Insect Wing Research

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Abstract:

This project highlights several of the observations and findings that were discovered when experimenting with the effects that a gust has on an insect. In this simulation, Julia was used to conduct several trials with different amplitudes, angles of attack, frequencies, and lags of pitch and heave. These variables were altered to try and best emulate the flight of an insect which was represented through a thin wing that oscillated in a viewing frame, this being represented by a thin insect wing. The first experiment was set under an environment with no gust and a configuration was made to attempt to mimic an insect hovering. The second experiment was with a slight gust, and findings of how an insect may respond to a wind or turbulence are shown. **It was noted that often higher frequencies, shallow angles of attack, and adaptive pitch and heave lags were necessary when producing the representation of an insect to stay in stable flight.**

Introduction:

The aim of this study is to explore the various methods of motion used by insects and fish, whether generating lift through the flapping of wings or the generation of forward motion against currents using fins. Focusing on insect flight, the goal is to find the optimal motion to achieve lift and hover in the air under certain circumstances, generating the highest amount of lift possible.

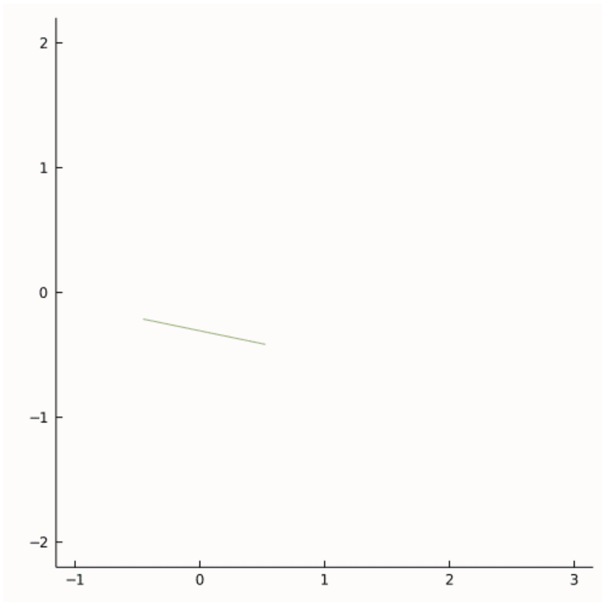	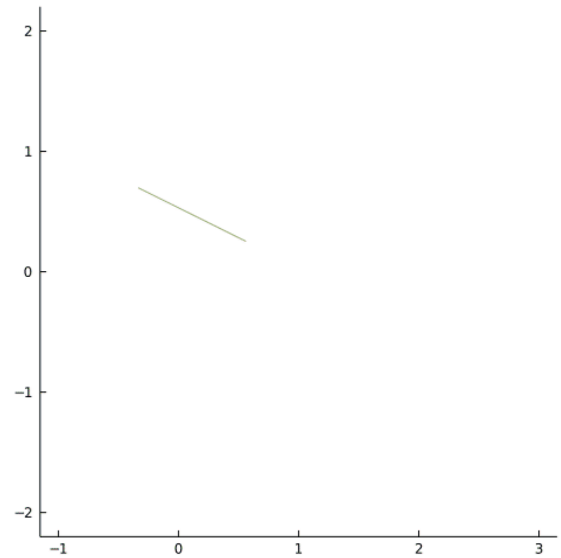
Figure 1.1: GIF of flow field with -π/8 angle of attack, -0.55 pitch, and 2π frequency	**Figure 1.2**: GIF of flow field with angle of attack: -π/8, pitch: 0, heave: 0, frequency: 4π/3

