Comparative Analysis of Stall Phenomena in Fixed-Wing and Rotary Aircraft: Aerodynamic Principles, Causes, and Recovery Strategies

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Abstract

A stall is an aerodynamic phenomenon which is caused by a loss of lift on an aircraft when it exceeds its critical angle of attack (maximum angle between an aircraft's wing or airfoil and the oncoming airflow at which the wing can still produce lift). Stalls pose a significant risk across all aircraft types, including the following: fixed wing(such as commercial jets) and rotary. Stalls have been known for many aviation accidents and major research has been done on this topic in the last couple of decades with conclusive results. The paper outlines the fundamental principles of flight and the aerodynamics of the process of lift generation in both forms of aircraft. This paper also covers the mechanisms as well as in the concept of flight, including the calculations involving the aerodynamics and prediction of stalls. Additionally, the paper examines the unique characteristics and causes of stalls in fixed-wing aircraft. It explains and links factors such as angle of attack, airspeed, and bank angles to stalls. The paper also discusses the methods by which the stall limits can be predicted and discusses ways through which an aircraft can safely reverse the effects of a stall. The analysis extends to rotor-craft, highlighting the complexities introduced by rotating blades, torque effects, and the diverse rotor configurations in helicopters. Through this study, the paper aims to enhance understanding of the distinct challenges each type of aircraft faces regarding stalls. Knowledge and research on stalls have been crucial for improving training programs, better aircraft designs, and the implementation of more effective safety measures in aviation. This ultimately contributes to the reduction of stall-related accidents in aviation.

Keywords: Stall, Airfoil, Lift, Angle of Attack

1. Introduction

Understanding the phenomenon of stalls is crucial for ensuring safety and efficiency in aviation. When an aircraft's wings or rotor blades fail to produce sufficient lift, leading to a sudden loss of control, a stall occurs. This may even happen while the engine might be able to run normally.

Stalls have remained a concern in aviation since the day the first aircraft was built. In the past years, stalls have accounted for more than 25 % of aviation accidents [1]. This ongoing challenge makes the study of stalls essential for the development of effective safety measures.

This paper aims to explore the nature of stalls in both helicopters and airplanes, providing a detailed comparison of their causes, characteristics, and recovery procedures. By understanding the unique challenges each type of aircraft faces regarding stalls, we can develop better training programs, improve aircraft design, and implement more effective safety measures. Through this comparative analysis, we hope to contribute to the ongoing efforts to mitigate the risks associated with stalls and promote safer skies for all aviators.

2. Basics of flight

Airfoils are essential for flight, whether in fixed-wing aircraft or rotor-craft. Fixed wing aircraft have airfoils on their entire wings. rotor-crafts may have airfoils on their entire rotor-blade, on only a segment of

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it.

Airfoils help generate lift which is crucial in order to achieve flight. The airfoil operates on Bernoulli's Principle, where the airflow over the curved upper surface of the wing travels faster than the airflow below, creating a pressure difference higher on the bottom of the wing. The curved airfoil forces the air above the wing to move faster in order to meet the air below the wing, which has to cover less distance due to its flatter surface. The point at which the airflow above the wing and airflow below the wing gets divided is known as in the stagnation point.

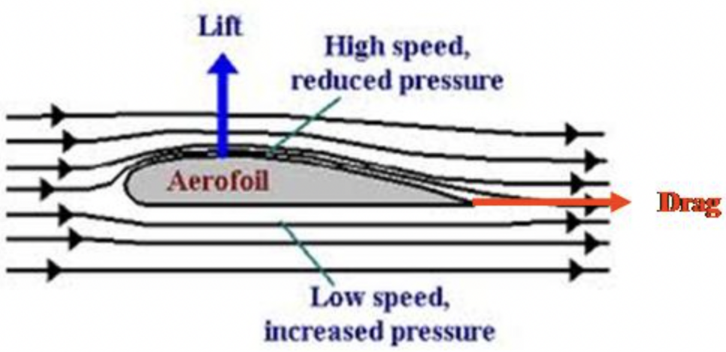

Figure 1: Parts of an airfoil and the speed and density of air flowing around the airfoil.[2]

The faster moving air above the wing, as a result, creates reduced pressure. This pressure difference results in an upward force known as lift. This relates to Bernoulli's principle:

$$P + \frac{1}{2}\rho v^2 + \rho g h = \text{constant}$$

Where:

