Rotary vs. Flapping-Wing Nano Air Vehicles: Comparing Hovering Power

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Abstract

This study has compared the hovering power of rotary-wing concept with the flapping-wing concept. The objective is to demonstrate which concept is more suitable for the design of NAV based on hovering power. Geometric similarity laws have been derived from a set of small unmanned air vehicles and simplified equations derived from the momentum theory are applied to rotary- and flapping-wing concepts to compare their respective power efficiency. The result shows that for nano air vehicles, both rotary- and flapping-wing concepts may produce similar efficiencies with only a slight advantage for a rotary-wing concept. Furthermore, the minimum induced loss theory is applied to design a rotary wing with airfoil AG38. Then the method derived by Ellington from the flight animals is used to design a flapping wing with referring to hummingbird. In both cases, the hovering power predicted by the concept design approach is higher than that estimated from simplified equations. Further analysis revealed that the reason is due to an overestimation of the rotor-wing power efficiency in the simplified equations. Finally, side-by-side comparisons suggest that the choice between the two concepts can be based on other considerations such as ease of fabrication and flight tests.

Nomenclature

A disk area
A_e effective operational area
AR aspect ratio
b wing span
$\hat{c}$ non-dimensional chord
$\overline{C_{D,\mathrm{Pro}}}$ mean profile drag coefficient
$\overline{C_L}$ mean lift coefficient
C_t coefficient of thrust
C_p coefficient of power
D diameter of rotor
FM figure of merit
g gravitational acceleration
$\overline{L}$ mean lift
m mass of air vehicle
n flapping frequency
P power
P_0 profile power
P_{aero} aerodynamic power
P_i induced power
P_{ideal} ideal induced power
$\overline{P_{ind}^*}$ induced power per Newton
$\overline{P_{pro}^*}$ profile power per Newton
P_{RF}^* Rankine-Froude estimate of induced power per Newton
p_w wing loading
R radius of rotor or wing length
$\hat{r}_k(S)$ non-dimensional radius of the k th moment of wing area
$\hat{r}$ non-dimensional radial position along wing
$\overline{\mathrm{Re}}$ mean Reynolds number
S wing area
T thrust
W weight of the flight vehicle
β stroke plane angle
β_r relative stroke plane angle
$\hat{\varphi}$ non-dimensional positional angle of wing in the stroke plane
Ω rotation speed
ρ density of the air
σ spatial correction for induced power
τ temporal correction factor for induced power
Φ stroke angle
μ dynamic viscosity of air
η_H hovering efficiency

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1 INTRODUCTION

With the development of small unmanned air vehicle (UAV), the requirement of military mission and civil defence, a type of UAVs even smaller than micro aerial vehicle (MAV) is expected to be developed. Thus, the conception of Nano Air Vehicles (NAV) is firstly proposed by DARPA as an unmanned aerial robot devoted to indoor recognition missions with requirements for both military and civil applications. With a dimension less than 3 inches (7.5cm) and a minimum payload of 2 grams, it should be able to enter buildings, penetrate narrow entries and transmit data without being detected. A detailed definition is shown in Table 1.

Compared with the definition of micro air vehicles, the size of NAVs is less than one half of that of MAVs. Because of their size reduction, they suffer from more severe problems than MAVs, such as the degradation of the aerodynamic performance resulting from the lower Reynolds number as small as 20,000 or less, a low efficiency of the propulsive system, the unsteady aerodynamic effects etc. Therefore, a concept design will be a challenge for the preliminary design of NAV. Fortunately, abundant studies could be referred from the design of MAV. In general, there are three concepts widely used in the design of the UAV, that is, fixed-wing, rotary-wing and flapping-wing. From the development of UAVs, the advantages and disadvantages of the three concepts can be analyzed. For fixed-wing flight vehicles, they has no complicate system and can fly at a high speed with less power, while they have no hovering or slow flight capabilities and require launchers. For rotary-wing flight vehicles, they do have good hovering performance, the ability of vertical takeoff and landing, and perching capabilities, but they are more complex than fixed wings. And for flapping wing flight vehicles, they have high manoeuvrability, ability of hovering and the ability of mimicking animals, but a fairly complex kinematics and unsteady and nonlinear aerodynamics are the key disadvantages to implement them. Obviously, fixed-wing concept should be discarded because of the lack of hovering ability. However, it is still an open debate to select a concept between the rotary-wing and the flapping-wing. Some research work has been carried on about the NAV design recently. Lockheed Martin company intended to develop a the maple seed like single rotary-wing NAV with jet motor and Draper Laboratories attempted to develop a counter-rotating wing NAV[2][3]. *Aerovironment* tried to develop a hummingbird like NAV, whereas *Micropropulsion* intended to develop an insect like NAV[3]. According to these research projects, both rotary-wing and flapping-wing have been considered as a concept to design NAV. So a criterion to judge which concept is fit for NAV has to be made. Taking into account the mission requirements of an endurance greater than 20 minutes and the existing MAVs whose endurances are always bottlenecks of designs, the power efficiency is ought to be the most important criterion to select a concept. Moreover, hovering flight usually consumes more energy than forward flight, so hovering efficiency is treated as the crucial factor for concept design.

