EAE 001

Team #7

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Question 97: Why do fighter jets have different shaped wings than regular air planes?

Problem Statement, Importance of Problem - Spencer Cheng

From transporting passengers and cargo to evading radar detection and enemy aircraft, each type of plane is designed around a specific task to specialize in, which in turn affects many aspects of their designs, the most notable being the shapes of their wings. Before we go in depth for the reasonings for wing shape variations, we must first identify how they are different. Notable differences of design include the wing sweep angles, presence or absence of winglets, and airfoil composition.

The shape of the wing is the most critical aspect of the plane when it comes to design. The wing shape is crucial for many functions of a plane including generating lift at different speeds, maximum speeds the plane can reach, maximum payload of the plane, required runway for takeoff, surrounding airflow, fuel efficiency, and much more.

The importance of wing shape variance lies in the effectiveness of each part, different designs are more efficient for accomplishing certain tasks like saving fuel or achieving higher velocities.

Background Research - Caleb Yasaki

Wings of an aircraft typically contain a supercritical airfoil, along with some sort of flaps, ailerons, slats and spoilers. The objective of a commercial airplane is to provide a safe, comfortable environment to its passengers, thus their wings are shaped to provide fuel economy, speed, and stability while adhering to wing length of airport gates. Currently most commercial aircraft sport the traditional swept back, dihedral, wings with an option of wingtip devices attached on their ends. These wings are usually placed below the fuselage to decrease noise emission and improve stability, and easier access to maintenance and refueling. Swept wingcraft have poor low-speed performance which is why most commercial aircraft use flaps and slats for takeoff and landing to assist in generating enough lift for the heavy plane to take off. While swept wings are not the most efficient type of wing shape, it is the best for the airlines' purpose of almost constant uptime and maintenance.The Boeing 787 is made up of mostly composite materials, including the wings. The purpose of the 787 was to replace the 767 and provide a long haul, better fuel economy for non-stop flights. It has a 60m wingspan and 4,058ft^2 area with around 500,000LBS of maximum taxi and takeoff weight while engines provide 50,000-74,000 pounds of thrust. The wings have a high aspect ratio and contain pivot trailing edge flaps, raked wingtips, and a fly-by-wire system. The aircraft utilizes two engines and has created numerous trans-oceanic and continental commercial flight routes due to its fuel efficiency and range.

On the other hand, the F-22 Raptor has a low aspect ratio with clipped delta wings and a reverse sweep on the rear. It has a 44.5 foot wingspan and $840ft^2$ area with a 83,500 lb maximum takeoff weight while its engines provide 35,000 pounds of force. The purpose of the F-22 is to provide a high speed/altitude, stealth fighter that can fly undetected, outspeed and outmaneuver other aircraft. Vastly different from the swept wing configuration of the 787 in appearance, the delta wing suffers from high drag and flow separation making it inefficient at low speeds. It's performance and maneuverability at high speeds make it favorable for intercept aircraft like the F-22. In order to perform, the F-22 has more controllable surfaces on the surface of the wings, especially a large leading flap, which negates the high drag effects at low speed and allows the fighter to turn and roll at a greater angle. F-22 wings are mounted through the fuselage but do not hold the engines, which are located on the fuselage itself. Instead the F-22 can be mounted with fuel tanks and air to air missiles on the wings. The F-22 has an internal weapons bay, two engines, twin vertical stabilizers, aerodynamic design and radar absorbent material, which allows it to function as a high speed stealth fighter. As a downside of this highly capable fighter, maintenance costs are high per flight hour, which is contributed to the stealth system and avionics. Compared to the F-22 the 787 has higher fuel efficiency, lower cost, and higher flight time while the F-22 has higher speed, altitude, performance and combat capabilities.

Another limitation to wings are their manufacturing ability. Many high performance planes have a high manufacturing cost which includes specialty and hand-crafted parts or the wing. Therefore many military planes average in the couple 100's per plane and require a long maintenance time. Conversely commercial planes which need low maintenance time to ensure up-time and revenue, depends on easily manufacturable parts for each wing. Each plane has different drawbacks but each perform their function by the design of their aircraft.