- P : Static pressure (Pa)
- $\frac{1}{2}\rho v^2$: Dynamic pressure (Pa), where ρ is the fluid density (kg/m^3) and v is the flow velocity (m/s)
- $\rho g h$: Hydrostatic pressure (Pa), where g is the acceleration due to gravity (m/s^2) and h is the height above a reference point (m)

Bernoulli's principle describes the relationship between internal fluid pressure and fluid velocity. According to Bernoulli's equation, as in the speed of the air increases, the pressure of the air does too. It is a statement of the law of conservation of energy. It helps explain why an airfoil develops an aerodynamic force. According to Bernoulli's equation, P must be equal to half rho v squared. Due to the shape of the airfoil, the speed of air on top of the wing is moving faster, which increases the velocity in Bernoulli's equation. To balance this increase in value, the static pressure has to be reduced by the square root of the velocity in order for the equation to stay constant. To summarize, the higher velocity on the top of the airfoil causes the static pressure (the force pushing the aircraft toward the ground) to go down. Since the force pulling the aircraft down is reduced, the aircraft is able to achieve lift.

Through the Bernoulli's equation, we can derive the lift equation. While the Bernoulli's principle provides a theoretical explanation of how varying pressures are generated by airflow, the lift equation gives a practical calculation of the resulting force (lift) based on aerodynamic factors. The Bernoulli's equation focuses on fluid dynamics, the lift equation is an empirical formula used in real-world applications like aircraft design. The equation of the lift force (L) is as follows:

$$L = \frac{1}{2}\rho v^2 S C_L \tag{1}$$

where:

- L is the **lift force**. It is the upward force that opposes the downward force(weight) of the aircraft.
- ρ (rho) is the **air density**. It represents the mass per unit volume of the air. The density decreases as in the altitude increases, affecting lift.
- v is the **velocity** of the aircraft relative to the air. Specifically, it is the velocity of the air under the wings or blades.
- S is the **wing area** or the **surface area** of the airfoil. This is the area over which the lift is generated.
- C_L is the **coefficient of lift**. This is a dimensionless number that represents the lift characteristics of the airfoil.

The aerodynamic forces and moments acting on the aircraft are generated by the properties of air mass in which the craft is operating. These properties include the following:

- Static pressure (The pressure that is exerted by the air when it is not moving)
- Temperature
- Density
- Viscosity (The resistance of a fluid to a change in shape, or movement. It is considered the opposite of fluidity)

Bernoulli's Principle states that an increase in the velocity of a fluid (in this case, air) occurs simultaneously with a decrease in pressure. For aircraft wings, this principle explains how lift is generated: faster airflow over the curved top surface of the wing creates lower pressure compared to the slower airflow under the wing, resulting in lift.

3. Fixed-Wing Aircraft Stalls

Fixed wing aircraft- such as in the Boeing 737 and the Airbus A380- rely on the aerodynamic properties of their wings to generate lift, which is essential for flight. The primary component responsible for lift is the aerofoil, a wing's cross-sectional shape designed to optimize airflow and minimize drag.

In fixed-wing aircraft, the mixture of different air densities from fast moving, low density wind on the top, and slower moving, high density wing on the bottom creates drag- sometimes in the form of wingtip vortex- when they meet at the back of the wing. Key factors influencing lift include the wing's shape (camber), surface area, air density, speed, and the angle of attack (AoA)—the angle between the wing chord line and the oncoming airflow.

A the AoA increases, lift also increases up to a critical point. Beyond this critical angle, the airflow can no longer adhere smoothly to the wing's surface, causing a separation of the flow and resulting in a dramatic loss of lift, known as a stall. Understanding these principles is vital for predicting and preventing stalls, which are pivotal in maintaining the safety and performance of fixed-wing aircraft.

This graph illustrates the relationship between the coefficient of lift (Cl) and the angle of attack. As the AoA increases, the Cl also increases linearly up to a certain point. This point, known as Cl max, represents the maximum coefficient of lift achievable before the airflow begins to separate from the wing's surface. The AoA at which Cl max occurs is called the critical angle of attack. Beyond this point, any further increase in AoA results in a decrease in lift and the onset of a stall.