However, it is still a great challenge to compare the hovering power efficiency of the two concepts globally. So in this study, a dimension of 7.5 cm and a mass of 10 grams are considered as the requirements to develop NAVs. Geometric similarity method and simplified equations are firstly studied to demonstrate the two concepts based on hovering power. But those two methods are too simple to have enough reliability. Therefore, detailed concept designs of the rotary-wing concept and flapping-wing concept have been presented with a survey on hovering power. Since different design methods will results in various magnitudes of hovering power, this paper has adopted the Minimum Induced Loss method to design the rotary-wing concept and the formulas summarized from the nature to design flapping-wing concept so that the minimum hovering power could be got and unsteady aerodynamic effects could be taken into account.

Specifications	Requirements	Detail
Size	<=7.5cm(3inch)	Maximum dimension
Weight	<=10g	Objective GTOW
Payload	2g	Mission dependent
Speed(Fast)	5~10m/s	High speed fight for >1000m
Speed(Slow)	0.5m/s	Low speed flight for >60s
Hovering ability	Yes	Hovering for >60s
Cruising ability	Upper three items	Total of the upper three items
Range	1km	Operational range
Endurance	>20min	Total mission duration
Navigation	MSRE<0.5m	Mean squared residual error

Table 1 : NAV design requirement[1]

2 GEOMETRIC SIMILARITY FROM MICRO UAVS

Since the sizes of birds and insects approach to those of micro UAVs, massive research efforts have been put on the flapping-wing concept over the last decades [4][5][6][7]. One of the most popular principles observed from the flight animals is the geometric similarity which relates dimension, mass, power or flapping frequency etc. However, the rules from nature still can not reflect the actual ability of the design and fabrication. So in the first step of study, a principle is pursued with geometric similarity from the small existing UAVs.

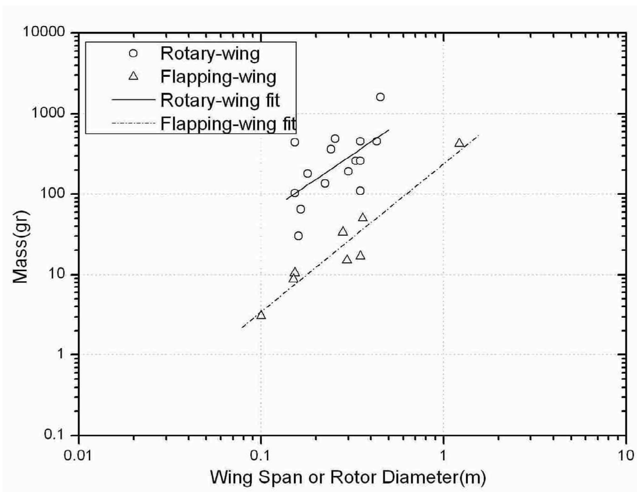

Figure 1: Mass vs. MAV wing span or rotor diameter

In the design of small UAVs, rotary-wing prefers to be used with its well-prepared theory and simplicity of fabrication. There are several configurations for rotary-wing concepts including the single rotor with tail rotor, co-axial rotors, multiple rotors, and ducted fans. Nevertheless, all types of configurations are considered in the statistics. The majority of small flapping-wing UAVs should not be regarded as a complete imitation of birds or insects, since they usually have a pair of flapping wings but with conventional control vanes. A statistics of weight and dimension (diameter for rotary-wing, wing span for flapping-wing) has been done as shown in Figure 1. Most of the data for small UAVs come from the international MAV competition “MAV07”[8] and the others come from current well-known MAVs. Functions to state the relation between dimension and the corresponding weight are fitted by equations as follows.

