

How_Mosquitoes_Fly_in_the_Rain_English_mp4_

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[00:00:19.86] PROFESSOR HU: Hi. My name is David Hu. I'm an assistant professor of mechanical engineering and biology at Georgia Institute of Technology. My lab is interested in how animals cope with their environments while they're moving. And today we'll be looking at how very small insects fly in the rain.

[00:00:40.42] Imagine that you've been shrunk down to the size of your pinky nail. The world then becomes a very dangerous place. Rain drops, which originally were only a nuisance, have become the equivalent of five tons in weight. And they fall at a speed of 1,000 of your body lengths every second. That's incredibly heavy and fast.

[00:01:03.45] Although this scenario sounds like science fiction, this is, in fact, a daily reality for the world's smallest insects. Mosquitoes thrive in rainy and humid conditions, and they've been around for 200 million years, and in that time have evolved a variety of mechanisms to deal with such conditions like wind gusts and the rain.

[00:01:22.48] By studying insects we can gain insight into the simple question of how to fly in the great outdoors. It's a difficult problem. There are wind gusts, rain. And this is especially important for technology.

[00:01:37.37] Recently, there's been a lot of interest in what's called the design of micro aerial vehicles, very small flying microrobots that can perform surveillance. These robots will also have to face the conditions that natural insects face. And by looking at how insects have adapted to such conditions, we can design better robots.

[00:01:56.00] We can also start to understand how weather affects the flight patterns of what's considered the world's most dangerous animal, as mosquitoes are responsible for the spread of malaria worldwide. However, very little is known about how mosquitoes behave in different weather conditions, such as precipitation.

[00:02:12.60] Today, we will ask the very simple question, how can mosquitoes fly in the rain? This will require knowledge from both biology and physics.

[00:02:22.63] Like any good scientist, let's start with a hypothesis. Let's see the two opponents. A mosquito's a centimeter in size, about the size of your pinky nail. And it weighs a very small amount, only 1 milligram. In comparison, how big and how fast is a raindrop? What forces are involved? See if you can talk to your neighbor and talk to your teacher and write down what forces dictate the terminal velocity and size of a raindrop as it hits the ground.

[00:03:11.04] Thanks for working that out with your classmates. We saw that raindrops, like this one, raindrops fall because of gravity. The influence of aerodynamic drag creates a high pressure in front of a drop. This pressure acts to

deform the drop like this. But surface tension acts to keep the drop spherical. The confluence of these three forces dictates the drop's size and speed as it falls to the ground.

[00:03:39.24] Raindrops are about 2 to 5 millimeters in diameter and about 5 to 10 meters per second. That means they're very dangerous from the perspective of a mosquito. They are 2 to 50 times heavier than a mosquito, and they fall more than 10 times faster than the mosquito can fly.

[00:03:57.66] How can a mosquito survive this? The first thing we'll do in this next session is look at how often the impacts occur. You have to understand rain intensity, basically the amount of rain that hits the ground. We measure this in inches per hour or centimeters per hour. And you have to know the size of the raindrop. Why don't you try to calculate the frequency of raindrop impacts, and we'll see you in a few minutes.

[00:04:42.74] We learned from our previous lesson that a flying mosquito will be struck about once every 20 seconds in moderate rain. Even if they were to hastily seek out shelter, they would still be struck on their way out.

[00:04:54.87] How do mosquitoes survive raindrop impacts? We answer this question by performing very simple experiments in our lab. We release very small drops from the ceiling of our lab and strike mosquitoes in front of a high-speed camera. From this video, you'll see an incoming drop striking the mosquito and then continuing on its path. The drop slows down very little as it hits the mosquito.

[00:05:19.64] So in the video you just saw, we saw a mosquito receiving a glancing blow. The blow applies a force F to the wingtips and causes the mosquito to angle by an amplitude θ . Let's use this glancing blow to figure out the force.