When a stall takes place on a fixed wing aircraft, it is mainly because the aircraft exceeds its critical angle of attack (AoA), the point at which the airflow over the wing can no longer remain smooth and begins

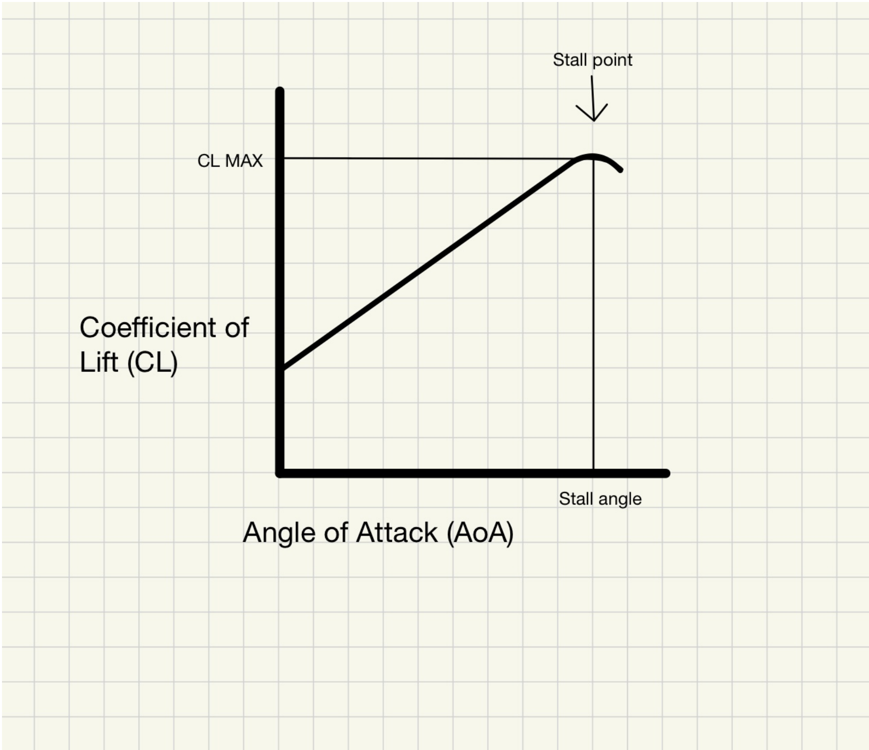

Figure 2: Cl Max graph

to separate from the surface, causing a significant loss of lift. The angle of incidence, which is the angle at which the wing is mounted to the fuselage, plays a critical role in how the aircraft generates lift. as in the aircraft slows down, the AoA must increase to maintain lift. However, if the angle becomes too steep, the airflow cannot adhere to the wing surface, leading to a stall. as in the angle of attack goes up, the aircraft requires more speed for the loss of lift. The most basic reason for such an occurrence is simply due to a high angle of attack due to pilot error. When a pilot pitches the nose of an aircraft higher than the critical angle, it can lead to a stall. However, there are more complicated reasons for a stall.

The speed or angle at which the aircraft stalls is not fixed for any aircraft. These factors vary with several factors:

- The aircraft's weight
- Center of gravity (CG)
- Load factor (G): (the ratio of the lift required to maintain level flight during a maneuver to the lift required during straight and level flight)
- The shape and structure of the aircraft

Changing the conditions of either factor during flight, requires the change of other factors to maintain the same amount of lift.

For instance, an increase in weight requires a higher AoA to produce the same amount of lift, bringing the wing closer to its critical AoA. Additionally, a forward CG position makes the aircraft nose-heavy, necessitating a higher AoA to maintain lift, thereby increasing the stall speed. The load factor, which increases during maneuvers such as turns, also raises the stall speed.

This can be explained by the following formula known as in the stall speed equation, which is derived from the lift equation.

For lift, we have

$$L = \frac{1}{2}\rho V^2 S C_L \tag{2}$$

and we also know that

$$W = mg \tag{3}$$

When a plane is in straight and level flight, we know the acceleration along the vertical (yaw) axis is zero. Therefore, $\sum F_y = 0$. If we assume that lift is acting in the positive direction and gravity is acting in the opposite direction, then we have $\sum F_y = L - W = L - mg = 0$ and thus $L = mg$. We can substitute this into eq. (1) to get