For mini- and micro- rotary-wing UAVs, the fitted relations are,

(1) $m = 1824.9D^{1.535}$

(2) $D = 0.0075\mathrm{m}^{0.651}$.

For flapping-wing MAVs, the equations fitted are,

(3) $m = 240.265b^{1.838}$

(4) $b = 0.0507m^{0.544}$.

From the equations above, it appears that expressions differ from each other for the two concepts. Basically, with the same mass, the dimension required by rotary-wing flight vehicle is smaller than that required by the flapping-wing flight vehicle. And the fitted equations of flapping wing are different from those derived from the birds proposed by Liu[9] and Shyy[10]. With the equations from the small UAVs, Table 2 can be given as follows by substituting the mass of 100g (for MAV) and 10g (for NAV) for the corresponding item ‘m’.

Table 2 indicates that the dimension defined for MAV is very close to that of the rotary-wing concept derived from Equation 2, but only 1/4 of the flapping–wing concept dimension derived from Equation 4. However, for 10gram NAV, the rotary-wing concept only requires about one half dimensions defined by DARPA, whereas the flapping-wing concept needs a larger dimension. In conclusion, with the geometric similarity by conveying the existing small UAVs, the rotary-wing concept can satisfy the requirement defined above, but the flapping-wing concept cannot.

	MAVs	**NAVs**
Mass(g)	100	10g
Defined dimension (cm)	15.24	7.50
Dimension from eqs. (1-2) Rotary-wing (cm)	15.10	3.37
Dimension from eqs (3-4) Flapping-wing (cm)	62.09	17.74

Table 2 Relations between weight and wing span or rotor diameter

3 SIMPLIFIED EQUATIONS FOR HOVERING PERFORMANCE

In the definition of NAVs, the hovering ability and a long endurance of 20 minutes is proposed. From the conventional helicopter, hovering flight will take more power than most of flight situations. Therefore, hovering performance is especially emphasized in the study of concept. Woods [11] and Lasek [12] tried to use conventional full scaled model equations to calculate the power of fixed-wing, rotary-wing, and flapping-wing flight vehicles of small size. The conclusion is that the suitability of flapping or rotary wing flight is dependent on the mission profile and ambient wind speed. Since typical NAV Reynolds numbers are much lower than in the case of full scaled model, it will not be precise to adopt the equations of full scaled model without modification. In this part, simplified empirical equations are utilised in the computation but with certain parameter estimated from the MAVs.

Generally, the hovering power of the rotary-wing flight vehicle consists of the induced power, the profile power, and the tail rotor power if any [13]. In this design, the tail power will not be considered. To show the propeller efficiency, a parameter called the figure of merit (FM) is always calculated as follows,

(5) $$FM = \frac{Ideal \quad power}{ActualPower} = \frac{Ideal \quad power}{InducedPower + ProfilePower} = \frac{P_{ideal}}{P_i + P_0} ,$$

(6) $$P_{ideal} = \frac{W^{3/2}}{\sqrt{2\rho A}}$$

where P_{ideal} is the minimum power derived from the momentum theory to support a weight of *W*. As the absence of the low Reynolds aerodynamics studies on small rotary-wing air vehicles and the detail information of rotors, figure of merit estimated from the MAVs could be used as a known parameter to computer the hovering power. So with the data presented, the value of the FM can be estimated. According to the experience of the coaxial rotor MAV *MICRO* [13], a value of 0.55 for the FM has been assumed in the computation of power efficiency. Then the expression of the aerodynamic power of hovering flight is simplified as,

(7) $$P = P_i + P_0 = \frac{P_{ideal}}{FM} ,$$

(8) $$P = \frac{1}{0.55} \cdot \frac{W^{3/2}}{\sqrt{2\rho A}} = 2.57 \cdot \frac{W^{3/2}}{\sqrt{\rho \pi D^2}} .$$