[00:05:50.04] The main equation we're going to use is the conservation of angular momentum. The inertia of the insect is on the left. The torque applied is on the right. You might have seen some of these terms before. I is the area moment of inertia. α is the rate of the angular acceleration, θ is the angle of the insect with respect to vertical, r is the radius that the torque is applied. And F is the magnitude of the force by the drop.

[00:06:22.94] In biology, often we can get a very close solution just by doing a scaling, by estimating the orders of magnitudes of each of these terms. I've done that here.

[00:06:37.61] Let's begin with the mass moment of inertia. That's the mass of the insect times the characteristic radius of the body to the power 2 and times $1/2$. A mosquito weighs 1 milligram. I'm going to be using centimeter-gram-second units. So all the lengths are going to be centimeters. All the masses are going to be in grams. And all the times are going to be in seconds.

[00:07:04.45] 1 milligram is 10^{-3} grams. The radius is about 1 millimeter. That's here. And so this value, a small value, is the XX MASS moment of inertia. The derivative of the rate of change of the angle of the insect is given here: Here's the angular acceleration. Theta from the video was 45 degrees, which in radians is π over 4.

[00:07:28.26] As you saw from the graph, the duration of the impact was 10 to negative 2 seconds. This gives us a value for the high rate of change of the insect. Remember, this was a high-speed video. So that's why this value's so high.

[00:07:44.96] Now, we determined most of these values. Let's plug that in to determine what F is. That's shown here. By plugging these values into this equation and substituting a value of 1 millimeter for the position of the drop with respect to the center of mass, we find that the force applied on the insect is one dyne.

[00:08:10.36] To remind you, a dyne is the unit of force in centimeter grams per second squared, in CGS units. And this is, in fact, the weight of a single mosquito. That's the smallest weight you can feel if you put a mosquito in the palm of your hand. That's about one dyne of force.

[00:08:35.02] This is a very low value. It's clearly survivable. So we see glancing blows are clearly survivable by these mosquitoes. But what about a more powerful blow, such as a direct impact? In this next video, you'll see a mosquito being struck in the middle of its wings by a falling drop.

[00:08:55.03] Now, get together with your neighbors and your teacher and see if you can calculate how much force is applied by that drop. And I suggest you begin by calculating the speed of the drop after impact compared to before impact.

[00:09:22.43] You've just seen videos of raindrops striking a mosquito and raindrops striking a mosquito mimic, which was the same weight as the mosquito. And you saw a very similar behavior, that the two joined together after impact. Let's try to figure out the final speed of this combined mosquito-cum-drop.

[00:09:46.53] We'll begin by characterizing the system, by the mass m_1 of the drop, its speed u_1 . And it strikes a mosquito of mass m_2 . After this impact, we have a combined mass of m_1 plus m_2 , and a new velocity, which we'll denote by u prime

[00:10:06.93] In the graph you're looking at, we systematize the masses of the mimics and changed the masses of the drops. And we plotted the final speed u prime, non-dimensionalized by u_1 versus different raindrops speeds, m_1 , non-dimensionalized by the mass of the mosquito.

[00:10:24.08] You see the trend is very regular among these data points. We can calculate exactly what the trend should be. You see this graph has a very systematic trend. And the reason for that is the conservation of momentum. The initial momentum in this system is characterized by momentum of the raindrop, m_1 times

u1. The momentum of the system at its end state is a combined mass of the drop cum mosquito and its final velocity.

[00:10:57.25] Using algebra, we can rearrange this equation to write the final speed of the mosquito and drop, non-dimensionalized by its initial speed. We find that's a simple relationship between the masses involved. In the graph, you'll see we've plotted this trend, and it matches the data very nicely.

[00:11:17.68] So using the trend that we predicted, let's estimate what this means for particular insects. A typical raindrop is 50 milligrams. Let's consider it striking a mosquito, which only weighs 1 milligram, much less than the raindrop.