$$L = \frac{1}{2}\rho V^2 S C_L \tag{4}$$

$$mg = \frac{1}{2}\rho V^2 S C_L \tag{5}$$

$$2mg = \rho V^2 S C_L \tag{6}$$

$$V^2 = \frac{2mg}{\rho S C_L} \tag{7}$$

$$V = \sqrt{\frac{2mg}{\rho S C_L}} \tag{8}$$

Therefore, from eq. (5), we can find the velocity required at a given C_L to maintain straight and level flight. We know that stalls are defined when we are at the maximum C_L. Therefore, let's substitute that value into eq. (5) to get

$$V_s = \sqrt{\frac{2mg}{\rho S C_{L_{max}}}} \tag{9}$$

Looking at eq. (6), that is the velocity required at $C_{L_{max}}$ to maintain $L = mg$ which is our stall speed for a given configuration. From eq. (6), we can see how different configurations would affect our stall speed.

Where:

- V_s is the stall speed.
- m is the mass of the aircraft.
- g is the acceleration due to gravity.
- ρ is the air density.
- S is the wing area.
- $C_{L_{max}}$ is the maximum coefficient of lift.

This equation shows that:

1. The stall speed V_s increases with the square root of the aircraft's mass m. A heavier aircraft requires a higher speed to avoid stalling.
2. The stall speed decreases as air density ρ increases. This explains why aircraft stall at higher speeds at higher altitudes where the air is less dense.
3. A larger wing area S reduces the stall speed, which is why aircraft often use high-lift devices like flaps to increase effective wing area during takeoff and landing.

4. A higher maximum coefficient of lift $C_{L_{max}}$ reduces the stall speed. This is why aircraft use wing designs and high-lift devices to increase $C_{L_{max}}$.

Using this equation, we can calculate how the stall speed increases in a 45-degree banked turn due to the load factor. The load factor for a 45-degree bank can be calculated using the following formula:

$$n = \frac{1}{\cos(45°)} \approx 1.41 \tag{10}$$

This means the aircraft experiences 1.41 times the force of gravity, requiring 41% more lift to maintain level flight.

To account for the increased load factor in a turn, we can modify our stall speed equation:

$$V_s = \sqrt{\frac{2mgn}{\rho S C_{L_{max}}}} \tag{11}$$

The relationship between the stall speed in level flight (V_{s_0}) and the adjusted stall speed in a turn (V_s) is given by:

$$V_s = V_{s_0}\sqrt{n}$$

Where:

- V_{s_0} is the stall speed in level flight.
- n is the load factor.

Substituting the values:

$$V_s = V_{s_0}\sqrt{1.41} \approx 1.19 \times V_{s_0}$$

This means that the stall speed in a 45-degree banked turn is about 1.19 times the stall speed in level flight. For example, if the stall speed in level flight is 60 knots:

$$V_s = 60 \times 1.19 \approx 71.4 \text{ knots}$$

The result 71.4 knots indicates that the stall speed in a 45-degree banked turn is about 71.4 knots, compared to 60 knots in level flight. This is a 19% increase in stall speed, which is consistent with the result from the previous equation.

This information is helpful in preventing stalls since pilots can do the calculation and adjust the speed higher than the stall speed while banking. This higher speed can be achieved by increasing the flow of fuel into the engines, causing it to exert more thrust or through the activation of afterburners. However, when increasing speed is not an option (such as in the case of commercial jets), pilots need to get out of the bank in order to end the stall. To do this, sometimes ailerons (small hinged sections on the outboard portion of a wing) can be used to get the plane out of the bank. However, this is not always successful since using this method requires ailerons on one wing to move in the opposite direction as in the aileron on the other wing, as shown in this picture:

as in the ailerons are deflected, the AoA on each wing is changed. In this case, the left wing is flying at a lower AoA than the right wing. Adding too much deflection will push the right wing over the critical AoA, stalling the right wing and causing the plane to roll to the right. This then causes the left wing to also stall. The more common approach to get out of a banking stall is through the use of the rudder(part on the vertical wing of an aircraft that controls rotation about the vertical axis). By using the rudder, the plane yaws (moves left or right). During a bank, yawing allows the planes' nose to pitch at an angle opposite to the side at which it is banking. This yawing motion then causes the plane to roll to the side where it is yawing and effectively ending the stall.

