Optimization of mechanism design of flapping wing MAV

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Optimization of mechanism design of flapping wing MAV

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Design and development of flapping wing MAVs has been a major thrust area of research for the past decade or so. However, design of MAVs is still a challenging task due to the complexity of MAVs and lack of adequate design tools that predict the overall performance of the design. A comprehensive dynamic mathematical model of the entire drive mechanism is needed. To this end, Theodoresen's theory for predicting the lifting force on an oscillating airfoil was chosen to calculate the lift force on the wing. Using the University of Maryland's Jumbobird as a base design, a dynamic model was developed using the free body diagram approach and programmed in Matlab. A sensitivity analysis was performed on the model to study the effect of system variables on the the performance parameters: lift produced, power consumed and lift-power ratio. The critical parameters were identified and run through an optimization algorithm to explore the design space for improving the performance of the MAV. It was seen that the power consumption was reduced by 73.8% without affecting the lift significantly. The results also suggest that some parameters affect lift and power differently, and in general, the variables do not compete with each other during the optimization. The methodology presented in the paper could serve as a tool to guide the design process during future MAV projects.

I. Introduction

The need and desire to develop highly versatile, miniature and easily controllable flying robots has fueled the development of Micro Air Vehicles (MAVs) over the past decade. Tremendous improvements in electronics and smart materials are pushing the boundaries of the possibilities of such machines[11].[13] Most of the thrust in research in this field is in the region of surveillance combined with reconnaissance for rescue. The ability of such MAVs to venture into territory inaccessible or dangerous to man makes them worthy of this amount of resources and effort.[19] Naturally, the limitations of size makes design of MAVs an arduous task. Although many a project has managed to develop successful MAVs which satisfy expected goals, some have taken as long as 5 years from proposal to completion. Flapping wing MAVs are one of the three main groups of MAVs, the others being fixed wing MAVs and rotary wing MAVs. As the name suggests, flapping wing MAVs use to and fro motion of wings for lift and propulsion. The sudden change in direction of the wing at the ends of the upstroke and downstroke makes predicting the aerodynamic behaviour of these machines rather difficult. Although many theories have been suggested to attempt to simplify the lift and drag calculation,[18] the applicability of these theories has been limited to problems similar to the conditions under which the equations were derived. Only CFD analysis seems to be able to predict the aerodynamic performance of flapping wings under different conditions.[10]

The use of compliant mechanisms is very beneficial to MAV design because they do not need assembly. With good design, it is possible to obtain very high accuracy in the motion of compliant mechanisms.[20] The lack of relative motion between moving parts reduces the need for lubrication and maintenance. There has also been some work on compliant mechanisms which suggests that optimization of the compliant elements can lead to reduction in power consumption.[12] Development of compliant mechanism theory over the past couple of decades has made it possible to predict the behavior of these mechanisms with very high accuracy.[6]

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This paper focuses on the design of the flapping mechanism of an MAV. The difficulty with the small size of these robots combined with the need for low mass and power consumption means that efficient design is very critical for achieving good performance. Currently, the development of the flapping mechanism usually follows a trial and error approach. Although most of these designs manage to satisfy the project goals, such an approach makes optimization and evaluation of the mechanism rather difficult. In this paper, we attempt to develop some guidelines regarding the effect of different parameters on lift production and power consumption. Optimization of these variables based on the project goals would improve the performance of the MAV considerably. Although it would be difficult to develop a generic model for all MAVs, the ideas used in this paper should be applicable for most systems.

As mentioned earlier, development of flapping wing MAVs currently follows a trial and error approach, where successive designs are tested until one is obtained that satisfies performance requirements. During the development of the Nanohummingbird,[8] the team at Aeroenvironment tried more than 50 different wing shapes and structures. Gupta et al[2] suggest a qualitative approach taking into consideration fabrication and strength limitations. However, such a process is not readily capable of providing a design that makes optimum use of the design space. An improved quantitative approach may be developed which can be undergo an optimization process so as to yield better performance in the form of increased lift, reduced power consumption or other key objectives. Three key performance characteristics for an MAV are power consumption, maximum payload the vehicle can carry, and the duration of the flight. The power and flight duration are linked by capacity of the energy storage device. Another performance parameter that has been used is the lift to power ratio[7](sometimes replaced by the thrust to power ratio[3]). The important parameters that affect these performance characteristics are the motor characteristics, the shape and size of the wing and the mechanism performance. The motor characteristics are defined mainly by the stall torque and no load speed. For the mechanism performance, the important variables are the dimensions of the linkages. The mechanism being considered has compliant elements, which leads to the definition of spring constants. By optimizing these parameters, we can expect an improvement in the performance of the MAV.

In this paper, we intend to introduce an approach for the design of the flapping mechanism of MAVs. We have already looked at the need for this design process, and discussed current methodology and its shortcomings. The aerodynamic theory used to calculate the load on the wing will be explained in Section II. The base mechanism chosen for the design process is the Jumbobird[1] developed by University of Maryland. The derivation of the dynamics of the system and the assumptions involved will be covered in Section IV, along with the highlights of the coding in Matlab. The details of a sensitivity study on the base mechanism will be covered and the important parameters highlighted. Section VI will provide the outline of the optimization problem and the setup of the process in Matlab, along with the results of the optimization and the inferences that can be drawn from it. Finally, we will draw inferences from the results obtained and provide basic guidelines on how to approach the design process of the flapping mechanism and discuss some of it salient characteristics.

