Optimizing Flapping-Wing Flight

New Mexico

Supercomputing Challenge

Final Report

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Table of Contents

Executive Summary

This project focuses on finding the optimal wing dimensions and flapping frequency based on user-input wing and load parameters. These include load mass, wing density, wing thickness, and much more.

For each test, the upward force generated by the pair of wings is calculated and it is compared to the power to move the wing. The goal is to find the wing parameters that result in the most power efficient flight. This is achieved by normalizing the power data and the force data and calculating the difference.

This program currently offers two basic shapes for wings: ovals and rectangles. Rectangles tend to be slightly more energy efficient than the ovals, but they do require more power overall, so they could be more useful to lifting larger loads.

As was expected, larger wing width and flapping frequency produce more efficient results to a point in terms of energy consumption versus force generated. At some point, however, these large widths and fast frequencies become less efficient. What was unexpected was that the wing length did not seem to follow this pattern; longer wings always appeared more efficient.

The Problem

The purpose of this project is to find the optimal wing shape and frequency for flapping-wing flight given specific parameters about the load and wings. Fixed wings are great for large aircrafts, but for smaller objects such as robots or individual humans, fixed wings can consume much more power than flapping wings. (Gold, 2009) This project aims to eliminate this inefficiency by providing the precise parameters for the optimal flapping wing based on its purpose.

There are four main stages of insect and bird flight: downstroke, upstroke, pronation and supination. The pronation and supination are necessary so that the wing has less surface area on the upstroke than it does on the downstroke (Chin & Lentink, 2016). When designing this program, these were the four different states that I made calculations for.

The equations I developed were more than simple force calculations. To truly model a flapping wing, I had to model the velocity of the wing as a function. This posed some problems because now the velocity variable in the source equation I used was a function rather than an easily substitutable variable. This especially made the integration of the force equations more difficult.

Method

Using the same four stages of flight, I created four equations to correspond to the net upward or downward forces and the overall power required throughout these stages.

I then summed these calculations to arrive at an equation for total force and power per cycle.

For each equation, I started with the equation for air resistance: $F_D = ½ \rho C_D A v^2$ where ρ = air density = 1.225 kg/m^3, C_D = coefficient of drag which is 2 for flat surfaces like the wing, A = area, and v = velocity. I used a negative cosine function for the velocity over time. Using integration across the wing and integration again across the swath of the wing downstroke (or upstroke), I arrived at a final equation for the downstroke and upstroke. I then subtracted the downward force of gravity based on mass of load and mass of wings using density and dimensions.

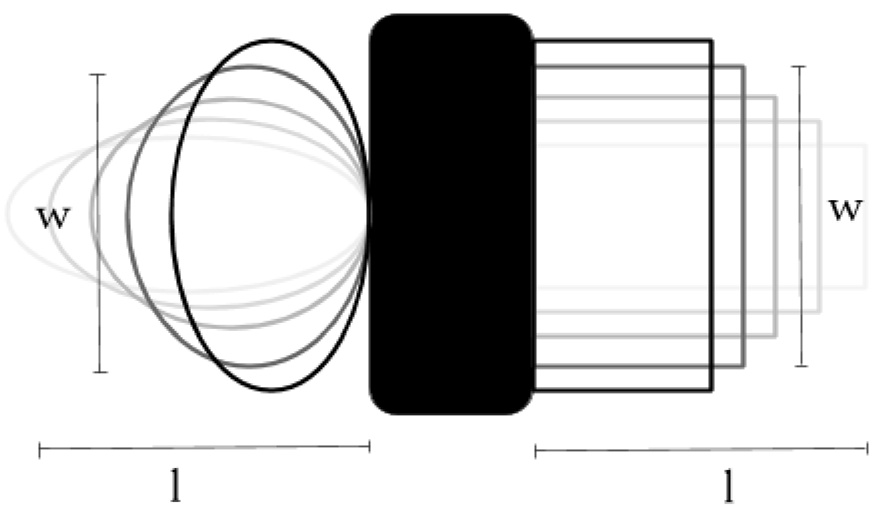

Figure 1: Variation on Wing Dimensions

Model Validation

To validate the model, I cross referenced basic properties of aerodynamics to make sure the results produced were logical. As expected, my results showed lower force generation with smaller wings and lower frequencies. The power requirements also followed this pattern as expected. When differencing the normalized power and force data, the