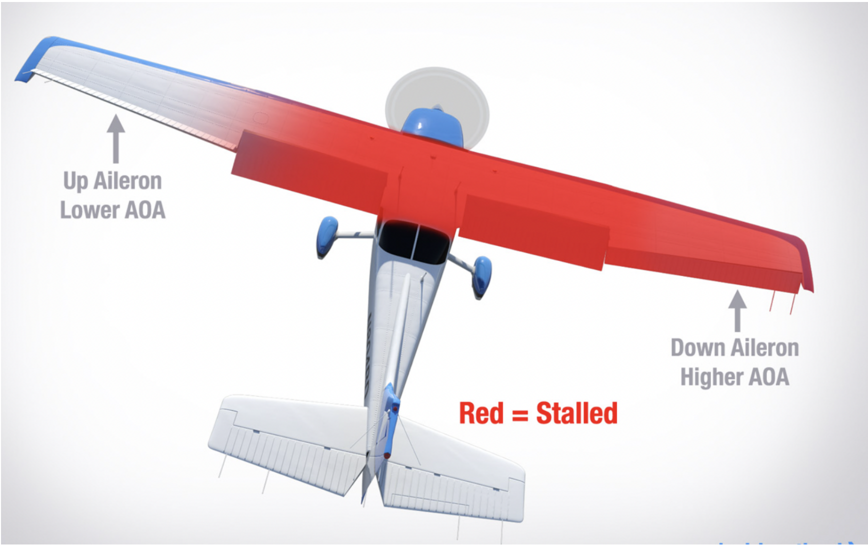

Figure 3: Use of ailerons to fix a banking stall. [3]

Another factor affecting stall limits is the deflection of slats(aerodynamic surfaces on the leading edge of an aircraft's wings, designed to improve lift at lower speeds, especially during takeoff and landing) on planes that are equipped with them. This allows an increase in the stall angle of attack. Due to the deployment of slats, airplanes are able to increase critical angle of attack. To understand this better, Bernoulli's equation can be used. Because of slats, air from the below the wing is able to pass through to the top part of the wing, speeding airflow on the top part of the wing. This keeps the wing in contact with the air for a longer period of time. By allowing air to flow through the gap and reattach smoothly to the wing, slats maintain higher airflow velocity over the wing, which is crucial for lift according to Bernoulli's Principle. The energized boundary layer helps the wing maintain lower pressure on the upper surface even at high angles of attack, preventing stall and maintaining lift.

Additionally, load factor doesn't affect the angle of attack, but instead, it affect its stall speed.

4. Rotor Aircraft Stalls

Unlike fixed wing aircraft that use thrust from engines attached to their body to propel themselves, rotor-crafts are lifted and propelled by one or more horizontal rotors, each rotor consisting of two or more rotor blades. The rotor blades on a helicopter provide lift without the requirement of it having to move forward. This gives rotor-crafts the ability for vertical take off and landings. The most common type of engine on rotor-crafts like helicopters is the turbo-shaft engine. This adaptation of the turbine engine provided a large amount of horsepower to the helicopter with a lower weight penalty than the previous piston engines.

The helicopter rotor consists of 3 main parts: mast, hub, and rotor blades. The mast, also known as in the rotor shaft, is a vertical component that connects the main rotor to the helicopter's transmission. It transfers the rotational energy from the engine (through the transmission) to the rotor blades. The engine powers the transmission, which turns the mast. as in the mast rotates, it causes the attached rotor hub and blades to spin. The mast's design must withstand the stresses of rotation and the aerodynamic forces acting on the rotor blades, since this is crucial for it to be able to produce lift. The hub is the central part of the rotor system where the rotor blades are attached. It serves as in the connection point for the blades and allows them to rotate and change pitch/angle to control lift and direction. The rotor blades are similar in function to the wings of an airplane, but rotate to create lift continuously. They are connected to the hub and spin when the hub is spun.

This image visualises the basic components of the rotor system.