II. The aerodynamic force

A lot of research has gone into developing simple aerodynamic models for the calculation of lift produced by a flapping wing.[4] The unsteady aerodynamics that affect this fluid flow regime make this a very challenging task, and most simplified theories are only valid in the flow regime of the experimental setup against which they were verified. Although CFD analysis has shown good agreement with experimental results[14] for a large range of flow regimes, including this in a design model is highly computationally expensive. With these points in mind, we decided to opt for a simplistic model that is sufficiently accurate for the system under investigation.

Theodoresen developed a set of equations[21] for the forces and moments that act on an airfoil with an aileron which is undergoing flapping motion in a stream of fluid of constant velocity. The flapping motion of the wing is described by the variable h, which is positive in the downward direction. Both h and the angle of attack of the wing (α) are described as a combination of sine and cosine functions of time. A simplified version of the wing, suitable for the current topic, is provided in Fig. 1.

The lift equation for the wing (ignoring the aileron) is given by

$$L = \rho b^2(\pi\ddot{h} + v\pi\dot{\alpha} - \pi b\alpha\ddot{\alpha}) + 2\pi\rho v b C(k) Q \tag{1}$$

where ρ is the density of air, b is half the chord length and v is the forward velocity of the wing. $C(k)$

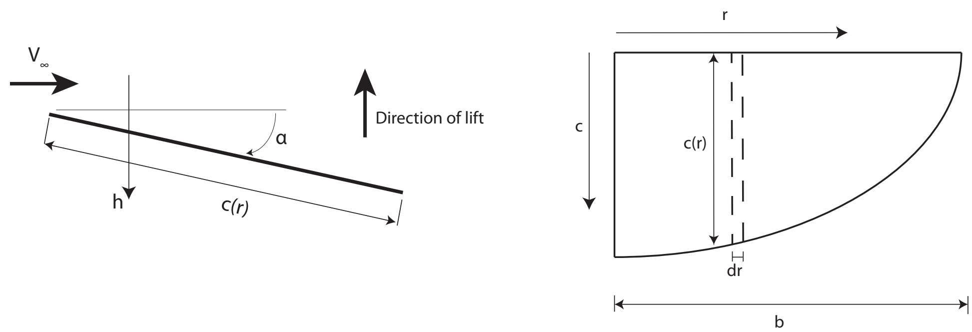

Figure 1. Section of spanwise blade element of wing and planform of wing

and Q are defined in Eqs. 2 and 3.

$$Q = v\alpha + \dot{h} + b(\frac{1}{2} - \alpha)\dot{\alpha} \tag{2}$$

$$C(k) = \frac{(J_1(J_1 + Y_0) + Y_1(Y_1 - J_0))}{((J_1 + Y_0)^2 + (Y_1 - J_0)^2)} \tag{3}$$

where J_0,J_1,Y_0 and Y_1 are standard Bessel functions of the first and second kinds of argument k.

The Jumbobird has a forward velocity of $4.04m/s$ and a flapping frequency of $6.1Hz$. The motor stall torque is $0.657Nm$. The wing span is $63.5cm$ and the wing area is $920.2cm^2$. An elliptic planform was assumed for the wing, while maintaining wing span and area. A significant feature of the design is that the root spar of the wing does not move during the flapping motion, which means that the angle of attack remains a constant (assuming a rigid wing). Since the wing motion considered here is relatively simple, some of the terms in the equation drop out. The simplified equation for lift produced is given in Eq. 4

$$L = \rho b^2 \pi \ddot{h} + 2\pi \rho v b C(k) Q \tag{4}$$

The above equation gives the lift per unit span of the wing. The total lift on the wing is calculated by integrating the equation for P over the wing area.

Before using Theodoresen's theory in the dynamic model of the flapping mechanism, we decided to verify the accuracy of the model by comparing lift values computed using the equation to experimental values in literature for wing size and motion similar to that of the JumboBird. As a first check, using data from the experimental tests done on the Jumbobird, the lift calculated using Theodoresen's theory was found to be $25.22g$ per wing. This is close to the experimentally determined value of $26g$ per wing. The equations also showed good agreement with values obtained from work done by Lin et al.[9]

III. Flapping mechanism of MAV

As previously stated, the mechanism under study is the flapping mechanism of Jumbobird developed by University of Maryland. Jumbobird is a multi-material compliant mechanism flapping wing MAV. It was fabricated using injection molding. Upon the completion of the project, the MAV performed admirably in indoor and outdoor flight.

The mechanism can be broken down into two 4-bar linkages. The first is a crank-slider mechanism and the second is a slider-rocker mechanism.[16] Fig. 2 shows the mechanism. The links are labeled 1 to 9. The motor drives the crank (link 1) which results in the vertical motion of the slider (link 3). The motion of the slider translates to the motion of links 4 and 5. The lower ends of links 6 and 7 are fixed to the frame of the mechanism. Links 8 and 9 are rigidly attached to links 4 and 5 respectively and represent the leading edge of the wing. The slider maintains the symmetric motion of the wings.