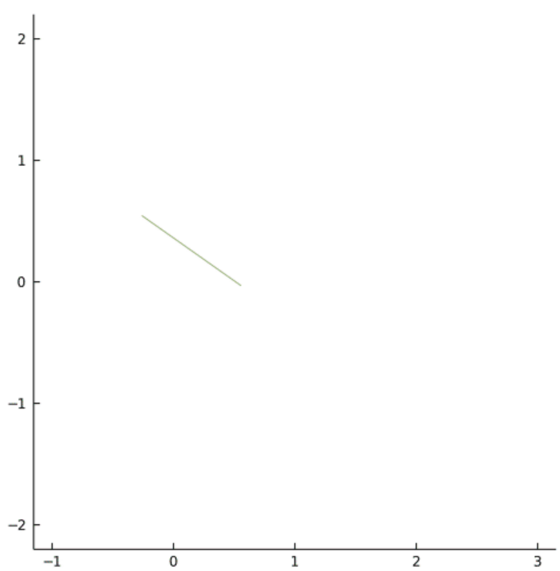	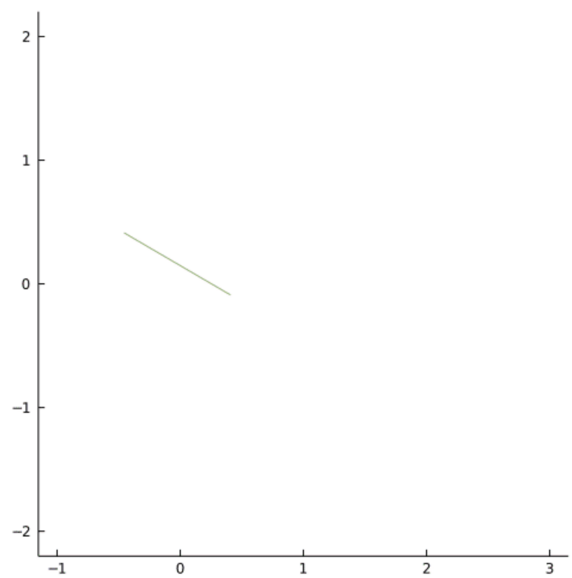
Figure 1.3: GIF of flow field with angle of attack: -π/6, pitch:π/2, heave:π/2, frequency: 4π/3	**Figure 1.4**: GIF of flow field with angle of attack: -π/7, pitch:π/2, heave:π, frequency: 4π/3

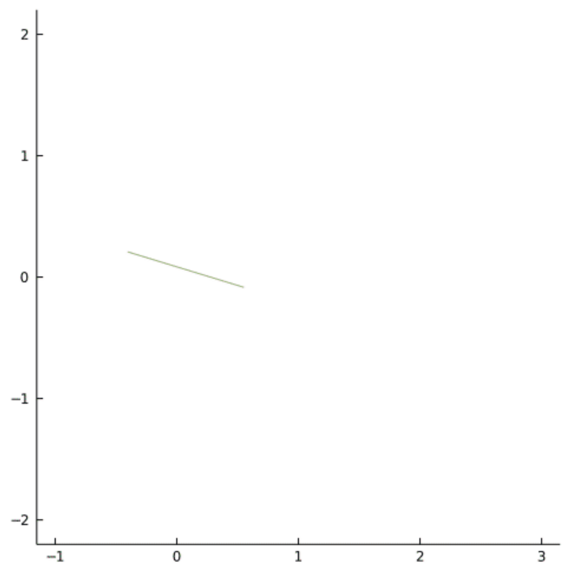

Figure 1.5: GIF of flow field with angle of attack: -5π/12, pitch: 0, heave: 0, frequency: 13π/12