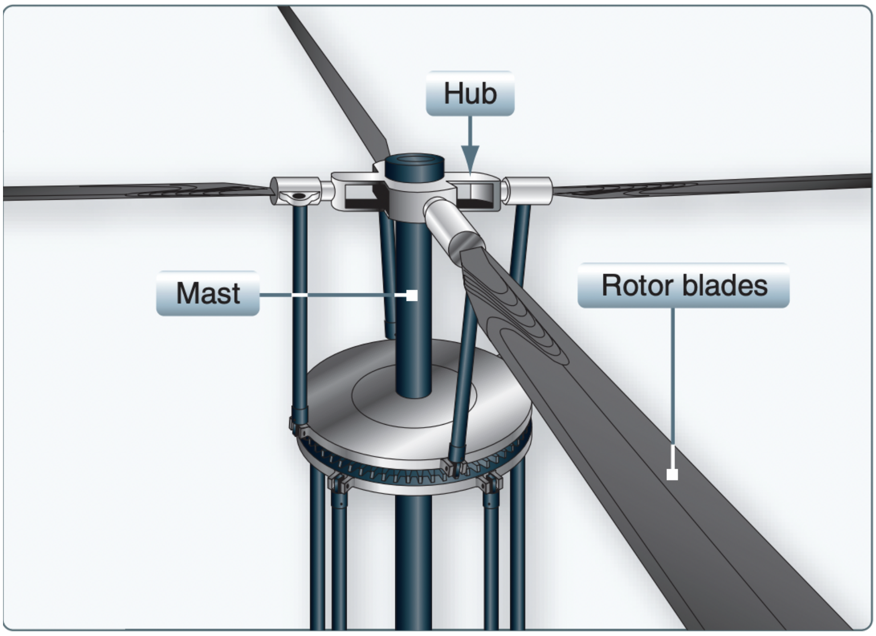

Figure 4: Basic components of the rotor system. [4]

In a single main rotor helicopter, the creation of torque as the engine turns the rotor, creates a torque effect that causes the body of the helicopter to turn in the opposite direction of the rotor. This is in relation to Newton's 3rd law of motion: Every action has an equal and opposite reaction.[5]To eliminate this effect, some sort of anti-torque control must be used with a sufficient margin of power available to allow the helicopter to maintain its heading and prevent the aircraft from moving unsteadily. This is accomplished through a variable pitch, anti-torque rotor or tail rotor. The tail rotor provides spinning force in the opposite direction, so the helicopter doesn't spin uncontrollably in one direction.

A helicopter operates on the gyroscope theory, which conceptualises on the kinetic energy of a spinning object. This is achieved by changing the pitch of the rotor blades, which then affects the angle of attack. By increasing the AoA on all of the blades, the helicopter achieves altitude. Decreasing AoA of all the blades reduces the altitude. The helicopter is able to change the AoA of a single blade during a specific part of its spin. For example, blades can achieve a 10 degree AoA during the back left portion of its spin, before going back to 8 degree like the other blades. By doing this, the blades push air back more than any other direction, causing the helicopter to move forward. This is important for flight according to gyroscope precession,

The lift generated by a helicopter is proportional to the square of its airspeed. as in the rotor moves, the advancing blade moves at higher velocities than the retreating blades. To make up for this difference in velocity, the retreating blade has to work in increasing angles of attack to make up for the increasing helicopter speed. It is understood that at some ratio (depending on the rotor-craft) of forward speed to rotational speed, the angle of attack on the retreating blade will reach a stall.

Stalls occur in helicopters when the rotor is unable to produce enough lift to keep the helicopter airborne. One of the main types of stalls in helicopters is the retreating blade stall. This type of stall can happen for a couple of reasons:

- The most common reason for a retreating blade stall is an excessively high forward airspeed. This happens when a helicopter exceeds the velocity never exceed. This is a speed released by the manufacturer which states that exceeding the speed can lead to consequences.

- Low rotor RPM is another reason for a retreating blade stall. To understand this better, we can use the lift equation. Velocity has an exponential effect on lift and drag. If the rotor slows down, there is a possibility of having high angles of attack at low rotor RPM's due to more drag being generated. This will lead to the helicopter reaching potential stall conditions sooner.

- Achieving too much forward cyclic by making the nose pitch down, causing the altitude to drop and increasing airspeed. The forward cyclic moves the center of gravity(COG) forward. This leads to the pitch being increased in the left side of the rotor spin. This agitates the rotor with an even higher angle of attack. However, this is accompanied by other factors such as airspeed to lead to a stall.
- There are other contributors that work along with the factors listed above to cause stalls. This includes high gross weights, high altitudes, ice buildup on rotor blades or a high G-loading, likely through a bank.