The lift calculated using Theodoresen's theory is perpendicular to the leading edge at all times. This means that to calculate the lift in the vertical direction, the aerodynamic load has to be transformed to the global vertical direction. Most of the joints are compliant joints and this lends stiffness and damping

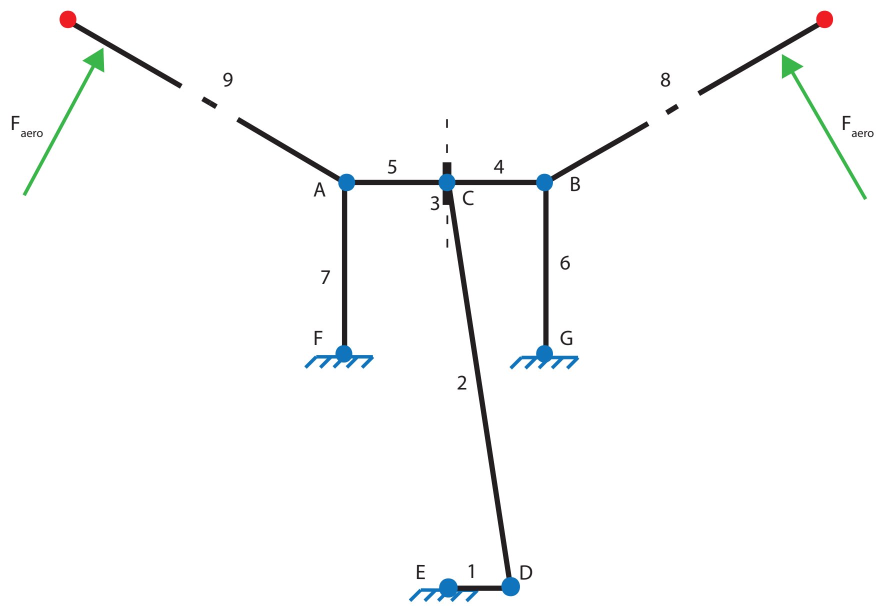

Figure 2. Schematic of flapping mechanism

characteristics to the mechanism. The stiffness of the compliant joints is represented using the pseudo-rigid-body model[5] as $k = EI/l$ where E is the modulus of elasticity of the joint material, I is the second moment of area of the cross section of the joint and l is the length of the joint. Such compliant joints are present at the points marked A, B, C, F and G in the figure. Since the aerodynamic load is distributed over the span of the wing, the center of pressure is calculated and the total force is assumed to act at that point.

IV. Dynamics model of flapping mechanism

The main focus of this work was to develop a dynamic model of the flapping mechanism of an MAV so that it becomes easy to study the effects of different parameters on the performance of the MAV. It was expected that the model will work as an effective and simple tool to simulate the working of the mechanism with a high degree of accuracy. The development of the model was divided into different modules for logical reasons. Such a structure would allow changes or improvements to be made to some parts of the model without the need to change the rest of the program. For example, the module that calculates the lift force could be changed to use some other aerodynamic theory if the need for more accuracy arose. Naturally, a modular approach also increases the ease of debugging.

The links of the Jumbobird are made of short glass fiber-filled Nylon 6,6. Using the dimensions of the links given in Table 1, the masses and moments of inertia of the rigid links were calculated. The values of the spring constants were calculated using the pseudo rigid body model discussed in Sec. III. For the sake of simplicity, all the compliant joints were assumed to be identical, but this can be changed without much difficulty. The equilibrium positions of each of the torsion springs was also defined. The main assumption in the development of the model was that the links were rigid bodies, that is, they do not undergo any deformation due to loading. The damping in the compliant joints was neglected. Elongation of the compliant joints was also neglected, which meant that the joints were like pin joints with torsion springs. The motor was modeled as a simple DC motor with the same stall torque as that used in the JumboBird. The equation for motor torque is given in Eq. 5, which is a simpler form of the expression for the motor model described by Nogar et al.[15]

$$\tau_{motor} = \tau_{stall}(1 - \frac{\omega_{motor}}{\omega_{max}}), \tag{5}$$

The aerodynamic force was calculated using Theodoresen's theory. The total force was assumed to act at the center of pressure on the leading edge of the wing, which was also calculated.

Free body diagrams were used to derive the dynamics equations of the system. Again, the choice of this

Table 1. Mechanism parameters

Parameter	Dimension value
l_1	4mm
l_2	28mm
l_3	3mm
l_4, l_5	8mm
l_6, l_7	17.5mm
l_8, l_9	10mm

approach over other methods such as Lagrangian techniques was made due to the ease of converting the code into modules. In the FBD approach, the dynamics equations for each link are written separately, whereas in the Lagrangian approach, the total energy of the system is written in a single equation and then relations are established between various parameters. The FBDs for links 2, 4 and 8 are given in Fig. 3.