Results

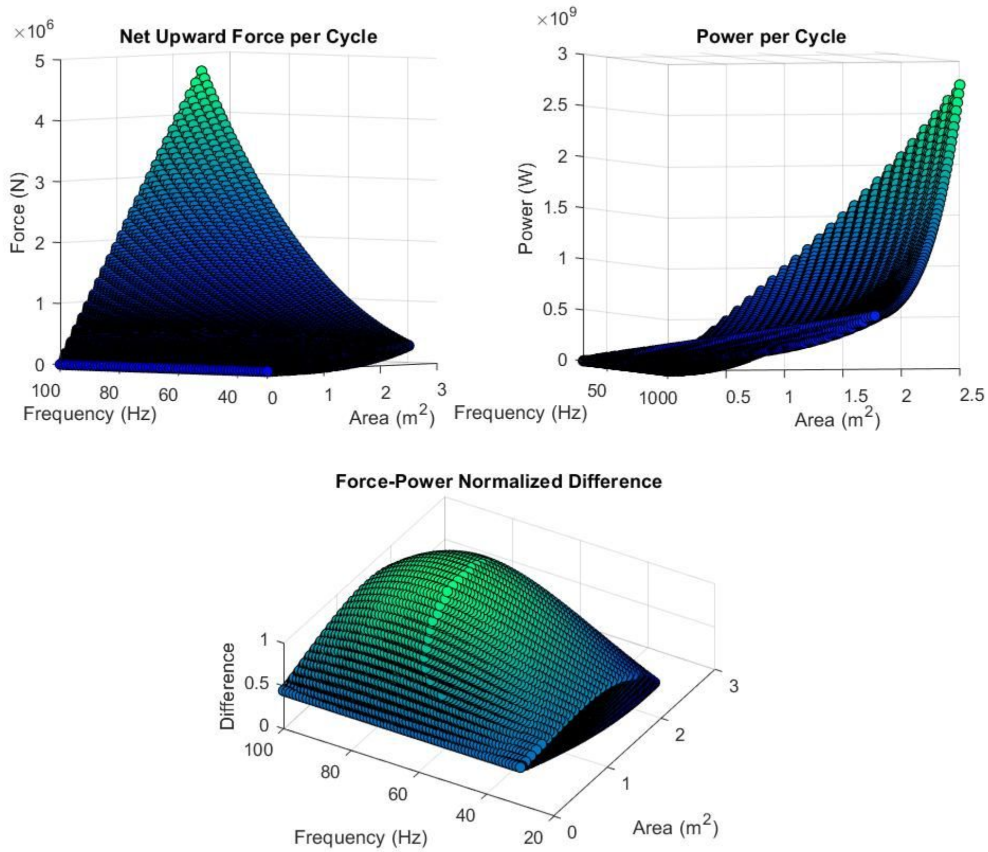

Figure 2: Large Range Analysis

I used larger ranges with less accuracy to locate the peaks of the normalized difference graphs.