[00:11:36.72] As we've found, the final speed of the combined drop and mosquito is given by the ratio of masses, and that's 98% of the initial velocity. That means the final raindrop has only lost 2% of its speed, a negligible amount. It's like it didn't even hit the mosquito.

[00:11:58.94] We can see a very different trend if we look at heavier flying insects. Let's consider dragonflies. A dragonfly is 1,000 times heavier than a mosquito, 1 gram. That means by the conservation of momentum that the final velocity, 50 milligrams over 1,050 milligrams, is only 2% of the initial velocity.

[00:12:25.47] So when a raindrop hits a dragonfly, it loses 98% of its momentum, or almost all of it, and it splashes. So we can see, depending on the insect at hand, the amount of momentum lost depends very strictly on how heavy the insect is.

[00:12:42.12] We just figured out what the difference is in the impact of two very different insects. We looked at the very slight-weight mosquitoes of only 1 milligram and the much heavier dragonflies on the order of grams.

[00:12:56.19] Now with your neighbor and with your teacher, try to figure out what happens to other kinds of insects. What is the final speed of the insect after it's struck by a drop, if the insect is, say, a flea, a fly, or a honeybee?

[00:13:29.14] So you've just calculated the final impact speeds of various insects. Now we can do the exact same thing in lab by using these Styrofoam balls of various masses. What you're about to see is a plot of the position of these balls and their velocity as a function of time. I've shown you a very heavy ball and a lightweight ball to simulate very heavy and lightweight insects. Now with your neighbor and the teacher, use these graphs to figure out how much force the ball receives.

[00:14:17.96] Welcome back. You've just calculated the amount of acceleration. Now I'd like to talk about acceleration in terms of gravities, how many times Earth's gravity. And if you convert your numbers to number of Earth's gravities, you'll find the two Styrofoam balls received 60 and 90 gravities of Earth's acceleration. That's 60 or 90 times the gravity that we feel on earth is felt they BY these balls in the instant of impact.

[00:14:49.13] Now what we see is another graph. This shows a broader range of the accelerations these Styrofoam balls receive. And it gives us an idea of how many accelerations insects of varying size would receive. On the vertical axis, we have the acceleration in number of gravities. And on the horizontal axis, we have the mass of a raindrop divided by the mass of the insect.

[00:15:14.35] And so we see the range of these points, which we found in experiments, ranges from 50 to 300 times Earth's gravity. So depending on the size of the raindrop, mosquitoes receive up to 300 times Earth's gravity.

[00:15:28.38] That might seem like a lot, but you have to keep in mind the insect is very lightweight. It's only 1 milligram. And so 300 times Earth's gravity for a mosquito is simply 0.6 grams, or the weight of a feather.

[00:15:41.64] That means every time a mosquito's struck by these drops, it receives just the weight of a single feather sitting on top of it. And that's easily survival because the insects have very strong exoskeletons that allow them to support great loads.

[00:15:56.94] So to summarize, we've seen that mosquitoes are completely invincible to raindrops. Their mass is so low that when the drop hits them, the drop loses very little momentum. And as a result, we calculated the force, and the force was also very low, allowing the mosquitoes to survive these large impacts.

[00:16:19.50] In this video, you'll see what happens if a mosquito we're sitting on a twig. It's an important counter example to what we just saw. We see if a mosquito sits on a twig here the drop falls and imparts a much larger force. The force you see is about 10,000 mosquito weights. And it's many times higher than the force of a mosquito in free flight.

[00:16:42.48] Tai Chi is a slow and graceful martial art. Its philosophy is to not resist the opponent's force, but instead allow the opponent's force to go through the practitioner.

[00:16:59.70] Mosquitoes are nearly indestructible. And the reason is because they're much lighter than everyday objects. As a result, you can try to slap mosquito, and no matter how hard you punch or hit it, it will survive. In that way, mosquitoes are the ultimate Tai Chi master.