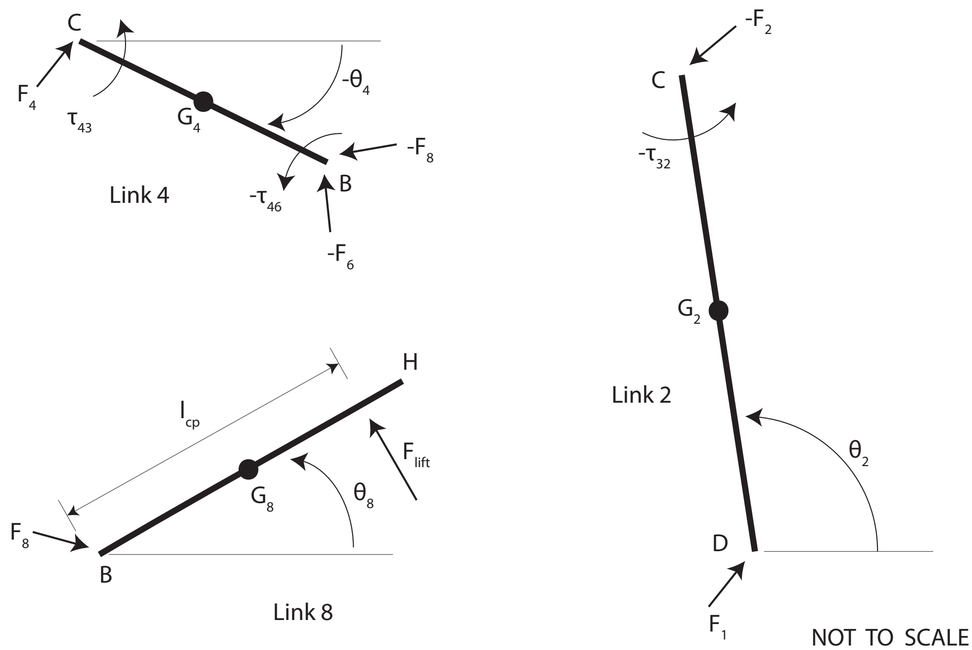

Figure 3. Free body diagrams of links 2, 4 and 8

Angles that each of the links make with the horizontal axis were defined using variables θ_1 to θ_9. The positions, velocities and accelerations of the ends of the links and the centers of mass were expressed as functions of these angles. The motor torque τ_{motor} acts on link 1. The joint between links 2 and 3 exerts an equal but opposite torque on both of the links. Similar is the case with all the compliant joints. All the forces and moments were expressed as vectors. Equations were derived for linear momentum balance and angular momentum balance for each of the links. As examples, the equations for links 2,4 and 8 are given below.

$$
\begin{aligned}
m_2\vec{a}_2 &= \vec{F}_1 - \vec{F}_2 \\
I_2\vec{\alpha}_2 &= (r_{\vec{G_2D}} \times \vec{F}_1) - (r_{\vec{G_2C}} \times \vec{F}_2) - \vec{\tau}_{32} \\
\\
m_4\vec{a}_4 &= \vec{F}_4 - \vec{F}_6 - \vec{F}_8 \\
I_4\vec{\alpha}_4 &= (\vec{r}_{G_4C} \times \vec{F}_4) - (\vec{r}_{G_4B} \times \vec{F}_6) - (\vec{r}_{G_4B} \times \vec{F}_8) - \vec{\tau}_{46} + \vec{\tau}_{43} \\
\\
m_8\vec{a}_8 &= \vec{F}_8 + \vec{F}_{lift8} \\
I_8\vec{\alpha}_8 &= (\vec{r}_{G_8B} \times \vec{F}_8) - (\vec{r}_{G_8cp_8} \times \vec{F}_{lift8})
\end{aligned}
$$

where m_j and I_j represent the mass and moment of inertia of link j, $\vec{F}_1$ to $\vec{F}_9$ are the internal forces between the links, $\vec{r}_{AB}$ represents the position vector from A to B and $\vec{\tau}_{ij}$ is the joint torque between links i and j.

Once all the equations were derived, the system was programmed into Matlab. Each of the equations represents differential equations of the variables θ_1 to θ_9. In order to simulate the system over time, we used a numerical ordinary differential equation solver and provided it with an initial condition. In this work, we used Matlab's ODE45 solver for the job. The initial condition must be picked carefully to ensure that mechanism constraints are not violated. In this case, picking the initial condition was simple since we could start the system at rest, and therefore, no constraints are violated. A few simple tests were used to determine whether the system behaves as expected. For example, the motor torque and lift force were turned off and the initial position of the mechanism was displaced from the equilibrium positions of the springs. As expected, the mechanism oscillated about the equilibrium position indefinitely since there were no damping forces in the system.