Technical discussion - Jeffery Earle

To highlight why these aircraft need of different wings, we will compare certain aspects of both and discuss how they relate to their wings. The F-22 is an air superiority stealth fighter that is designed to engage enemy aircraft in air to air combat. The 787, as discussed above, is a commercial jet airplane designed to transport passengers and cargo over long distances. Clearly these objectives are very different, so naturally these aircraft will have very different designs.

The best place to start is to examine what is required for each wing. In all aircraft, the main purpose of wings is to generate lift, so we will look at the different ways lift is created. If we look at the lift equation, $L = C_L \frac{\rho v^2}{2} A$, we see that there are multiple variables that contribute to lift. In this equation, C_L represents the coefficient of lift, ρ equals the air density, v equals the velocity, and A equals the wing area. To generate enough lift to keep the aircraft aloft in straight and level flight, the product of these variables must equal the weight of the aircraft. This is where we can begin our evaluation of the F-22 and the 787. The F-22 has a maximum takeoff weight of 83,500 lbs, and the 787-9 has a maximum takeoff weight of 560,000 lbs. This means the the 787's wings need to consistently generate 6.7 times the lift generated by the wings of the F-22 Raptor. Looking at the controllable variables in the lift equation (velocity, area, and lift coefficient), we can see why the wings on the 787 are so large compared to those on the F-22; the larger wing area dramatically increases the generated lift. In fact, the 787, with a wing area of 4,058 ft^2, has 4.8 times the wing area of the F-22 Raptor (840 ft^2). This allows the 787 to lift the heavier loads it is designed to support.

Another factor that is important in creating adequate lift for the aircraft is the velocity at which the plane travels relative to the outside air. Looking at the lift equation, we can see that increasing the velocity of an airplane is the most effective way to increase lift (because *v* is squared). Since the 787 has to lift much more weight than the F-22, it needs to travel at a higher speed to maintain stable flight. The cruising speed for the 787 is mach .85, or 488 kts. While the F-22 is capable for flying *much* faster than this, with a supercruise capability of mach 1.82, or 1,210 kts, it does not need to do this to support its weight in straight and level flight. Therefore, the Raptor has significant amounts of excess lift available for when it needs it. This leads into a very important factor that the designers of the aircraft had to consider, especially those who worked on the F-22. While both planes need to be able to perform basic climbs, turns, and descents, the F-22, as a fighter, and needs to be much more agile and aggressive in its maneuvers than the 787 does. Air to air combat is a game of energy; both pilots need to use their aircraft's current and potential energy to the best of their ability to gain a superior position. We will leave how to best use this energy to fighter pilots and military strategists, but as engineers it is important to focus on giving the pilot the highest amount of potential and kinetic energy to work with at any given time.

This is where wing loading becomes very important. Wing loading is the mass of the aircraft divided by the wing area ($WL = W/A$). This gives a value that shows how much weight each square foot of the wing has to support. If we calculate this for the 787-9 at maximum takeoff weight, we see that the wing loading is equal to $\frac{560{,}000\ lbs}{4{,}058\ ft^2} \approx \frac{138\ lbs}{ft^2}$. Compare this to the wing loading of the F-22 Raptor at maximum gross takeoff weight, which is equal to $\frac{83{,}500\ lbs}{840\ ft^2} = \frac{99\ lbs}{ft^2}$. Keep in mind that these aircraft usually do not fly a maximum takeoff weight, so the typical value for both wing loads will be lower than this. Even so, it is apparent that each section of the wing on the F-22 bears much less of a load than any section of the wing on the 787 does. This higher wing loading on the 787 means that it needs to generate more lift per square foot, which we have already established above. This is done by getting up to a fast enough speed on the takeoff roll that lift exceeds weight. Since the F-22 has a lower wing loading, it does not need to achieve the same speed on the takeoff roll. Because the lower airspeed is required to keep the plane aloft, this means that any additional airspeed can be used by the pilot to engage in more aggressive maneuvers, like a steeper climb. A good climb rate is vital for fighter jets, so having a low wing load is typical for them. A low wing load is also very important in making sustained tight turns. When an aircraft rolls into a bank, a large amount of the lift generated by the wings is parallel to the horizon. To get into the turn, the pilot will pull back on the stick, causing the elevators to rotate up, the same way they do in a climb. Therefore, we can think of turning as essentially climbing around a circle. This means that the additional airspeed that is not required to make the turn can be used to make the turn more aggressive. Naturally, a fighter should be able to turn as quickly as possible, so this low wing loading is beneficial for the F-22.