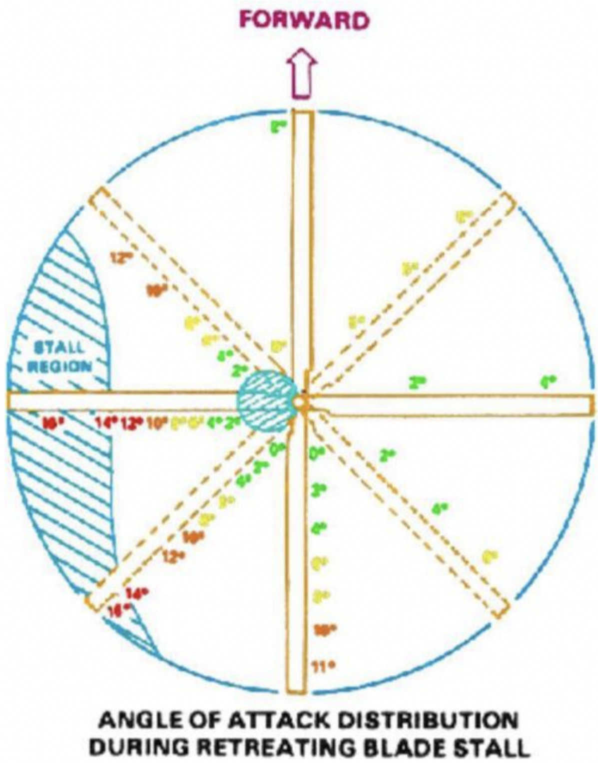

Figure 5: What a retreating blade stall looks like. [6]

5. Analysis

Stalls on fixed wing aircraft and rotor-crafts have many similarities since both types of aircraft work on similar principles. Stalls on

Stalls in both kinds of aircraft have similar symptoms, with the most common being vibration. As discussed previously, stalls happen when airflow over the wing is disrupted. Thus, causing the air to become turbulent after coming in contact with the wing and increasing drag. This turbulent airflow then hits other parts of the aircraft, which leads to vibrations. In the case of fixed wing air-crafts, these turbulent airflows would repeatedly touch the surface on the wing, leading to vibrations. In older fixed-wing air-crafts(when all controls were manual), when this turbulent airflow would hit the ailerons, it would cause them to vibrate. This would lead to the controls of the pilot to shake as well. This method- known as in the stick shakerwould alert the pilot of a stall. On a rotor-craft, a stalls first symptoms will be a roughness on the rotor[2] which is accompanied by a low frequency vibration. Similar to fixed-wing air-crafts, the turbulent air from the rotor will hit other parts of the helicopter causing vibrations.

In both types of aircraft, a stall will present itself with a wing drop. On fixed wing aircraft, a low speed accompanied with a high bank angle, exceeding the critical angle can cause a stall on either both wings or on a single wing. The stalling wing on the fixed wing aircraft will lose lift, causing it to drop. If not dealt with in the proper method, this could result in a dangerous roll on the stalling side. Fixed wing aircraft experience sudden altitude drop in stalls, sometimes along with a dive. In most cases, these stalls are recoverable. For most cases, this means increasing airspeed and reducing AoA. Additionally, though it is not a aerodynamic flaw, accidental activation of thrust reversers (a device used on aircraft to redirect the engine's thrust forward, rather than backward, to help slow the aircraft down after landing) can lead to a dangerous stall. The only recovery method for such a stall is to de-activate the thrust reverser. In rotor-crafts, a similar situation occurs when it encounters a retreating blade stall. In a retreating blade stall, only the retreating side of the blade experiences a stall. The retreating side continues to provide lift. Depending on the severity of the stall, the helicopter will lose lift on the stalling side and begin to bank towards that side, followed by a pitch of the nose. This bank is most likely to occur on the retreating side of the spin.

6. Conclusion

This comparative analysis of stall phenomena in fixed-wing and rotary aircraft highlights the critical importance of understanding aerodynamic principles in aviation safety. While both types of aircraft share fundamental concepts of lift generation and stall occurrence, they each present unique challenges and characteristics. Fixed-wing aircraft primarily contend with angle of attack and airspeed management, while rotary aircraft face additional complexities due to their rotating blade systems and the phenomenon of retreating blade stall. The study of stalls, including their causes, symptoms, and recovery strategies, have been crucial for improving pilot training, enhancing aircraft design, and developing more effective safety measures. This ongoing pursuit of knowledge and innovation in aerodynamics will undoubtedly contribute to the continued progress and safety of the aviation industry.

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