The values of the angles, velocities, motor torque and lift force were output from the solver and plotted in the form of graphs so that the performance of the system could be studied. The power input to the mechanism was defined as the product of motor torque and crank velocity (Eq. 6). The payload capability of the MAV is the difference between the lift force produced and the mass of the MAV. The ratio of payload to power is defined in Eq. 7.

$$P = \tau_{motor} \times \omega_{motor}, \tag{6}$$

$$L/P = \frac{L - mg}{P}, \tag{7}$$

where m is the entire mass of the MAV and g is the acceleration due to gravity. The system was simulated for a time span of 5 seconds. It was observed that after a short starting phase which was due to the inertia of the mechanism, the system settled into an approximately periodic motion. The duration of the starting phase was about 2-3 flap cycles, well below 1 second. Since we were primarily interested in the flight performance of the MAV, the mean values of the various parameters were calculated for the time after 1 second. The main performance parameters were mean lift, mean input power and lift to power ratio. Once the correctness of the model was deemed to be satisfactory, the simulation was repeated while varying different parameters.

V. Sensitivity analysis

Sensitivity analysis is the study of how the uncertainty in the output of a mathematical model or system (numerical or otherwise) can be apportioned to different sources of uncertainty in its inputs .[17] Sensitivity analysis is often used to study the relationships between variables in a system, generally exploring relations between input and output. The MAV, being a complex system, has a large number of parameters that can be varied, which means that the design space would extend into a large number of dimension. Since our goal is the optimum design of the MAV mechanism, we looked at the how different system parameters affect the performance of the system. With this data, we could try to identify the crucial variables and work on optimizing only these parameters which would significantly reduce the load on the optimization algorithm.

A. Variation of kinematic parameters

The kinematic parameters mainly refer to the lengths of the different links, and these affect the kinematics of the mechanism. For example, changing the length of the crank changes the displacement of the slider, which in turn affects the motion of the wing. Changing the lengths of links 4 and 5 affects the amplitude of the flapping motion. These changes in kinematics were found to affect the lift production and power consumption rather significantly. Fig. 4 shows the variation of lift and power when each of the link lengths was varied while keeping the other values constant. The symmetry of the system was always maintained, that is, links 4 and 5 were always the same length, and so were links 6 and 7. Links 8 and 9 are part of the wing structure and do not affect kinematics, therefore, their effects were not studied. It was observed that links 1 and 4 affected lift production and power consumption significantly, whereas link 2 affected only power consumption.

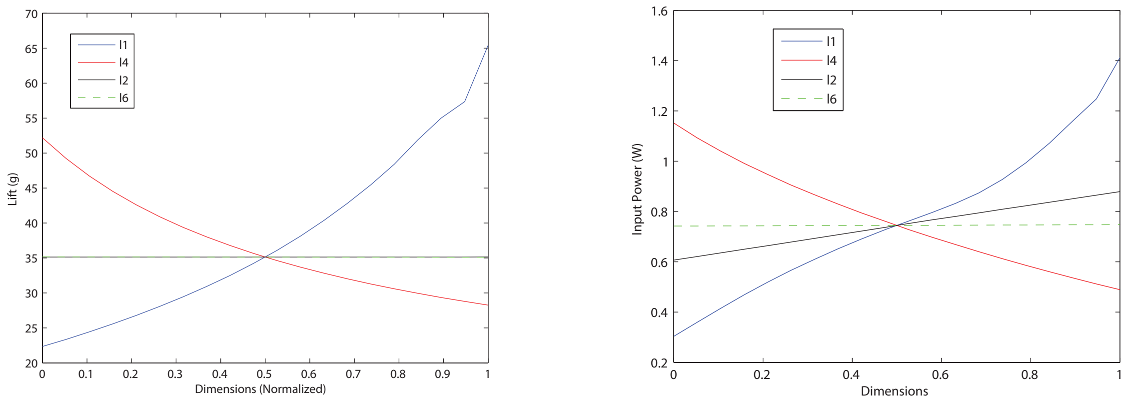

Figure 4. Variation of (a) lift and (b) power with kinematic parameters

B. Variation of system parameters

The system parameters refer to other variables in the system, such as wing size, motor characteristics and joint stiffness. Although the forward velocity would be a function of the thrust developed by the MAV, due to the limitations of the aerodynamic force model, it was assumed to be a constant value during each simulation. The important system parameters which were incorporated in the model were identified as angle of attack of the wing, the average flapping frequency, the forward velocity of the MAV, and the wing size which was determined by mean chord length and wingspan. Fig. 5 is a graph showing mean lift produced with variation in different parameters while keeping the other values a constant. The horizontal axis represents the values of the parameters normalized within the range of variation. All the parameters have positive effects on the value of lift, but the effects of wing size are more pronounced. Frequency and angle of attack are the parameters that can be varied relatively easily in the design by choosing a different motor or changing the point of attachment of the wing, respectively. It was observed that apart from frequency, none of the system parameters affected power consumption to a large extent. It was also observed that a much smaller motor stall torque would be sufficient to drive the mechanism, which would mean that the motor size and mass could be significantly reduced.