While low wing loading seems to have many advantages over high wing loading, high wing loads come with other benefits that may better suit an aircraft's specific function. What is a desirable factor in the eyes of the Raptor designers is not necessarily important or relevant for the 787. For example, a commercial airliner does not need to maneuver as tightly as a fighter does, so there is no need to focus on it to the extent that the Raptor engineers did. In fact, many of the benefits of the F-22 come with negative side effects for an airliner. Low wing loading means that the wing is relatively big compared to the mass of the aircraft, which offers a larger area for turbulent air to act on. Therefore, a relatively smaller, highly loaded wing will provide less area for turbulence to act. It makes sense that passengers on a plane want as smooth a ride as possible, so therefore a high wing loading would be beneficial on an aircraft like the 787. In addition, because the size of the wing is smaller relative to the mass, there is also less drag created by the wings, which means that a high wing load is better for travelling at high speeds and is also more efficient. These are two of the main reasons that the 787 opted for a high wing loading. It is important to note that while the 787 has a larger wing area than the F-22 does, the wing area is smaller relative to the mass of the aircraft, so the wing loading is higher. If the 787 decided to increase its wing area by a variable amount, the wing loading would decrease proportionally and the aircraft would gain more of the characteristics found in a plane wing low wing loading.

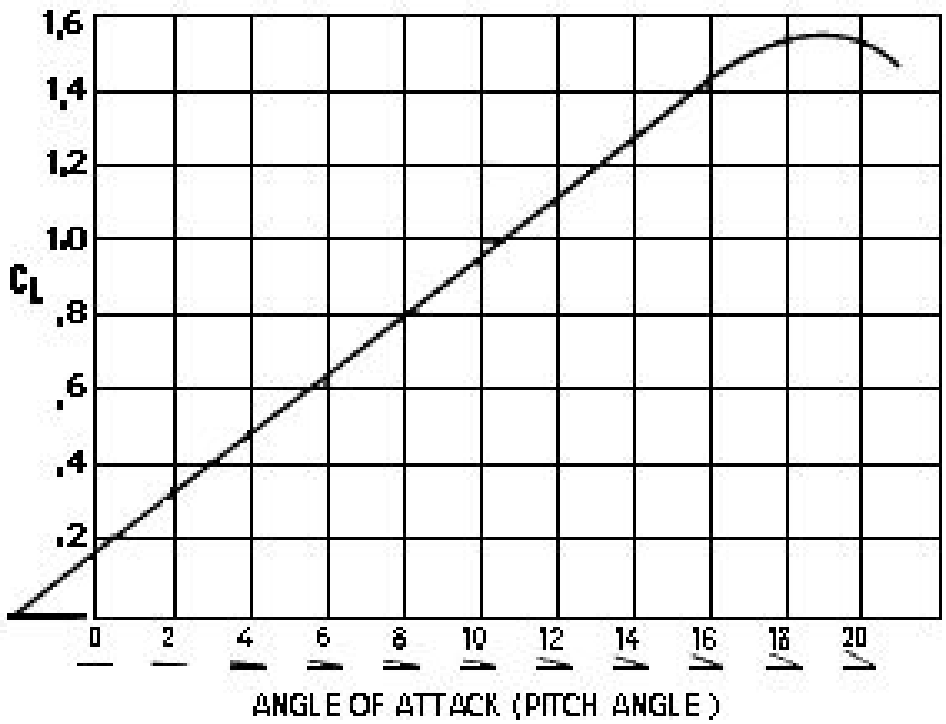
The final variable we will examine that can control lift is the lift coefficient. This is an experimental value that is unique to each aircraft and can be found using all of the other variables in the lift equation. It is essentially a simplifying variable that is result of several factors, including the shape of the wing, the wing twist, the airfoil, the flap settings, and the downwash. The lift coefficient is different at different angles of attack, and at a certain angle it reaches a maximum value. When that critical angle of attack is exceeded, the aircraft will stall and the coefficient of lift will decrease. This is important for any type of aircraft, as it helps determine its normal operating range. It is useful to think about the lift coefficient as a variable to make the product of all of the variables in the lift equation equal the lift actually created by the aircraft. This means that in straight and level flight, aircraft with a large amounts of excess lift due to other variables will have low lift coefficients, and that aircraft that are just barely managing to stay in stable flight will have high lift coefficients. Knowing this, it makes sense to say that engineers designing aggressive aircraft would want a lower lift coefficient, as it means that there is plenty of excess lift for the pilot to use for maneuvering, which is something discussed in the wing loading section above. For instance, the F-22 has a lift coefficient of .186 at mach 1.5, and has a max C_L of 2.6 at sea level. This shows that the aircraft is very capable of high angles of attack and steep turns; in fact, the Raptor has so much excess lift available to use that in straight and level flight, it would need to be nearly 14 times heavier than its actual weight before it would stall. All airplanes need to have a lower lift coefficient than they need to stay airborne, but the degree to which having a low C_L is a focus varies from plane to plane. For instance, fighters aim for very low lift coefficients, while passenger planes don't need to worry about this to the same extent. If we look ar the 787, which has a cruising lift coefficient of .508 at mach .85 and a takeoff C_L max of 1.91, we see that the Raptor has *much* more excess lift to work with than the 787 does, and that while still relatively low compared to its maximum lift coefficient, the cruising lift coefficient is significantly higher on the 787. This means that while the 787 can still climb, turn, and descend well, It cannot be as aggressive as the F-22 because it has less excess lift available.