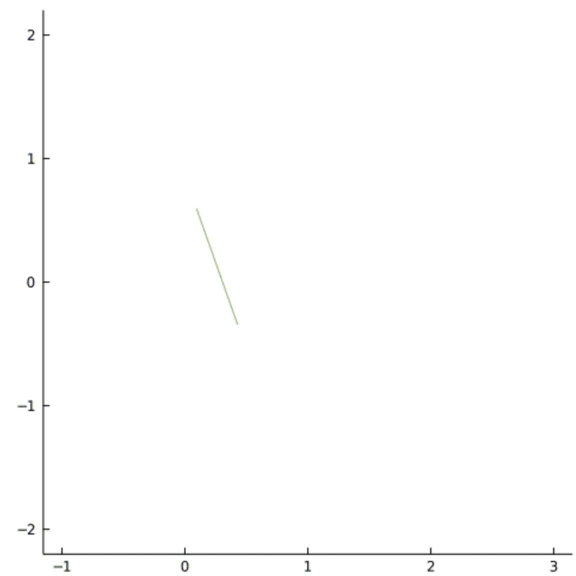

Figure 1.6: GIF of flow field with angle of attack: -3π/12, pitch: 0, heave: 0, frequency: 4π/3

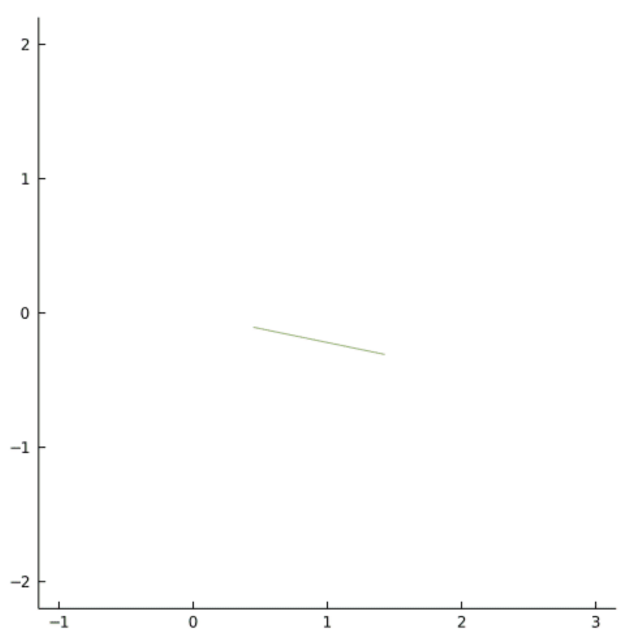

Figure 1.7: GIF of flow field with angle of attack: $-$ π/8, pitch: -0.55, heave: 0.05, frequency: 2π, U_0:0.15

Problem Statement:

Our experiment was designed to take into account 4 main independent variables: angle of attack, pitch, heave, and frequency. All other variables stayed constant throughout all experiments. Figure 2.2 displays the parameters which remained unchanged throughout all simulations. However, free stream velocity (U) is changed depending on the type of movement being experimented on, and is 1.0 for fish movement and 0.0 for wing movement. The free stream serves to act as the current pushing against the fish swimming upstream. The plate, which served to illustrate an insect wing/fish fin, started in the same position and was the same size in each experiment. Figure 2.1 illustrates the independent variables, we mostly focused on frequency, mean angle of attack, and phase lag of pitch and heave. Other variables had negligible effect on the observations, so those were held constant in the tests depicted.

```
In [74]: a = 0.3 # location of pitch axis, a = 0.5 is leading edge
         φp = -π/4  # phase lag of pitch
         φh = 0.0 # phase lag of heave
         A = 0.7  # amplitude/chord
         fstar = 1/π # fc/U
         α₀ = -π/8 # mean angle of attack
         Δα = π # amplitude of pitching
         U₀ = 0.0 # translational motion (set to zero in place of free stream)
         K = (7π/6)*fstar # reduced frequency, K = πfc/U

         oscil1 = RigidBodyTools.PitchHeave(U₀,a,K,φp,α₀,Δα,A,φh)
         motion = RigidBodyMotion(oscil1)
```

Figure 2.1: Variables changed throughout testing

Methodology:

The software that we used to run simulations was the ViscousFlow package running on Julia language. To actually run the code and document our findings, we used Jupyter Notebooks. As illustrated in Figure 2.2, we used delta x and delta t values of 0.02 and 0.01 respectively, and set step sizes based on the Reynolds number. Our plate consisted of 50 points with length 1.0 and thickness 0.0, as referenced in the abovementioned figure.

```
In [4]: Re = 200; # Reynolds number
        U = 0.0; # Free stream velocity
        U∞ = (U,0.0);

In [5]: xlim = (-1.0,3.0)
        ylim = (-1.0,1.0);
        Δx, Δt = setstepsizes(Re,gridRe=4.0)

Out[5]: (0.02, 0.01)

In [6]: body = Plate(1.0,1.0Δx)
        T = RigidTransform((0.,0.),0.)
        T(body)

Out[6]: Plate with 50 points and length 1.0 and thickness 0.0
           Current position: (0.0,0.0)
           Current angle (rad): 0.0
```

Figure 2.2: Constants held throughout testing

Results and Discussion:

To best visualize our findings, Figure 2.3 and Figure 2.4 illustrate two graphs, with the left showcasing the drag coefficient vs time, and the right showcasing the lift coefficient vs time. C_D and C_L are inversely related, so as one increases, the other will decrease. In an unsuccessful instance of insect flight, as depicted by Figure 2.4, both graphs remain relatively constant, with little variation. In successful insect flight and hovering, C_D will at the start drastically fall as the insect takes off, and then follow a sinusoidal curve of increasing and decreasing as the insect's wings flap to generate more lift. It is due to this sinusoidal curve that we are able to tell that the insect stays in the air, as on average C_D will be smaller than or equal to C_L in all instances, meaning the insect does not lose lift. In the unsuccessful test, while C_L is positive and lift is being generated, C_D stays positive at all times, and outweighs the lift force being generated. When a gust is introduced to the field conditions, there is much less variation in both C_D and C_L due to an additional force pushing the insect sideways, meaning it is harder to both achieve lift and overcome the gust, and harder for the drag force to overpower the gust and bring the insect back down onto the ground. The negative C_D values mean that lift is being generated, or thrust.

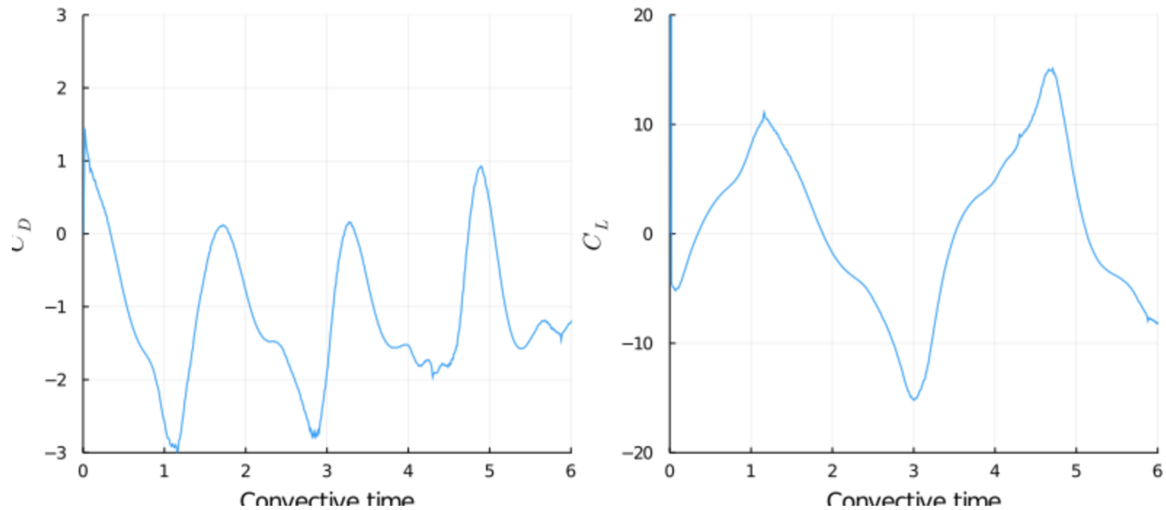

Figure 2.3: Reference graph of C_D (drag coefficient) and C_L (lift coefficient) vs convective time for successful insect flight