Compliant joints Since the mechanism has a few compliant joints, there exists the possibility of using the parameters of the compliant elements to achieve the required system performance. As explained earlier, the compliant joints were modeled as torsion springs, and therefore, it would be possible to vary the equilibrium positions of the springs. In reality, this can be achieved by changes in the fabrication process, such that the spring compliant elements are in a prestressed state when assembled. Fig. 6 describes the effect of varying these equilibrium angles on lift and power. Keep in mind that the zero value on the x-axis represents the default condition of the system, and positive and negative values represent changing the equilibrium position counter clockwise and clockwise respectively. The variation in lift is not very high, whereas power varies

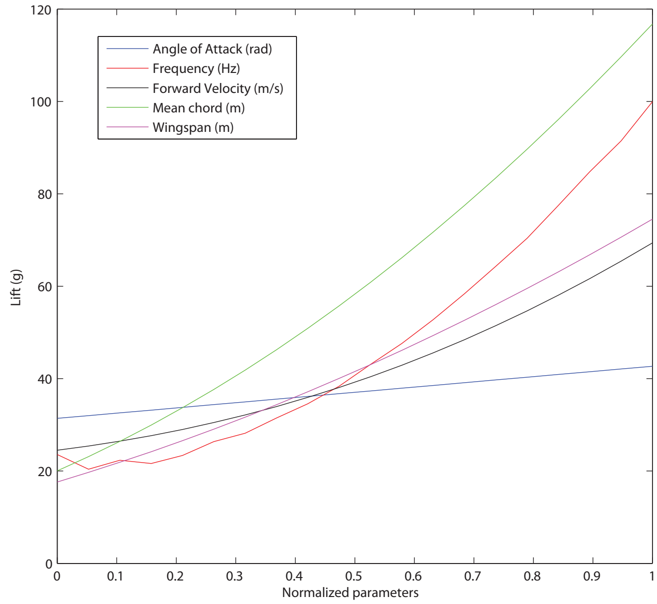

Figure 5. Variation of lift with system parameters

significantly. It is clearly beneficial to assemble the mechanism such that certain springs are always in a state of compression or expansion.

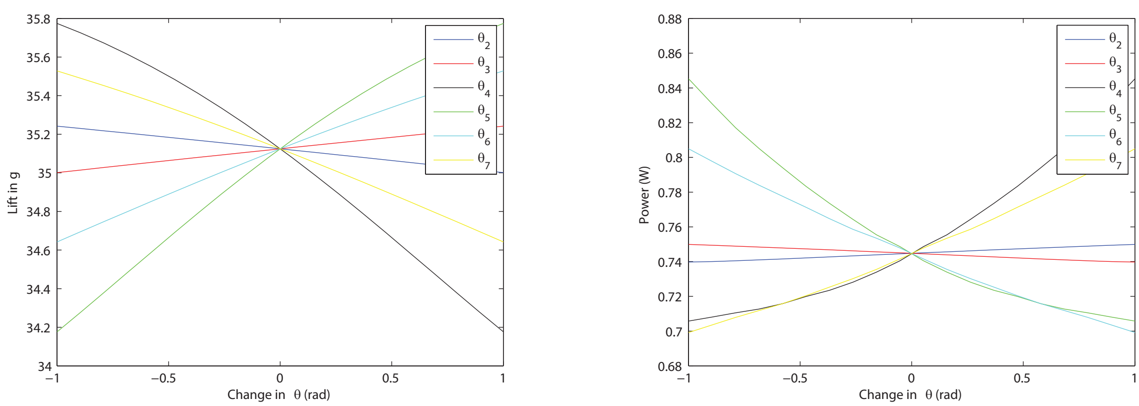

Figure 6. Variation of (a) lift and (b) power with equilibrium position of springs

C. Combined variation of select parameters

In the previous subsections, the important kinematic and system parameters were identified. Since individual variation may not provide a clear picture of the effect of optimizing many variables at the same time, the effect of combined variation of groups of two parameters was also studied using contour plots. In the contour plots, the color spectrum from blue to red indicates an increase in value, that is, red represents the highest value of the performance parameter in the design space and blue represents the lowest. Fig. 7(a) shows the variation of the ratio of payload to power over a range of values of lengths of links 1 and 4. The white triangular space in the top left corner represents an infeasible portion of the design space. The red circular regions are points of high payload-power ratio, very close to the end of the design space. (The red circles would be replaced by a single curve if there were infinite data points, but the study was restricted by computational limitations) However, the highest values are actually at the bottom right corner where the decrease in power dominates the increase in lift. Therefore, the lift-power ratio can be increased by keeping $l1$ to a minimum and increasing $l4$.

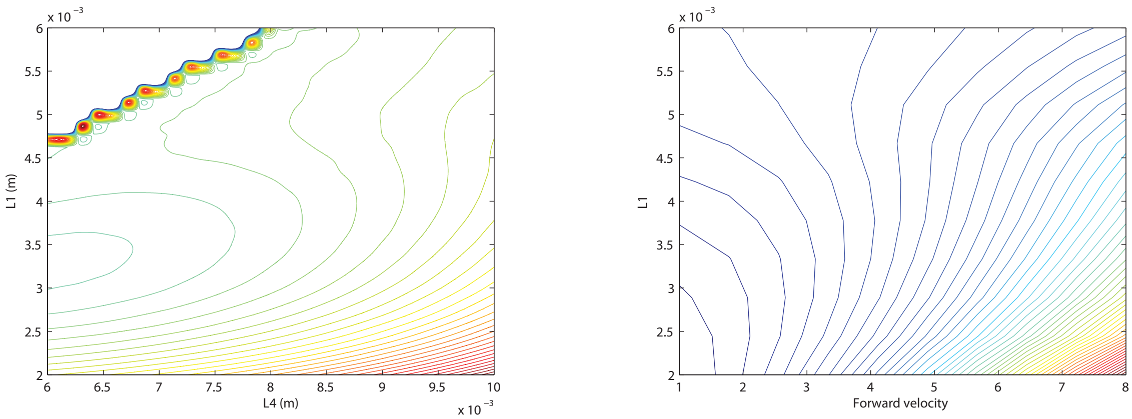

Figure 7. Variation of payload-power ratio with (a)L1 and L4 (b)L1 and forward velocity

