AIAA AEROSPACE MICRO-LESSON

Easily digestible Aerospace Principles revealed for K-12 Students and Educators. These lessons will be sent on a bi-weekly basis and allow grade-level focused learning. - AIAA STEM K-12 Committee.

WINGTIP VORTICES AND AIRPLANE LIFT

Flying an airplane disturbs the air. The larger the airplane, the larger the disturbance. In this lesson, we discuss the disturbance and what people do about it.

Next Generation Science Standards (NGSS):

- Discipline: Physical Science.
- Crosscutting Concept: Energy and matter: Flows, cycles, and conservation.
- Science & Engineering Practice: Developing and using models.

GRADES K-2

NGSS: Matter and Its Interactions: Plan and conduct an investigation to describe and classify different kinds of materials by their observable properties.

NGSS: Motion and Stability: Forces and Interactions: Plan and conduct an investigation to compare the effects of different strengths or different directions of pushes and pulls on the motion of an object.

Up in the sky! It's a bird! No, it's a plane! No, it's a vortex? You have seen birds and know that birds fly. You've probably also seen planes, either at airports or flying high in the sky. Maybe you've even flown on one yourself. But what about a vortex? Do you know what a tornado is? Have you ever seen one on television? If you've seen a picture of a tornado, then you've seen an example of a large and powerful vortex. Vortices can be small too, like the little "dust devils" that you might see twirling leaves across a playground, or extremely large, like a hurricane.

Vortices (the plural form of "vortex"), whether small or large, are made up of a fluid—air or water, most commonly for us—spinning around. If you were to imagine a long stick at the center of the spinning air, then you'd have an idea of the imaginary line at the center of the vortex. So if weather patterns can create a big vortex like a tornado or a small vortex like a dust devil, then what else can form a vortex? One thing that can form a vortex is a sink or bathtub full of water going down the drain; another thing is an airplane wing.

GRADES K-2 (CONTINUED)

The shape of an airplane's wing causes an area of high pressure below and low pressure above. That is what gives the airplane its lift and helps it to fly. What is high pressure? It is a condition where lots of air molecules are pressed together and push hard against each other and against any solid surface; low pressure is a condition where there is more space between the molecules and they do not push so hard.

Think about how a balloon feels very soft when it is empty, then becomes more rigid or stiff as you fill it with air. You are forcing more molecules into that small space to fill the balloon; it is very crowded in there. The higher-pressure air inside the balloon pushes harder against the balloon's surface and makes it harder for you to push on it. What happens when you leave the neck of the balloon open? The molecules start pushing each other out of the balloon and moving back into the space outside the balloon that is not so crowded.

The same thing happens with the air molecules around an airplane's wings. The molecules that are crowded together under the wing begin pushing each other up into the space above the wing that is less crowded. That causes the air to swirl around the wingtips. Scientists study this by using smoke to make this swirling action easier to see. You can also see this in clouds that an airplane passes through. Here are some videos showing examples of vortices; look at them and see if you can tell how the molecules are moving and causing the vortex to spin.

- The wingtip vortex of a C-5A airplane
- Wingtip vortices shed from an airplane as it flies through a cloud
- Wingtip vortex examined in a smoke tunnel

Where else have you seen examples of a vortex? Have you seen other examples in the air? Have you seen any examples anywhere else? Look around you and watch for examples. You might see some in the air; you might also see some examples in water.

GRADES 3-5

NGSS: Matter and Its Interactions: Develop a model to describe that matter is made of particles too small to be seen.

GRADES 3-5 (CONTINUED)

NGSS: Motion and Stability: Forces and Interactions: Plan and conduct an investigation to provide evidence of the effects of balanced and unbalanced forces on the motion of an object.

Have you ever stuck your hand out the window while riding in a car and held it at a slant with the thumb side upwards? You feel the air flowing over your hand, pushing up on it. An airplane flies in exactly the same way, because of the air pushing up on its wings.

Isaac Newton's Third Law of Motion states that "every action has an equal and opposite reaction." This means that if you push on something, it pushes back on you with exactly the same amount of force but in exactly the opposite direction.

Now apply this law to an airplane wing. The wing works because the air under it has higher pressure than the air above it; the difference in pressure results in a net lift force upward on the wing. In short, the air is pushing up on the wing. But by Newton's Third Law, the wing is pushing down on the air. Behind an airplane, there is a region of disturbed air which is flowing downward; this is called "downwash." There are many videos available on the internet showing downwash; here is a short one.

Now think for a minute about how air flows. It will always flow from a region of higher pressure to a region of lower pressure. With a wing, there is higher-pressure air beneath it and lower-pressure air above it; the wing pushes on the air, turning it downward. The air will flow from the high-pressure region beneath the wing to the low-pressure region above the wing. One direction in which this flow happens is around the wingtip. This creates a vortex, like a miniature tornado, that the main flow over the wing then pushes downstream. A picture of a vortex caused by an airplane flying through a cloud of smoke is shown at the right.

GRADES 6-8

NGSS: Matter and Its Interactions: Develop a model that predicts and describes changes in particle motion, temperature, and state of a pure substance when thermal energy is added or removed.

The presence of vortices behind the wingtips of aircraft has been known for as long as airplanes have flown. These vortices started to become serious problems, however, with the advent of much larger airplanes in the 1950s and 1960s. The National Air and Space Administration (NASA), as part of its "Air" research, ran a series of tests in which airplanes flew past a tower with smoke generators at different heights. The airplanes would fly past on the upwind side of the tower, allowing the natural wind to convect the wingtip vortices past the tower and its smoke generators. The resulting paths of the smoke trails showed the wingtip vortices quite spectacularly. One video shows an L-1011 airliner flying past such a tower; another video shows the C-5 military transport aircraft flying past a tower. In these videos, the second vortex is much more easily seen than the first because it causes the smoke trails to move upwind relative to the main flow.