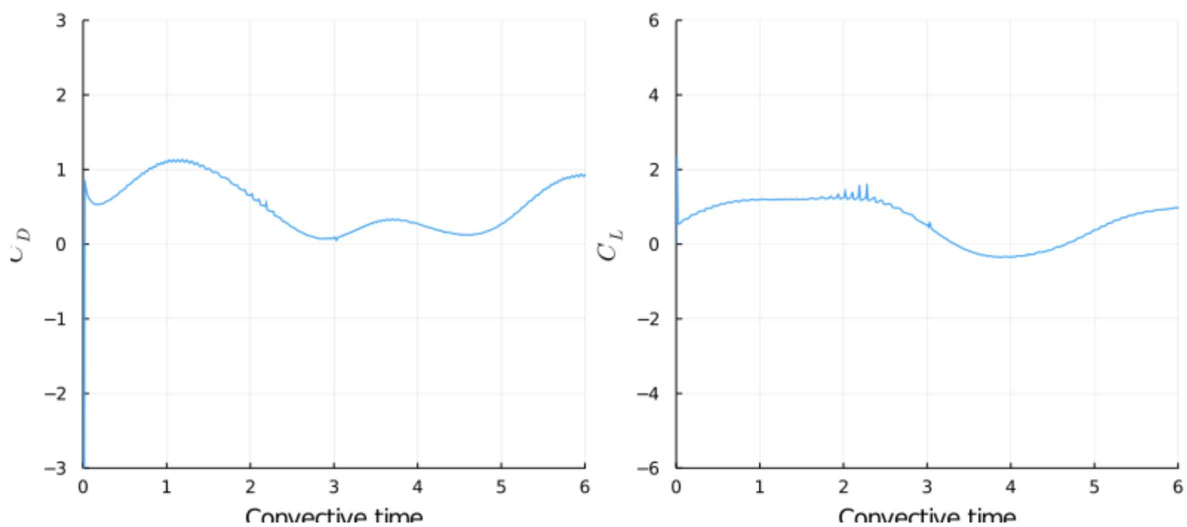

Figure 2.4: Reference graph of C_D (drag coefficient) and C_L (lift coefficient) vs convective time for unsuccessful insect flight