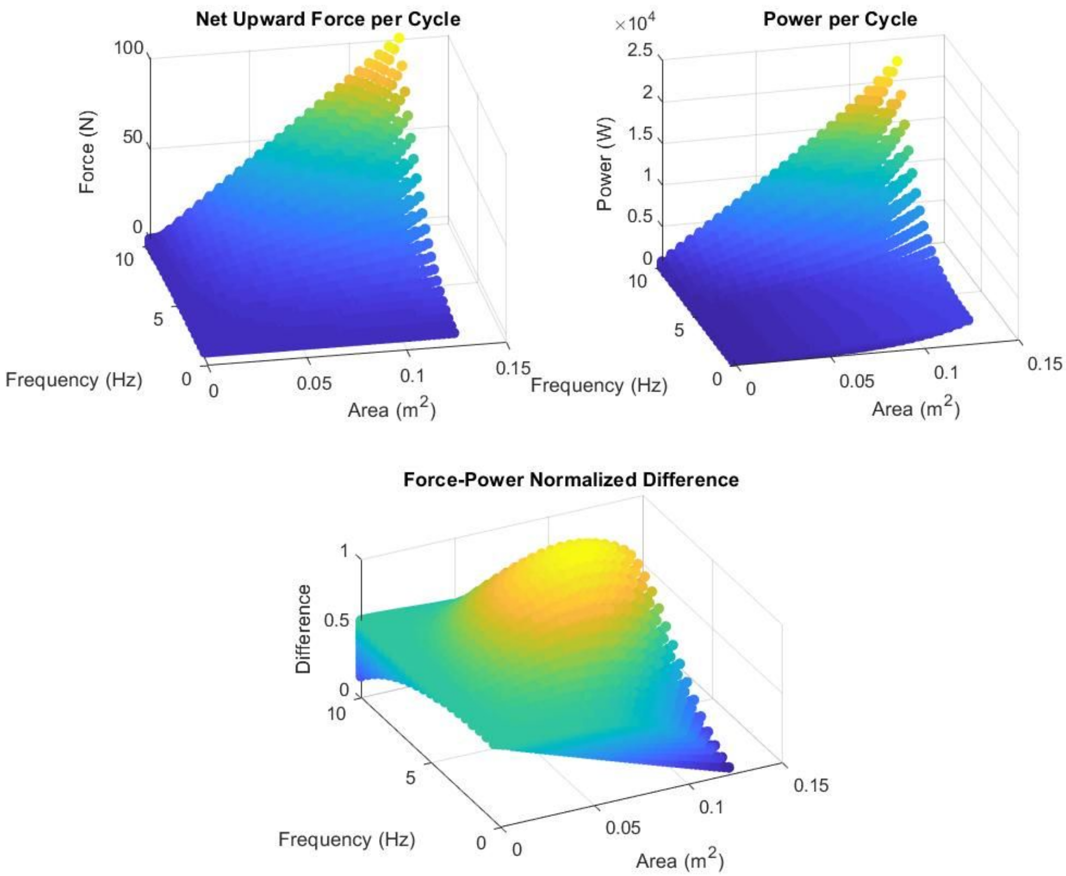

Figure 3: Small Range Analysis

After using larger ranged graphs to find the peaks, I can use smaller ranges to more precisely locate the optimal wing parameters.

```
>> findOptimalParameters(.5:.5:10, 0:.01:.5, 0:.01:.25, .001, 2*pi/3, 0.01, 10, .02, "oval")
Optimal parameters at:
2.0944 Radians Stroke Angle,
0.0010 m Wing Thickness,
10.0000 kg/m^3 wing Density,
0.0100 s proation/supination rotation time,
and 0.02 kg Load Mass

Optimal Width: 0.18 m
Optimal Length: 0.50 m
Optimal Frequency: 8.0 Hz

Upward Force Generated: 32.12 N
Power Required: 5196.12 W
```

Figure 4: Example Console Output

Output to the console is the data about the highest point on the normalized difference graph. This is useful if designing a wing because it shows the precise optimal values the computer found.