When the relative humidity of air is near 100 percent, the air is holding almost as much water vapor as it can. We call this state "saturated." If the pressure or temperature of the air decreases, the air cannot hold as much water vapor and the excess condenses out into fog. If the air pressure or temperature increases again, the water will go back into vapor form and the fog will disappear.

This phenomenon applies to airplanes in two ways. First, as air flows over the top of a wing, its pressure decreases and the temperature also decreases. If the air was nearly saturated upstream of the airplane, water vapor will condense out of the air as it flows over the top of the wing and create fog above the wing and nowhere else. Then as the air passes the wing and regains its pressure and temperature, the fog disappears. An internet video of airliners landing in humid weather shows this phenomenon very well.

The second effect of the condensation of water vapor is to make vortices visible. As the air swirls around in a vortex, the centrifugal force reduces the pressure at the core of the vortex. (This is the same effect that causes the atmospheric pressure to be so low in the eye of a hurricane and is also why the water surface at the center of a vortex in a bathtub drain is lower than the water around it.) Again the temperature at the vortex core is reduced along with the pressure and if the air is nearly saturated with water vapor, some of the

Grades 6-8 (continued)

water vapor will condense into a fog and make the vortex core visible. The video linked to at the end of the previous paragraph shows the vortex condensation clearly on the first and fourth airplanes landing.

Another video also shows the vortices coming off of aircraft wings.

We should note that the vortices do not always come off of the tips of the wings. Any place that there is a sideways-facing edge on a wing, there is the possibility of creating a vortex. On one side of the edge, the solidity of the wing is forcing the air to flow downward; on the other side of the edge, the air is flowing more-or-less directly downstream. The difference in the flow directions creates the vortex. On a real wing, this happens when high-lift flaps are extended at take-off and landing.

Grades 9-12

NGSS: Motion and Stability: Forces and Interactions: Analyze data to support the claim that Newton's second law of motion describes the mathematical relationship among the net force on a macroscopic object, its mass, and its acceleration.

Wingtip vortices do not affect only the air behind the airplane that generates them. The lift from the airplane wing creates downwash which changes the angle of the incoming flow at the horizontal tail stabilizer. This changes the net angle of attack of the horizontal tail, making it less effective than it would be without the wing present. And it is not just the horizontal tail that is affected; the downwash affects the wing itself, bringing air above the wing downwards and reducing the wing's effective angle of attack. In addition to reducing the lift force from the wing and horizontal tail, this downwash also adds to their aerodynamic drag. This additional drag is called the "induced drag."

In recent years, aircraft manufacturers have taken to adding small vertical winglets to the tips of their wings. These winglets reduce the strength of the wingtip vortices; while the total amount of downwash (dictated by the airplane's mass and speed) remains the same, it is distributed more widely and its effects are less. This translates into a measurable reduction in the drag on the airplane, allowing for more efficient flight.

Let us estimate the strength of the downwash from an airliner. The Boeing 777-200 airliner has a mass of 247,000 kilograms, or 16,900 slugs (or 545,000 pounds, one slug—

GRADES 9-12 (CONTINUED)

abbreviated "sl"—being 32.174 pounds of mass). Its takeoff speed is around 80 m/s, or 270 ft/sec, and it cruises around 250 m/s, or 810 ft/sec, at an altitude in the neighborhood of 36,000 feet. We will assume—and this is an order-of-magnitude assumption—that the air that gets pushed downward by the wing will be in a square as wide and as high as the airliner's wingspan, which is about 60 meters or 200 feet. The density of air at sea level is 1.2 Kg/m^3, or 0.0024 sl/ft^3 and at 36,000 feet is 0.36 Kg/m^3 or 0.071 sl/ft^3.

With these figures in hand, it is possible to estimate the strength of the downwash behind an airliner. At takeoff, the air is pushing upward on the airliner with a force of about 2,400,000 Newtons or 545,000 pounds of force (one pound of force is one slug-foot-per-second-squared). By Isaac Newton's Third Law, the airliner is pushing downward on the air with exactly the same force. At takeoff, the airliner pushes about 60 × 60 × 80 cubic meters = 300,000 m^3 (200 × 200 × 270 cubic feet = 11,000,000 ft^3) downward in one second. At sea level density this comes to about 350,000 Kg (26,000 slugs or 830,000 pounds of mass) of air being pushed downward in one second. Since this air is being pushed downward with a force of 2,400,000 Newtons or 545,000 pounds of force, its change in speed is the force divided by the mass per unit time and comes to about six meters per second, or 20 feet per second. It should be repeated that this calculation depends on a very approximate guess on the amount of air disturbed. While this is a fairly stiff breeze, it is nothing destructive. There is a video on the internet showing the effects of downwash as a military transport airplane makes touch-and-go landings.

At cruising altitude, the process for estimating the air speed of the downwash is the same although the numbers are different. The mass of the airplane is a little less—it has burned off some fuel since takeoff—and it is moving faster through thinner air. If we assume a mass of 200,000 kilograms, we get a weight of about 2,000,000 Newtons. The volume of air that the airliner pushes down every second is about 60 × 60 × 250 cubic meters = 900,000 m^3 which, at an altitude of 36,000 feet, is about 320,000 Kg of air every second. Interestingly, the lower mass and higher speed of the airplane reduce the speed of the downwash by about the same amount that the lower density of the air at cruising altitude increases it, giving a downwash speed of about 6 meters per second again.

Sixty Years Ago in the Space Race:

February 5: The American Vanguard TV-3 Backup exploded less than a minute after liftoff in an attempt to launch a satellite into orbit.