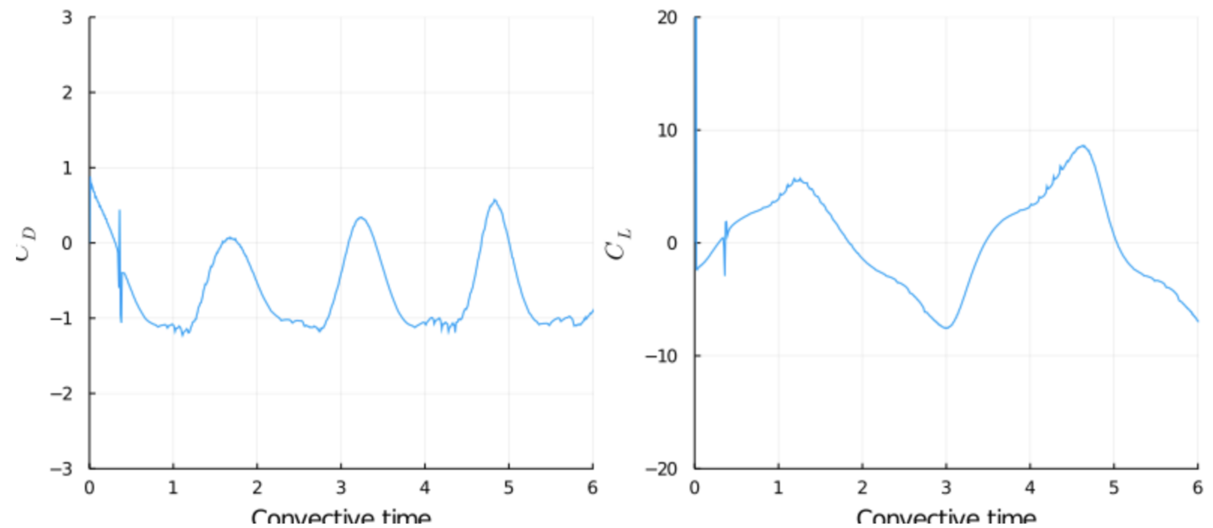

Figure 2.5: Reference graph for C_D (drag coefficient) and C_L (lift coefficient) vs. convective time for Figure 1.7, when gust is present

Rationale:

The motion of an insect wing is most similar to sinusoidal motion which is clearly seen in Figure 2.3 as well. These graphs illustrate the component of the drag coefficient and the lift coefficient respectively. These graphs were taken from the results of running the test in Figure 1.1. The GIF in this figure is a test that was run with a translational gust of zero as well, so there were no significant outside resistive forces acting on the insect. Several traits that can be taken from this test include how the frequency is relatively higher than most of the other tests, and the amplitude is slightly higher than the rest. In terms of motion, this means that since the frequency is higher, the insect wing is flapping more often in a time interval compared to a lower frequency. Also due to the higher amplitude the insect is going through the repeated higher and lower flapping motions at a faster pace. This is what sets up for a successful hovering motion for an insect to stay suspended in the air when there is no external gust. This reason why this insect is able to stay suspended is due to its ability to create lift in both the positive and negative y direction when the wings go up and down. The wing is able to utilize the amount of resistance it can get from “dry air” and efficiently use fluid dynamics to create the oscillation of lift forces.

Pertaining to the equation, the y component of displacement of the wing can be modeled by $Y(t) = \frac{1}{2}A_0 cos(2\pi f t)$and the x component is 0 as the wing does not go to the left and right significantly (Credit: Professor Jeff D. Eldredge). These equations can be adapted to these tests based on

Professor Eldredge's previous research he has done on this topic. As seen the amplitude and frequency are two key components in the equation for the y component as well. The displacement in the y component is directly proportional to the amplitude and the period of the oscillation will decrease if the frequency increases. The frequency dictates how often the wing will go through one complete cycle as well and is important when deciphering the graphs. As seen in Figure 1.2, 1.3, and 1.4, low frequencies were used and do not seem to create any disturbance in the flight of the insect, but there are discrepancies. The motion is slow and in turn cannot generate constant and repetitive lift necessary to keep an insect suspended in the air. As seen in Figure 2.4 the graph for the lift and drag coefficient vs time is still relatively sinusoidal, but the graph oscillates between fairly small lift coefficients, in this case, roughly between 0 and 2. However, when the frequency is increased the sinusoidal lift and drag coefficient values go between -3 and 1 and -20 and 20 respectively as seen in Figure 2.3. Additionally the period of the graph is much smaller as well so the insect wing can alternate between its lift and drag continuously to stay in flight. Hence, when Figure 2.3 and 2.4 are compared Figure 2.3 illustrates a more dramatic trend than Figure 2.4.

The equation for $Y(t)$ also indicates why the wing seems to be moving in higher magnitudes in the up and down direction when amplitude is high and when frequency is high it makes more oscillations per time interval. This equation is very similar to simple harmonic motion as that equation is modeled by $y(t) \ = Acos(2\pi ft)$which means that this motion must resemble some harmonic motion. This is reasonable because harmonic motion resembles motion where there is an acting force, equilibrium position, and restoring force. In this situation the acting force would first be caused by the initial lift the insect creates when rotating its wing and causing it to displace upward, then moving to its highest amplitude to where the wing rotates again and the restoring force is the lift acting in the opposite direction, and finally reaching the equilibrium position which is where it had begun from at an angle of 0.

