambda)}\sqrt{\frac{S_{wing}}{AR}}$$

Then, by substituting the value of c_r, in Eq. (7), we get:

$$t_{wing} = t_{MAC} = 0.06MAC = 0.06 \times \frac{2}{3}\frac{2}{(1+\lambda)}\sqrt{\frac{S_{wing}}{AR}}\left(\frac{1+\lambda+\lambda^2}{1+\lambda}\right) = 0.08\sqrt{\frac{S_{wing}}{AR}}\left(\frac{1+\lambda+\lambda^2}{1+2\lambda+\lambda^2}\right)$$

If we consider a delta planform with $\lambda > 0.375$ and using Eq. (16), the tail arm can be expressed as:

$$l = c_r - x_N - 0.1\bar{c}$$

Substituting Eq. (15) into Eq. (6), and using the calculated formula for c_r, one gets:

$$\begin{aligned} l &= c_r - x_N - 0.1\bar{c} \\ &= c_r - \frac{c_r}{4} - \frac{b}{6}\frac{1+2\lambda}{1+\lambda}\tan_{\Phi_{0.25}} - 0.1 \\ &\quad \times \frac{2}{3}c_r\left(\frac{1+\lambda+\lambda^2}{1+\lambda}\right) \end{aligned}$$

Using the previous expression and Fig. 7, $\tan\Phi_{0.25}$ can be written as:

$$\begin{aligned} \tan_{\Phi_{0.25}} &= \frac{c_r - 0.25c_r - (c_t - 0.25c_t)}{b/2} = \frac{0.75(c_r - c_t)}{b/2} \\ &= \frac{1.5(c_r - c_t)}{b} = \frac{1.5c_r(1-\lambda)}{b} \end{aligned}$$

Substituting $\tan\Phi_{0.25}$ in the expression of l, one obtains:

$$\begin{aligned} l &= c_r - \frac{c_r}{4} - \frac{b}{6}\frac{1+2\lambda}{1+\lambda} \times \frac{1.5c_r(1-\lambda)}{b} - 0.1 \\ &\quad \times \frac{2}{3}c_r\left(\frac{1+\lambda+\lambda^2}{1+\lambda}\right) \end{aligned}$$

The previous expression can be simplified to be:

$$l = c_r\left[0.75 - 0.25\left(\frac{1+\lambda-2\lambda^2}{1+\lambda}\right) - \frac{0.2}{3}\left(\frac{1+\lambda+\lambda^2}{1+\lambda}\right)\right]$$

Substituting c_r by its expression, we have:

$$\begin{aligned} l = \frac{2}{(1+\lambda)}\sqrt{\frac{S_{wing}}{AR}}&\left[0.75 - 0.25\left(\frac{1+\lambda-2\lambda^2}{1+\lambda}\right)\right. \\ &\left. -\frac{0.2}{3}\left(\frac{1+\lambda+\lambda^2}{1+\lambda}\right)\right] \end{aligned}$$

Simplifying the previous expression, one gets:

$$\begin{aligned} l &= \sqrt{\frac{S_{wing}}{AR}}\frac{2}{(1+\lambda)} \\ &\quad \times \left[\frac{2.25(1+\lambda) - 0.75(1+\lambda-2\lambda^2) - 0.2(1+\lambda+\lambda^2)}{3(1+\lambda)}\right] \end{aligned}$$

And then:

$$l = \left[\frac{2.6(1+\lambda+\lambda^2)}{3(1+\lambda)^2\sqrt{AR}}\right]\sqrt{S_{wing}}$$

As for Eq. (71), we have:

$$W_f = 0.45\rho_f t_f\left(c_r + 0.1\sqrt{AR \times S_{wing}}\right)\sqrt{AR \times S_{wing}}$$

Substituting c_r by its expression, we have:

$$\begin{aligned} W_f &= 0.45\rho_f t_f\left(\frac{2}{(1+\lambda)}\sqrt{\frac{S_{wing}}{AR}} + 0.1\sqrt{AR \times S_{wing}}\right) \\ &\quad \times \sqrt{AR \times S_{wing}} \end{aligned}$$

Then,

$$W_f = 0.45\rho_f t_f\left(\frac{2S_{wing}}{(\lambda+1)} + 0.1\left(AR \times S_{wing}\right)\right) \tag{71}$$