Fig. 7(b) represents the variation of the payload-power ratio with variation in link length $l1$ and the forward velocity. Although varying the forward velocity is not a straight forward task, the plot is an indicator that a higher forward velocity is generally beneficial as far as lift to power ratio is concerned.

VI. Optimization and results

The sensitivity analysis provided a good indication of which parameters influence the performance of the MAV the most. Using this information, a series of optimization runs was conducted where different groups of parameters were optimized for different performance parameters. A range of values was provided for each of the variables keeping in mind the size of the system and other practical constraints. Due to factors pertaining to the accuracy and robustness of the aerodynamic model, care was taken to ensure that the flight regime of the MAV did not change drastically.

The optimization was executed using $fmincon$ function in Matlab. It used an active-set algorithm to solve the problem. $fmincon$ is only capable of finding local minima, therefore, it was necessary to run the optimization multiple times with different sets of normally distributed random starting points. If all the trials converge to the same result, it could be safely assumed that the result is a global minimum. The problem definition for minimizing mean power to the mechanism while varying $l1$, $l4$, angle of attack α and compliant joint width w is given below.

$$Minimize \quad \overline{P_{(t)}(l_1, l_4, \alpha, w)} \quad , \quad t \in [1, 5]$$

$$subject\ to:$$

$$0.002 \leq l_1 \leq 0.006,$$
$$0.006 \leq l_4 \leq 0.010,$$
$$\arcsin(\tfrac{1}{8}) \leq \alpha \leq \arcsin(\tfrac{1}{4}),$$
$$0.001 \leq w \leq 0.0025,$$

where l_1, l_4 and w are in meters and α is in radians. t represents time, and the bounds of t represent 1s, which is time beyond which the system is assumed to be in steady state, and 5s is the time limit of the simulation. These variables were chosen because they represent a mix of kinematic parameters and system parameters, and affect the value of power significantly. For this case, it was seen that the optimal values were $l_1 = 0.002$, $l_4 = 0.010$, $\alpha = 0.2527$ and $w = 0.001$. These are the values of the individual variables for which the power is minimum. This seems to suggest that the effect of the variables is independent of one another. In other words, they are not competing for a reduction in power. The value of power for the optimized parameters was $0.1952W$, whereas the value for the default mechanism is $0.7448W$, which is a 73.8% change in power consumption. Table 2 shows the results of some of the optimization attempts, where the different performance parameters are minimized or maximized.

Table 2. Optimization results

Sl. No.	Parameters	Upper bound	Lower Bound	Optimized values	Optimal performance parameter
I	l_1	2mm	6mm	2mm	Max $L/P = 1.3930$ N/W
	l_4	6mm	10mm	10mm	
	α	0.1253rad	0.2527rad	0.2527rad	
	w	1mm	2.5mm	1mm	
II	l_1	2mm	6mm	2mm	Min $P = 0.1831$ W
	l_4	6mm	10mm	10mm	
	$\Delta\theta_6$	-1rad	1rad	1rad	
	w	1mm	2.5mm	1mm	
III	l_1	2mm	6mm	4.8mm	Max $L = 0.7353$ N
	l_4	6mm	10mm	6mm	
	α	0.1253rad	0.2527rad	0.2527rad	
	w	1mm	2.5mm	1mm	
IV	l_1	2mm	6mm	2mm	Max $L/P = 1.0252$ N/W
	l_4	6mm	10mm	10mm	
	$\Delta\theta_6$	-1rad	1rad	1rad	
	w	1mm	2.5mm	1mm	

When the objective function of the optimization problem was to maximize the mean lift produced, it was observed that the optimal values of the kinematic parameters are on the curve beyond which the crank ceases to rotate through 360 degrees. This curve can be seen on the contour plot between $l1$ and $l4$ (Fig. 7). When minimizing power, the optimal values were at the limits of the variables for which the power consumption was lowest as per Fig. 4. For the case of maximizing the payload to power ratio, it was seen that for most of the parameters, the effect on power is greater than the effect on lift. This means that although it is possible to maximize payload-power ratio by increasing lift, the optimization converged towards decreasing power consumption.

Fig. 8(a) shows the change in lift produced from optimization for maximum lift. In this case, the mean power consumption is not allowed to exceed the base value of 0.745W. The graph clearly demonstrates the increase in lift with higher and wider red peaks compared to blue peaks. The changes in the variables leads to a shift in phase between the flapping motion of the two designs, but this is not very relevant since we are more concerned with mean values and periodic motion of the wing. Fig. 8(b) shows the possible reduction in power consumption when 35g of lift is required. Since the negative power values are ignored, it is seen that the positive peaks are smaller than before optimization, and should result in lower power consumption.