Equations - Spencer Cheng

Modern Lift Equation: $L = C_L \frac{\rho v^2}{2} A$; where L = Lift, C_L = Lift coefficient, ρ = Air Density, v = aircraft velocity, and A = Wing Area

Wing Loading Equation: $WL = W/A$; where WL is the wing loading ratio of W = Aircraft mass and A = Wing Area

Plot - Below is a general plot, provided by NASA, comparing angle of attack to the lift coefficient. Though this plot may be stretched or shifted across the axes to properly represent each aircraft, this basic model holds the components which they all share: angles of constant increase, slowing increase, rapid decrease, and the critical/stalling angle. For this model, this aircraft would gain a lift coefficient linearly as the AoA is changing from about -2 to 15°. From then, as the angle of attack were to continue increasing, the plane would gain reduced lift coefficient as increasing the AoA too far reduced effectiveness. At about 19° on this graph, we have the critical/stalling angle where the max coefficient through AoA is achieved. Continuing to increase the AoA past the critical angle will put the aircraft into a stall, decreasing the lift coefficient.



Conclusion- Jeffery Earle

While the reasons that fighter jets have different wings than other aircraft are vast, they all originate from differences in the aircraft's mission. A fighter jet needs to be fast and maneuverable, while a passenger jet needs to comfortable, and efficient. This leads to differences in the size and shape of the wing. While many of the topics discussed above, like wing area, wing loading, and lift coefficient are all important factors in designing the best wing possible, hopefully it was demonstrated that there is no one right answer when it comes to creating the best wing. For every benefit a certain type of wing brings, it also brings a drawback, and the best solution usually lies somewhere in the middle. What wing is "best" is entirely relative to the function of the aircraft, which is why there are so many different wing designs. However, the importance of choosing the appropriate wing for an aircraft cannot be overstated. That is why it is critical as engineers to gain a strong understanding of what the plane is meant to do in the planning phase; the better defined the mission is, the better everyone can contribute to make the most successful plane possible.

Further Research-Spencer Cheng, Jeffery Earle, Caleb Yasaki

Future research could include an analysis of different types of airfoils and different aspects wing designs, focusing more on characteristics like wing sweep, twist, dihedral, and taper rather than wing area and wing loading. This would provide better insight into why certain aircraft use different shaped wings rather than simply why they use different sized wings.

Along with the development of new materials, the airfoil of aircraft can also change to provide more fuel, armaments or other devices that can be attached to wings. The airplane itself can also change if a better propulsion system is produced so that the wings will have to carry less weight. In an extreme case, or sometime further down in history the whole plane, including the wings, could designed around the new propulsion system, making an entire new standard for aeronautical engineering. Research around these technologies would be particularly interesting to explore in the future.

As the colonization of another planet, such as Mars, becomes more and more realistic, research must be done of how the laws of aerodynamics would function in a different atmosphere with different variables such as air composition and gravity. How would differences in the actual composition of the space we fly in effect how aircraft function? Flying aircraft at different conditions may introduce new phenomenon during flight or even new materials that may be lighter or sturdier that may be applied to future designs.

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