According to Tables 11 and 14, for leading edge spar, we have:

$$W_{LE-Spars} = \frac{\pi}{4}\rho_{Ls}D_{Ls}^2\sqrt{AR \times S_{wing}}$$

Substituting the corresponding values for the density and the diameter of the carbon rod and aspect ratio, one obtains:

$$\begin{aligned} W_{LE-Spars} &= \frac{\pi}{4}\rho_{Ls}D_{Ls}^2\sqrt{AR \times S_{wing}} \\ &= \frac{\pi}{4} \times 1400 \times 0.005^2 \times \sqrt{3.85 \times S_{wing}} \\ &\approx 0.04\sqrt{S_{wing}} \end{aligned}$$

$$\begin{aligned} W_{Diagonal-Spars} &= \frac{\pi}{2}\rho_{ds}D_{ds}^2\sqrt{\frac{AR \times S_{wing}}{4} + c_r^2} \\ &= \frac{\pi}{2} \times 1400 \\ &\quad \times 0.0025^2\sqrt{\frac{3.85 \times S_{wing}}{4} + c_r^2} \end{aligned}$$

$$W_{Diagonal-Spars} \approx 0.014\sqrt{0.9625S_{wing} + c_r^2}$$

$$c_r = 0.35 \times b = 0.35\sqrt{AR \times S_{wing}} = 0.7\sqrt{S_{wing}}$$

$$\begin{aligned} W_{Diagonal-Spars} &\approx 0.014\sqrt{0.9625S_{wing} + 0.49S_{wing}} \\ &\approx 0.02\sqrt{S_{wing}} \end{aligned}$$