For the flapping way, the balanced flight hovering power can be simplified as [4],

(9) $$P_n = P_0 + P_i \cong \frac{P_i}{\eta_H} = \frac{1}{\eta_H} W \sqrt{\frac{W}{2\rho A_e}} = \frac{1}{\eta_H} \frac{W^{3/2}}{\sqrt{2\rho A_e}}$$

(10) $$A_e = \frac{2}{3} A = \frac{2}{3} \times \frac{1}{4} \pi b^2 = \frac{\pi b^2}{6}$$

where η_H is hovering efficiency which is about 2/3. So, the expression of the hovering power of the flapping wing flight vehicle can be given as,

(11) $$P_n = \frac{1}{\eta_H} \frac{W^{3/2}}{\sqrt{2\rho A_e}} = \frac{3}{2} \frac{W^{3/2}}{\sqrt{2\rho A_e}} = 2.60 \cdot \frac{W^{3/2}}{\sqrt{\rho \pi b^2}} .$$

After substituting a diameter of 7.5 cm and a mass of 10 g in Equation 8 and Equation 11, the hovering power necessary for the rotary-wing flight vehicle is about 0.536W, whereas it is about 0.542W for flapping-wing flight vehicle. Consequently, the hovering power required by the rotary-wing flight vehicle is a little less than that required by the flapping-wing vehicle. With the analysis above, it shows that the rotary-wing configuration is a little more efficient than the flapping-wing configuration. However, most of the equations above are based on the approximation of the parameter such as FM, A_e and η_H etc. which may lead to some errors. Therefore, the conclusion will not be convincing enough. This simplified computation can only give us an overview of the hovering power consumption of both types of flight modes. So in the following part, detailed design of rotary-wing concept and flapping-wing concept are carried out.

4 WINGS CONCEPT DESIGN

4.1 *Rotary-wing Design*

In this part, a design of a single motor with a diameter of 7.5cm and a thrust of 10g is shown. Since the power efficiency is one of the most important parameters for NAV, optimization of a rotor to reduce the energy loss is utilised in the design. In the past years, lots of researches have been done on the optimization of propeller. Larrabee[14] has proposed the minimum induced loss (MIL) to optimize the propeller. Adkins[15] proposed another method departure from that of Larrabee but still based on Betz's method. Gur[16] etc. have proposed a more sophisticated methods with multidisciplinary design optimization approach. As a preliminary design, MIL method is applied to this design with a software of *XROTOR*[17]. For this computation, potential Goldstein formulation is chosen so that tip boundary conditions and a finite hub can be accounted for.

At the beginning of the design, an airfoil with a good performance at low-Re number shall be determined. After comparisons of several airfoils, AG38 is chosen as the candidate airfoil to design the rotor since AG38 is one of low-Re number airfoil with well-documented experimental data [2]. At a Re number of 20,000, the $C_l^{3/2}/C_d$ reaches a maximum value of 11 at the angle of attack of about 4° with excellent low speed performance. With the input of the aerodynamic parameters of airfoil into *XROTOR*, a single rotor of two blades with a diameter of 7.5cm and a thrust of 10g is designed. The rotational speed (RPM) of the rotor is 9,000 and the radius of hub is confined to 20% of the rotor radius. Finally, a chord distribution and a pitch angle distribution are computed from the method of optimization. However, due to the limitation of the theory, the blade root chord turns out to be too long to be fabricated. So a small modification with the chord length is completed at the root of the rotor and the performance of new blades is recalculated with *XROTOR*. Figure 2 shows the final form of the rotor.

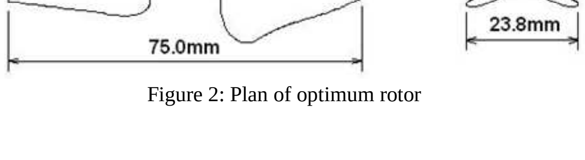

Figure 2: Plan of optimum rotor

From the computation, the performance of the rotor is achieved with a FM of 0.504 and hovering power of 0.585W. A thrust coefficient of 0.0145 and a power efficiency of 0.024 are calculated from the following equations,

$$C_T = \frac{T}{\rho A(\Omega R)^2} \tag{12}$$

$$C_P = \frac{P}{\rho A(\Omega R)^3} \tag{13}$$

Comparing the hovering power of optimized rotor with that calculated by simplified equations, one can find that there are some distinctions between them by virtue of the difference of the figure of merit. As the FM from simplified equations is estimated basing on certain rotary-wing MAV, two reasons are analyzed. One reason might be the difference of airfoil selected for the rotor design; the other reason might be the reduction of the Reynolds number causing the degradation of aerodynamic performance.