The angle at which the insect rotates can be modeled by another equation derived from Professor Eldrege, $\alpha(t) \ = \alpha_0 + \ \beta sin(2\pi ft \ + \ \Phi)$. This equation includes variables such as the initial angle of attack (α_0), the frequency (f), and constant such as $\beta$and Φ which were not altered. This equation shows a similar relationship to that of displacement where the frequency did decrease the period once again, and that meant the angle would change more often in one time interval. This is probable due to the fact that the wing was displacing more often, the angle at which the flap turned would have to be just as consistent so it would turn at the correct time when the wing had reached its peak amplitude. However, the initial angle of attack, α_0, was only added and not multiplied to the rest of the equation which meant it had less of an impact on the overall angle of the wing. This can be seen when the angle of initial attack had to be kept relatively shallow because the lift force would often alter the angle at the same time. The restoring and acting forces from the harmonic motion had played a role in altering the angle and the initial angle was important to keep shallow or else steeper angles would cause results similar to Figure 1.5 and 1.6. These angles were more dramatic so it can be seen how the acting forces had overpowered it and eventually rotated the wing to an unstable direction.

The angle at which the insect wing is rotated always plays a significant role in the lift force. Using a similar rationale to how planes generate lift, the angle at which insect rotates their wings carry connections to Bernoulli's principle, which can be depicted by:

$$P_1 + \rho_1 g y_1 + \frac{1}{2}\rho_1 v_1^2 = P_2 + \rho_2 g y_2 + \frac{1}{2}\rho_2 v_2^2$$

where the top half of the wing can denote variables with subscript 1, and the bottom half of the wing can denote variables with subscript 2. Pdenotes the pressure, $\rho$the density of the fluid, $g$the acceleration due to gravity, $y$the displacement in they y direction, and $v$the velocity of the fluid. In this situation the density of the fluid is the same in both situations, $g$is constant, and the y_1 and y_2 values carry very similar values because the wing is fairly thin so we can simplify Bernoulli's principle to $P_1 + \frac{1}{2}\rho_1 v_1^2 = P_2 + \frac{1}{2}\rho_2 v_2^2$ due to cancelling. With this equation it can be seen how the fluid, in this case air, passing on the top of the wing is moving at a faster velocity than the air passing below the wing as seen in Figure 3.1. Therefore $v_1 > v_2$, and at the same time in this equation both sides have to equal each other so P_1 must be less than P_2 for the equation to stay balanced. Since $P = \frac{F}{A}$and the area at which each pressure is acting on is relatively the same on the top and bottom of the wing, the force must be greater for P_2. This force is greater on the bottom so lift is generated. One caveat is that insect wings do not have a significant airfoil shape so to make up for this they often have wings that round off at the ends and they utilize the angle at which they attack the air so the velocity is higher on the top of their wing when they need thrust force. Vice versa is true when they want to go downward as well as the angle is changed so the velocity is higher on the bottom of the wing then. This consistent repetition of shifting between periods can be contrasted with how airplanes fly. Where airplanes use a large angle of attack which eventually enacts the stall process where there is small lift force and large drag force momentarily; insects do not use these dramatic angles of attack, so they are able to avoid this stall and oscillate between lift and drag forces. This also may explain why insects do not have an airfoil shape because the transition between upward and downward is so frequent that the airfoil would generate too much lift and cause them to make dramatic changes in flight. Rather, changing the angle at which they fly is more suitable for slight changes in displacement.

When an external gust is applied onto a body, as seen in Figure 1.7, the gusts creates an outside force that the insect has to respond to with another force in the x direction. In this scenario in Figure 1.7, the insect would have displacement in the x direction, but in order to counter this the insect may flap its wings more frequently or change its angle of attack. These steps can be taken to reduce the net force in the x direction back to zero and some propulsion in the x direction would be needed to generate this. As seen with the parameters in Figure 1.7, similar settings are used compared to the situation where the insect successfully stayed suspended with no external gust, but due to this external gust the same parameters are not as effective. In an attempt to solve this the pitching and heaving were slightly modified, which could ultimately change when the wing is rotated so it could potentially generate some propulsion in the x direction to combat the gust.