VII. Discussion

A salient feature of a majority of the results was that the optimal values were usually at the upper or lower bounds of the variables, which means that improvements in the performance of the MAV appear to be limited only by fabrication and size constraints. However, some of the assumptions involved in the development of the model must be kept in mind while attempting to change the parameters. One of the significant limitations is the reliability of the aerodynamic model in accurately predicting the forces on the wing. Although the theory may not be valid for a different flow regime, since the values obtained provide a good estimate for the type of wing size and motion that is expected from the MAV under discussion, this theory provides a good starting point for the model. With time, we may be able to incorporate a more accurate and robust calculation of the aerodynamic force. The wing flexibility has also been ignored, the

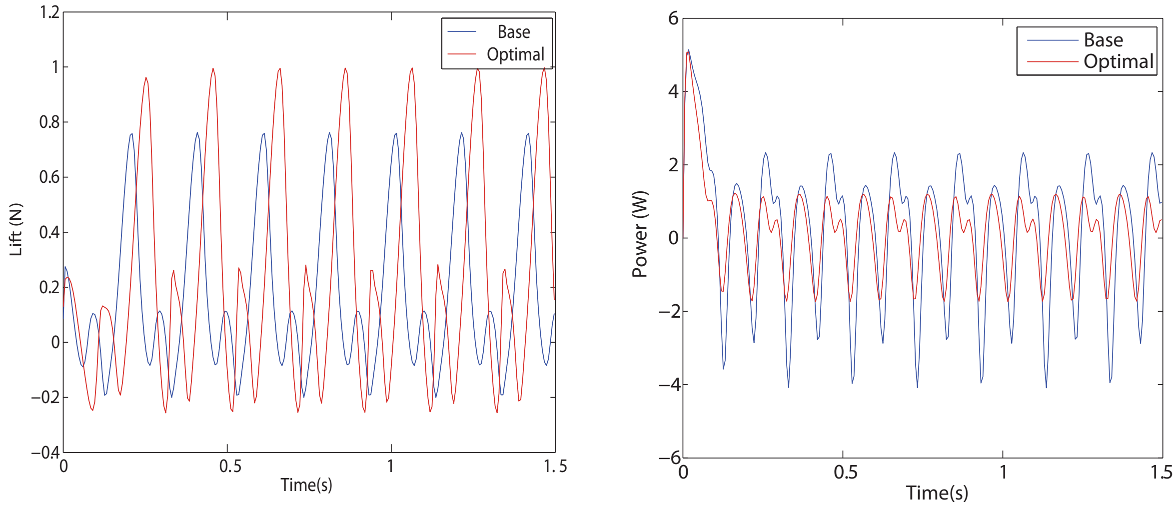

Figure 8. Optimization results (a)Max lift with power constraint (b)Min power with lift constraint

effect of which may be highly significant for larger wings, or for wings of a different membrane material. Since the mechanism is made of polymers, if the interaction forces between the links are large, there may be deformation, whereas the model assumes rigid links. Similarly, there are limitations for approximating the compliant joints using the pseudo rigid body model. Some of these issues can be overcome by developing a better system model, which may require higher computing ability. The aerodynamic model itself can be improved if a model can be developed that captures all the dominant aerodynamic effects. Considering how complex such a force model would be if derived from basic principles, a heuristic or surrogate model would be much more compatible.

Once the dimensional scale and the performance goals of the MAV are decided upon, a dynamic model can be developed for the flapping mechanism, wing and motor with a basic mechanism using the techniques outlined in this paper. This should provide the researcher with a good indication of the expected performance of the MAV. By maintaining the modular approach, different types of power and control systems can be integrated into the model. The effect of different parameters on the performance can be studied using sensitivity analysis. Once the right mechanism, power source and wing type are arrived upon, the system can be optimized to yield the most suitable values. Therefore, within reasonable limits, it is safe to say that this dynamic model can function as a tool to predict the performance of such a system and analyze the effect of various parameters, so that the the design process can be guided in the right direction.

VIII. Conclusion

In this paper, we developed a comprehensive model of the flapping mechanism of an MAV that incorporates a multibody dynamics of the transmission linkage, an aerodynamic model for lift force calculation, and a power consumption model of DC motors. We then optimized the parameters of the mechanism for improving the performance of the MAV. We discussed the need and scope of optimization, and looked at its potential benefits. Since aerodynamics is an important factor in the MAV system, Theodoresen's theory was selected as the tool for calculating the lift force generated by the wing, after validating it for a particular flow regime. University of Maryland's Jumbobird was chosen as the base mechanism to develop the model. The steps involved in the development of the model were outlined, along with the assumptions. Once the correctness of the model was deemed satisfactory, a sensitivity analysis was performed on the model to understand the effect of different variables on the three main performance parameters: lift, power and lift-power ratio. The critical parameters were identified and the design space was explored for optimal values of these variables. It is hoped that this work serves as a tool to help guide the design process of future MAVs.

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