4.2 *Flapping-wing Design*

Over the last century, flight insects and birds are studied by many scientists including the flight mechanism, aerodynamics and kinematics. Those researches have provided abounding information for engineers to implement a flapping-wing air vehicle. After the first well-known flapping-wing air vehicle *MicroBat*, plenty of flapping-wing air vehicles have been developed with various sizes[18][19]. Most of the theories about the flapping-wing come from the nature, such as the geometric similarity mentioned above. Similarly, a concept of flapping-wing NAV with the wing span of 7.5cm and a mass of 10g is designed in this part with referring the theory and parameters derived from the flight of insects and hummingbirds.

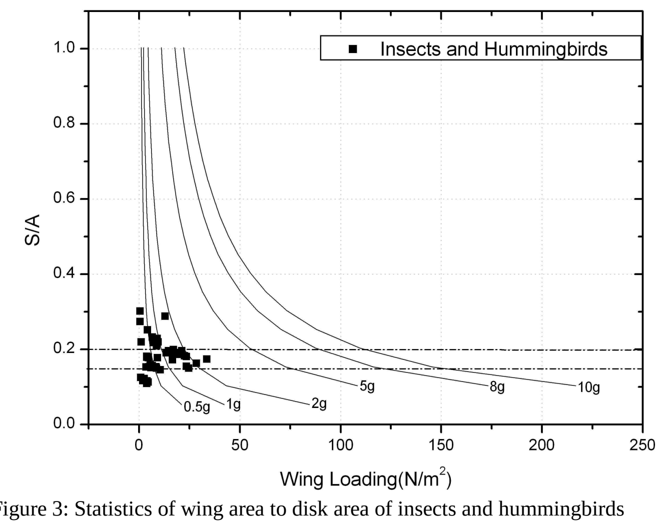

Figure 3: Statistics of wing area to disk area of insects and hummingbirds

To start with, the wing area of the flapping air vehicle shall be decided. In the nature, the insects and birds have the ability to fly with the flapping wings. Because of complicate flapping mechanisms utilised by birds, most of existing flapping-wing air vehicles imitate the flight insects despite the fact that they are even larger than the insects. In this study, the principles derived from insects have been applied with taking account to the even larger flight animals of hummingbirds. Through observing most of the insects and hummingbirds listed by Ellington[21]and Chai[26], a statistics of wing area to disk area ratio changing with wing loading is presented in the Figure 3. Six curves to state the relation between the ratio and the wing loading at different weights are also shown. The ratio distributes between 10% and 30% for the animals surveyed, while it distributes between 15% and 20% at a higher wing loading especially for hummingbirds which nearly have the same dimensions and weights as the NAVs defined above. So the average ratio of about 18% is selected as the ratio of this design.

Since the flapping mechanism is similar to insect, the flapping wings to be designed are preferred to refer the wing shape of insects. Ellington[21] proposed the chord distribution with a Beta distribution from the summary of enormous of insects as follows,

(14) $f = x^{p-1}(1-x)^{q-1} / B(p,q),$

(15) $B(p,q) = \int_0^1 x^{p-1}(1-x)^{q-1} dx$,

where p and q are calculated from wing area as 1.24 and 1.58. Then, the following equations can be obtained as

(16) $\hat{c}(\hat{r}) = 2.4\hat{r}^{0.41}(1-\hat{r})^{0.49}$.