Referring to the lift and drag vs time graph (Figure 2.5) for the trial seen in Figure 1.7 the trend of lift and drag coefficients also seem different when a gust is introduced. This scenario depicts a less sinusoidal trend for the lift and instead presents a graph more related to $cos^2(t)$where the lift coefficient never dips below -1 and becomes slightly higher as time passes. Not as consistent as Figure 2.3. The drag coefficient is still slightly the same with a less dramatic trend which is most likely due to the external gust absorbing energy when coming through.

Figure 3.1: Representation of wind going past angled wing (Credit: 1983 NACA Langley)

Experimental Error:

Potential errors that could have arised in these trials include not taking into account the force of gravity and only looking at the effect of gust from one angle. Insect's are generally carry very little mass, and even more so their wings so the force of gravity that these insects have applied on them is not very significant as $F_g = m_{insect}g$, where when $m_{insect}$is small $F_g$is small. However, this still is a present force and it was not taken into account during these trials and the wings were tested in a simulation which did not take into account gravity. This could possibly alter the situation as the weight of the wing or insect, may cause more lift to be generated when positive y displacement is occurring and less lift in the negative y direction. These imbalances in lift required when going up and down may mean an inconsistent angle of attack when going up and down as well, but since the F_g is not mostly significant; the angle and required force are not due to significant change either.

The second cause of potential error is due to the perspective at which these results are taken from where only the side of the wing is taken into account to evaluate lift and drag. Although this is a reliable source of demonstrating an insect's lift and drag, the shape of the wing and the fluid travel on the other sides of the wing are not entirely taken into account. In order to receive a better understanding of the generated forces, a flow field from the top and bottom of the wing may be helpful in understanding more about the harmonic motion as well.

Challenges:

Challenges that were faced during this trial and simulation research include not being able to experiment with higher amplitudes and frequencies due to computer capabilities, transitioning to moving bodies, and working between several more variables at a time. Often when running the Julia program to test simulations the program would crash or give an aborting error when trying to reach higher frequencies and amplitudes, which made it difficult to mimic an insect's movement when suspended in the air. Insect's use very high frequencies to generate a continuous oscillation of lift, but in this case it was only possible to get close to that high frequency due to the computers limitation when running tests. Additionally, when working with moving bodies compared to fixed bodies the amount of variables and things that can be altered become more difficult. For example when running tests, it was often difficult to understand which variables need to be changed to achieve certain results and it was no longer single variable work. This new obstacle required more attention to detail when going from trial to trial to identify what each change in the variables translated to when viewing the GIF's.

Conclusion:

After performing various experiments and referencing the equation for calculating net displacement, we can conclude that **-π/8 angle of attack, -0.55 pitch, and 2π frequency are the optimal angles and frequency** of wing parameters needed to generate the most optimal oscillatory movement for an insect to stay suspended in the air. Angle of attack is the most important part of lift generation, as if it is too drastic, there is often an imbalance in the force generated due to differences in pressure, and if angle of attack is too small in magnitude, lift will not be sufficiently captured below the wing to propel the insect upwards. When a gust is introduced, the insect will be able to generate the same amount of lift and hovering motion as before keeping the same vertical position, but will not be able to hover in the same horizontal position. As for fish movement, the optimal parameters are: **angle of attack $-\pi/6$, pitch: $\pi/2$, heave: $\pi/2$, frequency: $4\pi/3$**. Since fish experience an aquatic environment, we simulated that by using a free stream pushing against the fish fin, and calculated the optimal parameters based on how strong the motion was in pushing against the free stream to simulate a fish swimming against the current.