[00:17:20.63] The only way to truly kill a mosquito is either to hit them with a car or pin them between two surfaces like this. Only by doing so can you generate the 10,000 mosquito body weights necessary to kill them. In fact as we saw, raindrops apply 1/10 that force, and there's still able to easily survive and fly away.

[00:17:46.06] Thank you for spending time with me. Mosquitoes are 200 million years old. Yet the research and the activities you did today represent new work that was just published in 2012.

[00:17:59.29] You can do these kinds of things yourself. Just remember to look at the world around you and keep on asking questions. And don't forget even in this day of computers, rough, back of the envelope calculations and approximations still remain very useful. If you want to learn more, feel free to email me or check out my website. Thank you.

[00:18:31.05] Thank you for considering this module for your class. What we've seen today is a neat example of how some simple Newtonian physics can be applied to understanding the world around us.

[00:18:45.48] The students will have used conservation laws, conservation of linear momentum, conservation of angular momentum. And they'll use those with actual numbers, numbers in biology for how big insects are, and how big raindrops are.

[00:19:01.48] And they'll discover new things. For example, they'll have figured out that raindrops can apply forces that are survivable by these insects. So by using these things from the classroom and applying it to this new area of biology, they'll be able to figure out on their own some new principles.

[00:19:21.83] One other thing that students will learn is how to use real experiments and extract data from them. And that's a useful skill they'll use in their scientific careers. We had examples of high-speed video, where we've taken data from the video. And the students will have to think about what this data means and be able to calculate things based on this data.

[00:19:44.74] In order to do these things, the students will have to have a few prerequisites. They'll have to have taken high school physics, have an idea about what force and momentum are, know their units, have some facility with small and large numbers, be able to use scientific notation. A lot of the numbers we have are quite small. So they'll need to be able to write those easily.

[00:20:13.01] The other prerequisite that they'll need to have is an experience with the outside world. They'll have to know raindrops are so big, mosquitoes are so big. And to use some physical intuition. There's no calculus involved in this video, so the students should be able to have everything that they need from high school physics, and a little bit of knowledge of biology.

[00:20:36.05] I have a few suggestions for activities to do between the breaks. Some of the questions I've asked are quite open-ended. So for example, students can answer these by doing their own experiments. Someone can easily bring in a ball. You can have balls being struck together and measure their initial and final velocities. Sometimes having a visual aid, such as this, is important. This is the Georgia Tech mascot here, Buzz.

[00:21:05.07] We have this activity where we estimate the number of drops that are applied to the insect. As you'll see from the text file that I provide, that involves knowing the cross-sectional area of the insect and knowing the mass of a drop, and

then calculating how many of these drops fall into this space in order to achieve the rain intensity that you've given them. So I think it's helpful to have some physical props to be able to demonstrate these things.

[00:21:39.76] Another activity that I've taken advantage of in these videos is showing the high-speed videos and providing the graphs for how to extract the tracked position of the bug and the drop.

[00:21:53.90] The students can also do these on their own. There's free online tracking software that, in fact, we used in our lab that the students can input a video and then extract the position or the velocity of the tracked objects as a function of time. They're quite easy to use. They're just clickable interfaces. And the students might enjoy generating their own data.

[00:22:15.73] And if that's not available, of course, I provided the graphs in PDF format on the website. So you can also provide students with these graphs and have the students mark them up on their own as they do these exercises.

[00:22:29.09] If we're successful in this module, the students will have learned a few important skills. They'll be able to apply these physics concepts to a very different and strange context. And hopefully, they'll take that skill with them and apply them to other problems in the world around them. The students will have learned how to approximate answers, do quick, back-of-the-envelope calculations. And that's a very important skill for whatever field they'll go in.

[00:22:56.47] I hope you've enjoyed this video as much as I enjoyed making it. If you have any questions about how to do this, I'm happy to discuss things over email. Here's my email. And thanks again for watching.