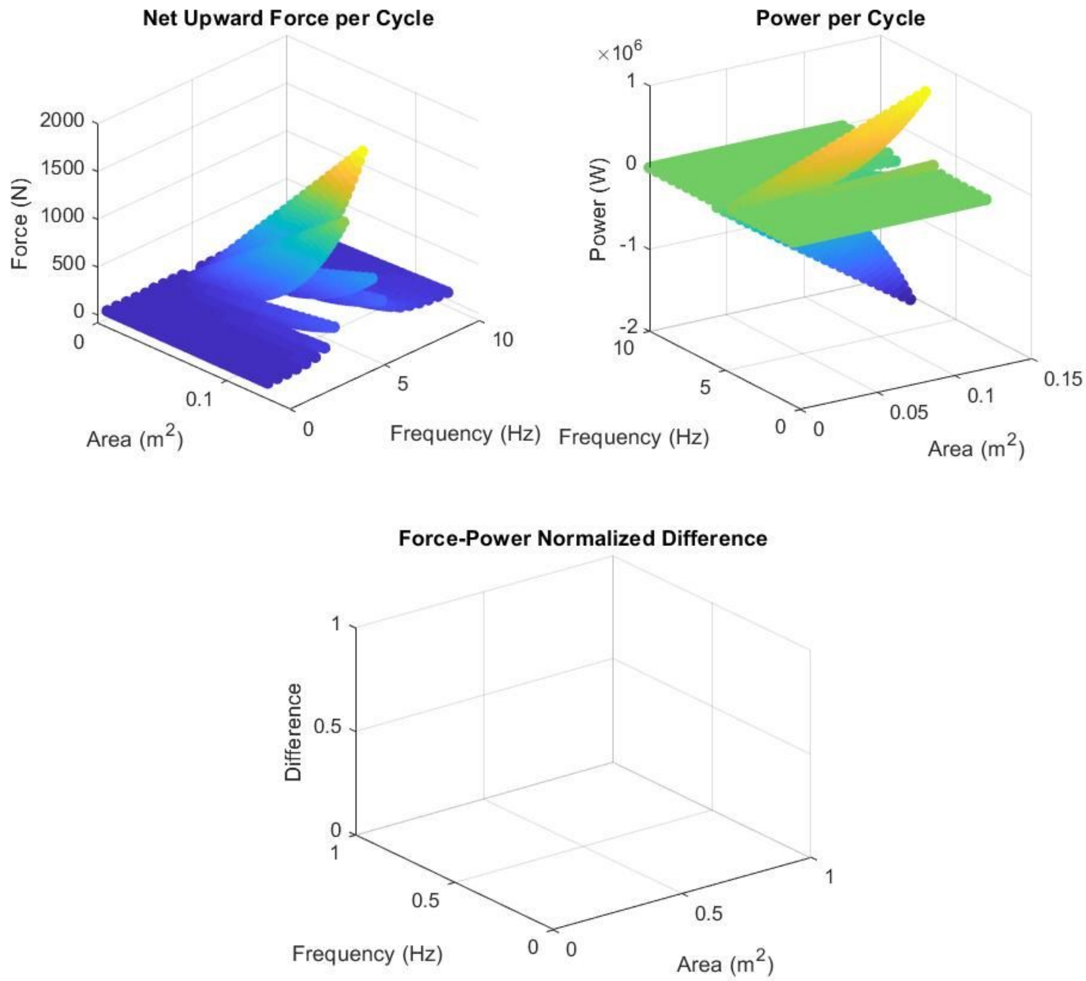

Figure 5: Error In Graphing

I have found an unusual error when the time it takes to rotate the wing for pronation and supination is set to a higher value. This produces a large spike around a specific frequency, which is unnatural when considering the nature of force and power relation to flapping frequency. Error handling could be implemented to prevent acceptance of the large turn time values.

Conclusion

Both the wing width and the flapping frequency appear to have a point of diminishing returns where the cost of the power becomes greater in proportion to the force produced than lower values. Strangely, however, the wing length did not appear to follow this pattern, so this suggests that an infinitely long wing would be optimal. Using logical reasoning, it is obvious that this is untrue, so there must be a factor I have not accounted for that limits the length of optimal wing shape in the real world.

More important than the statistical data I retrieved from this program, this program has the potential to be used as a personalized optimizer calculator. It also has the potential to be incorporated into larger programs that could find trends in wing shape based on load mass, flapping angle, or desired speed. Although by itself this program just finds optimal wing shape and frequency, it can be easily incorporated into new code to accomplish so much more.

Recommendations

I wrote this program with the intent that it could be easily editable so that a multitude of changes can be made to it to increase the precision as well as the range of tests that it would go through and optimize. That being said, I do have some specifics in mind that could be added to this program to enhance the quality of the results.

Firstly, the program is made for direct induction and external method calls, so it is far from as user friendly as it could be. A user interface could be added that prompts the user for the specific data that is needed such as the wing thickness and load mass. After the data is processed, graphs could be used to show the dimensions of the optimal wing shape.

The precision of the model could also be improved. There are five actions flapping organisms utilize to increase lift. These are leading edge vortices, added mass, wing-wake interactions, rotational circulation, and clap and fling. (Chin & Lentink, 2016) I did not include these in this model because they are much harder to analyze due to their seemingly random behaviors. According to Anderson, 2011, " if the MAV designer builds to the quasi-steady model, he can expect to be able to generate greater lift than expected, but will also experience greater drag, and thus, greater power requirements." This would likely cause a shift in the point with the greatest lift to power, thus slightly changing the optimal point.

Other features could be added for cross analysis with variation in other parameters such as load mass. If a function were created for this purpose, an equational model could be created to predict the how load mass relates to wing shape and frequency.

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