References

1. Srigrarom S, Chan WL (2015) Ornithopter type flapping wings for autonomous micro air vehicles. Aerospace 2(2):235–278

2. Ellington CP, van den Berg C, Willmott AP, Thomas ALR (1996) Leading-edge vortices in insect flight. Nature 384:626–630
3. Jones KD, Platzer MF (2009) Design and development considerations for biologically inspired flapping-wing micro air vehicles. Exp Fluids 46:799–810
4. Fenelon MAA, Furukawa T (2010) Design of an active flapping wing mechanism and a micro aerial vehicle using a rotary actuator. Mech Mach Theory 45:137–146
5. Hassanalian M, Radmanesh M, Sedaghat A (2014) Increasing flight endurance of MAVs using multiple quantum well solar cells. Internat J Aeronaut Sp Sci 15:212–217
6. Xiaolei Z, Xiaoyi J, Yang X, Liqiang Z (2014) The research and design of experimental prototype in flapping-wing micro-air-vehicles. Adv Nat Sci 7:1–7
7. Abdelkefi A, Ghommem M (2013) Piezoelectric energy harvesting from morphing wing motions for micro air vehicles. Theor Appl Mech Lett 3:052004
8. Mueller TJ (2001) Fixed and flapping wing aerodynamics for micro air vehicle applications. AIAA, New York
9. Hassanalian M, Khaki H, Khosrawi M (2014) A new method for design of fixed wing micro air vehicle. Proc Inst Mech Eng J Aerosp Eng 229:837–850
10. Kurtulus DF, David L, Farcy A, Alemdaroglu N (2007) Aerodynamic characteristics of flapping motion in hover. Exp Fluids 44:23–36
11. Liu H, Wang X, Nakata T, Yoshida K (2013) Aerodynamics and flight stability of bio-inspired, flapping-wing micro air vehicles. In: Autonomous control systems and vehicles. Volume 65 of the series intelligent systems, control and automation: Science and Engineering. Springer Japan, pp 145–157
12. Mohamed A, Abdulrahim M, Watkins S, Clothier R (2015) Development and flight testing of a turbulence mitigation system for micro air vehicles. J Field Robot 33:639–660
13. Combes TP, Malik AS, Bramesfeld G, McQuilling MW (2015) Efficient fluid-structure interaction method for conceptual design of flexible, fixed-wing micro-air-vehicle wings. AIAA J 53(6):1442–1454
14. Shyy W, Aono H, Chimakurthi SK, Trizila P, Kang CK, Cesnik CE, Liu H (2010) Recent progress in flapping wing aerodynamics and aeroelasticity. Prog Aerosp Sci 46(7):284–327
15. Mountcastle AM, Thomas LD (2010) Aerodynamic and functional consequences of wing compliance, animal locomotion. Springer, Berlin, pp 311–320
16. Nakata T, Liu H, Tanaka Y, Nishihashi N, Wang X, Sato A (2011) Aerodynamics of a bio-inspired flexible flapping-wing micro air vehicle. Bioinspir Biomimet 6(4):045002
17. Jung S (2004) Design and development of a micro air vehicle (MAV): test-bed for vision-based control. Doctoral Dissertation, University of Florida, USA
18. Jouannet C, Silva SE, Krus P (2004) Use of CAD tools for weight estimation in aircraft conceptual design. In: 24th International congress of the aeronautical sciences, Yokohama, Japan, 29 August–3 September 2004
19. Ardema MD, Chambers MC, Patron AP, Hahn AS, Miura H, Moore MD (1996) Analytical fuselage and wing weight estimation of transport aircraft. NASA Technical Memorandum, 110392
20. Roskam J (1985) Aircraft design part I: preliminary sizing of airplanes. Darcorporation, Lawrence
21. Torenbeek E (2013) Synthesis of subsonic airplane design: an introduction to the preliminary design of subsonic general aviation and transport aircraft, with emphasis on layout, aerodynamic design, propulsion and performance. Springer, Berlin
22. Raymer DP (2006) Aircraft design: a conceptual approach and Rds-student, software for aircraft design, sizing, and performance set (AIAA Education). AIAA, New York
23. Hassanalian M, Abdelkefi A (2016) Design, manufacturing, and flight testing of a fixed wing micro air vehicle with Zimmerman planform. Meccanica 51:1–18
24. Hung C-C, Lin C-H, Teng Y-J, Chang C-M, Wu Y-K (2010) Study on mini UAV designs to payload requirements by airplane sizing methodology. In: AIAA 2010 conference and exhibit, Atlanta, Georgia, USA, 20–22 April 2010
25. Mueller TJ, Kellogg JC, Ifju PG, Shkarayev SV (2007) Introduction to the design of fixed-wing micro air vehicles including three case studies. AIAA, Reston
26. Beasley B (2006) A study of planar and nonplaner membrane wing planforms for the design of a flapping wing micro air vehicle. Doctoral dissertation, University of Maryland, College Park
27. Gillis B, Kozak J, Baker J, Hein D, Lemieux A, Fu TC, Hess JED, Phadnis A, Grilly A, Le C, Schoennagel V (2005) RIT micro air vehicle preliminary design report. Rochester Institute of Technology, New York
28. Gerrard C, Ward M (2007) Final year honours project micro air vehicle. The University of Adelaide, Adelaide
29. Ryan M (2012) Design optimization and classification of compliant mechanisms for flapping wing micro air vehicles. Doctoral dissertation, The Ohio State University, Columbus, Ohio
30. Beng TW (2003) Dynamics and control of a flapping wing aircraft. Doctoral Dissertation, National University of Singapore
31. http://aerosapien.blogspot.fr/2011_09_01_archive.html
32. Silin D (2010) Aerodynamics and flight performance of flapping wing micro air vehicles. University of Arizona, Tucson
33. Müller M, Schröter A, Lindenberg C (2007) Technical description of the M.A.2C.'08 MAV. ENAC, Toulouse
34. (2006) IUT aerospace team report. Design, fabrication and flight test of HOMA MAV. Isfahan University of Technology
35. Bode F, Lindenberg C, Müller M, Schröter A (2005) The Glotzer MAV: real time video from a low cost autonomously flying aircraft
36. Coopanah D, Krashanitsa R, Malladi B, Silin D, Shkarayev S Design of dragonfly micro air vehicles at the University of Arizona. In: The 2rd US-European competition and workshop on micro air vehicles, September 2006, Florida, USA
37. Richardson T (2007) Micro UAVs. In: The institution of engineering and technology seminar, University of Bristol, 20th February 2007
38. Somers DM (2005) Effects of airfoil thickness and maximum lift coefficient on roughness sensitivity: 1997–1998. Period of performance. National Renewable Energy Laboratory
39. Ma D, Zhao Y, Qiao Y, Li G (2015) Effects of relative thickness on aerodynamic characteristics of airfoil at a low Reynolds number. Chin J Aeronaut 28(4):1003–1015

40. Schmidt LV (1998) Introduction to aircraft flight dynamics. AIAA, New York
41. Stevens BL, Lewis FL, Johnson EN (2015) Aircraft control and simulation: dynamics, controls design, and autonomous systems. Wiley, London
42. Roskam J (1995) Airplane flight dynamics and automatic flight controls. DARcorporation, Lawrence
43. Hepperie M Basic design of flying wing models. www.wh-aerotools.de/airfoils
44. Hassanalian M, Abdelkefi A, Wei M, Ziaei-Rad S (2016) A novel methodology for wing sizing of bio-inspired flapping wing micro air vehicles: theory and prototype. Acta Mech. doi:10.1007/s00707-016-1757-4
45. Hassanalian M, Abdelkefi A (2016) Effective design of flapping wing actuation mechanisms: theory and experiments. AIAA Science and Technology Forum and Exposition, San Diego