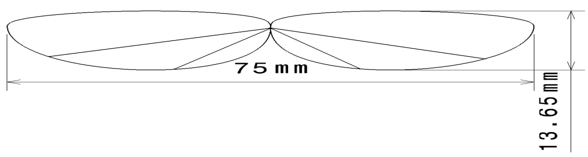

Figure 4. Flapping wing shape

The chord distribution along the wing could be derived from Equation 16. Two separate wings are formed as shown in Figure 4. For this wing, the span aspect ratio is about 7.1, while the wing loading exceeds to 123 $N \cdot m^{-2}$. Now, the wing shape and main parameters have been decided. However, other parameters are still needed to determine to compute the hovering power. With the definition of the wing shape, the flapping frequency obtained from geometric similarity is not capable of satisfying with the design requirement. For hovering flight, the flapping frequency may be obtained by the balance of weight and lift.

In the traditional methods, the equation [25] of mean lift over a half-stroke derived from hovering insects by Ellington is always used to calculate the mean lift. But for this case, it is preferred to use the mean lift to obtain the flapping frequency with the following equation,

(17) $$n = \sqrt{\frac{\rho\Phi^2 R^2 S\hat{r}_2^2(S)\overline{(d\hat{\phi}/d\hat{t})^2}\cos^2\beta}{8\cos^2\beta_r \bar{L}}\overline{C_L}} \ .$$

To simply the design, the lift generated by up stroke is assumed to be the same with down stroke. In this equation, some parameters concerned with the kinematics still can be obtained from the nature. Stroke angle Φ is about 120° for most insects[22], but from the Chai[26], black–throated, magnificent, black-chinned and *Rufous Hummingbird* (Selasphorus *rufus*) have a stroke angle of 150°, 150°, 126° and 163° respectively. So the stroke angle of different flight animals varies greatly even they are the same kind. Nevertheless, 120° is chosen as a popular stroke angle because of the flapping mechanism of insects. Ellington[20] stated that two types of hovering mechanism are widely used by insects and birds, one is the horizontal stroke in which the stroke plane is an approximately horizontal stroke plane, the other is the incline stroke in which the stroke plane has a certain angle with horizontal plane. Most of insects and hummingbird hover with the first mechanism. Thus, the horizontal stroke is adopted in the design without stroke angle β . Besides, all of the moment parameters of the flapping wing can be computed with the laws of shape summarized from the insects' wing [21]. Since the no-dimensional parameters about wing stroke movement have no relation with frequency and most of them of different insects varies little from each other, they are calculate from the experimental data of insects. Until now, most of parameters have been obtained except the mean lift coefficient. The hovering fight of insects and birds involve unsteady aerodynamics so that the mean lift coefficient isn't fit for being computed with steady aerodynamic methods. Again, from the clues of the nature, the mean lift coefficient could be obtained with taking the unsteady aerodynamics into account. As shown in the reference [26], only a little distinction exists among different hummingbirds even that the dimension and Re number varies greatly. In fact, most of insects fly at an ultra-low Reynolds number not in the same range of NAVs here. But the dimension and the mass of NAV are close to those of hummingbirds. Consequently, the mean lift coefficient could be obtained from them. With parameters obtained above, flapping frequency n is calculated with three groups of solutions obtained. After the analysis of the possibility of every solution, the frequency is confirmed to be about 177 which are higher than that of most insects and birds.

With the value of flapping frequency and geometric parameter of the flapping-wing, the hovering power could be computed. In this paper, only aerodynamic power will be calculated including the induced power and profile power. Ellington[24] adopted the Rankine-Froude momentum theory to calculate the ideal induced power, then he adopted the vortex theory to give a spatial correction and the wake periodicity theory to give a temporal correction.

(18) $$\overline{P_{ind}^*} = P_{RF}^*(1+\sigma+\tau)$$

(19) $$P_{RF}^* = \left[\frac{2p_w}{\rho\Phi AR\cos\beta}\right]^{1/2}$$

After substituting relative parameters obtained with the method mentioned above into Equation 16, the ideal induced power per Newton P_{RF}^* is computed as 3.69 $W \cdot N^{-1}$. Then with the correction, the mean specific induced power $\overline{P_{ind}^*}$ is obtained as 4.12 $W \cdot N^{-1}$.

Next, the profile power shall be calculated. Similarly, a quasi-steady method[25] is adopted during the computation to assume a mean value of coefficient of profile drag and a mean Re number.

(20) $$\overline{\mathrm{Re}} = \frac{4\rho\Phi R^2 n}{\mu AR}$$

With the flapping frequency of 177, the mean Re number is about 20,000 at sea level. As the profile drag is not very well documented in the case of ultra-low Reynolds numbers, the empirical equation determined by Ellington[25] is used. After substituting $\overline{\mathrm{Re}}$ into Ellington's equation, $\overline{C_{D,\mathrm{Pro}}}$ could be obtained. And from the appendix of reference [11], the drag coefficient estimated shows a reasonably good agreement. Then with the formula of mean specific profile power proposed by Ellington[25]

(21) $$\overline{P^*_{pro}} = \frac{\rho n^3 \Phi^2 R^3 \hat{r}_3^3(S)\overline{\left|d\hat{\phi}/d\hat{t}\right|^3} \cos^3\beta}{16 p_w \cos^3\beta_r}\overline{C_{D,pro}},$$

the profile drag power could be calculated. In equation (21), the parameter related to the kinematics and the parameter related to the flapping-wing moment could be obtained as stated above. With those parameters, the mean specific profile power can reach 1.70 $\mathrm{W\cdot N^{-1}}$. Finally, the aerodynamic hovering power could be determined from the following equation,

(22) $$P_{aero} = (\overline{P^*_{ind}} + \overline{P^*_{pro}}) \times mg\ .$$

For this design, the hovering power is about 0.571W which is still a little bit higher than that obtained from simplified equations in section 3. With the results from the two concepts design, it is found that the flapping wing is more efficient than rotary wing for hovering flight.

5 CONCLUSIONS

This paper have surveyed both the rotary wing and the flapping wing concept to determine a suitable concept for a NAV design with a dimension of 7.5cm and a mass of 10g. Firstly, a geometric similarity law is derived from MAVs existing and it is found that the flapping-wing cannot satisfy the design requirement. Secondly, the hovering performance is studied with simplified equations. The result states that rotary-wing is more efficient than flapping-wing for a hovering flight. At last, to further compare both concepts, a single rotor wing is designed using the MIL theory with a low-Re airfoil of AG38. Modifications have been introduced to eliminate the defect of theoretical results. In addition, the rotor is recalculated to get the hovering power. And then, a pair of flapping wings is designed with a counter method derived from insects and birds. In fact, this method is firstly used to calculate the flight parameters of insects and hummingbirds. In this paper, it is utilized to design the flapping wings and calculate the necessary flapping frequency with kinematic parameters, wing shape parameters and mean lift coefficient achieved by applying laws from nature. Unsteady effects have been considered with the parameters from the nature. After that, the hovering power including the induced power and the profile power are calculated.

However, the hovering power calculated from the simplified equations is different from that of the design method about 8% for rotary wing and 5% for flapping wing respectively as shown in Table 3. Moreover, the conclusion is reverse. As far as we know, the FM of full-scaled helicopter is about 0.7 to 0.8[13], but it reduces rapidly with the decrease of the Reynolds number. In the hovering power computation of rotary-wing with simplified equations, the FM of 0.55 is utilized, while it is only about 0.504 based on rotary-wing design. It means that an overestimation of FM has been made in the computation without considering the effect of the Reynolds number reduction. For the flapping wing, the induced power computed from simplified equations is approximately equal to that in the concept design, but the hovering efficiency in the design is lower than that assumed in the simplified equations.

Concept \ Methods	**Simplified Equations**	**Concept Design**
Rotary-wing	0.536W	0.585W
Flapping-wing	0.542W	0.571W

Table 3: Comparison of hovering power derived from simplified equations and concept design

In conclusion, the hovering efficiencies of both concepts only differ from each other by less than 5%. Consequently, each of the concepts could be used to design the NAV with the approximate hovering ability. However, more factors shall be considered such as the theory, the reliability and the maneuverability and the fabrication complications. Considering the conditions and means of the laboratory, rotary-wing is preferred as a NAV concept.

Since the absence of detailed information in the preliminary design, massive parameters are estimated according to the flight animals in the nature and MAVs. So in the future work, elaborate design should be carried out and the method to estimate the hovering power shall be improved. Experiments shall be done to evaluate the hovering performance of small rotors.

6 ACKNOWLEDGEMENTS

The authors would like to thank the support of China Scholarship Council and the laboratory of DAEP of ISAE.

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