

# Compressor Stall-It's Growth and Effects on Engine Performance

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**Abstract** - In today's world, most of the commercial aircrafts and the military aircrafts are powered by the gas turbine engines or most known as jet engines. The jet engines are designed to produce maximum efficiency at the given amount of the air intake and produces a desirable amount of thrust to move the aircraft at a desirable Mach number. Most of the jet engines utilizes axial flow compressors to compress the incoming air to a very high pressure suitable for the entry to the combustor chamber. These axial flow compressors have a smaller diameter, light in weight, and have a greater capability to produce high compression ratios. One main disadvantage of these compressors is the susceptibility to the Foreign Object Damage (FOD) which can lead to disastrous effects.

The main highlight of this report is to the study the effects of these FOD leading to the Compressor Stall. This generation of compressor stall begins with the disturbance in the angle of attack on the rotor blades which increases and effects the other neighboring blades and then lead to the formation of the Rotating Stall.

In the report, main highlight is given on the Compressor Rotating Stall, which with increase in time can lead to the final failure of the compressor function and is known as the Compressor Surge.

## 1. Compressor Stall

The axial-flow compressors used in the jet engines are used to compress the air to a high pressure using the axial flow of the incoming ambient air. The air gets compressed by series of rotating blades called rotors and series of stationary vanes called stators. Multiple stage compressor is used for high performance output. The pressure loss in the axial flow compressors is low and thus allows multi staging. The mass flow rate is extremely high (>100kg/s). The axial-flow compressors used in modern jet engines are more prone to compressor stall and compressor surge. The compressor stall occurs when the flow on the suction surface of the rotor blades gets disrupted. This disruption of flow can result from ingestion of FOD.

The stall inception occurs on the single blade when the flow over it gets disturbed. This disturbed flow also affects the relative flow angle ( $\beta$ ) over the other blades. An increase in angle of attack would result in the air flow separation leading to generation of stalling phenomenon. The stalled airflow then propagates in the direction opposite to the blade rotation and results in the formation of the rotating stall. The stall cells are formed and perform to and fro motion at a single place.

These stall cells formed can result in the flow reversal and result in the stall to propagate in the opposite direction. This phenomenon is known as rotating stall. The rotating stall can severely damage the compressor performance as it goes on increasing. The stall cells block the actual flow path of the air and result in the flow separation from the blade tips due to which adverse pressure gradient is generated. The rotating stall covers entire compressor annulus in which all the rotor blades stall if they are not controlled.

The compressor surge is the global stall occurrence phenomena where the entire compressor annulus gets completely choked due to many stall cells formation. Compressor surge is the last stage which can result in severe engine damage and the capability of the engine to produce thrust. The surging phenomena can occur both during-take off and cruise. The incoming flow get completely reversed and no amount of air passes through the compressors. This is a critical situation as compressor would not be able to compress the air suitable for entry to the combustor chamber. This results in the loud bang and is followed by violent engine vibration. The phenomena of surging can be more clearly explained using compressor performance map.

### 1.1 Stalling Phenomenon

During the normal operation of the compressor, there may be possibility of sudden drop in the efficiency of the compressor and engine may not be able to produce enough thrust. These adversities can lead to the drastic effects and are established with the phenomena called Compressor Stall.

In the case of the isolated compressor rotor airfoil blades, the phenomena of the compressor stall arise when the excessive air flow distortion takes place over the airfoil suction surface or the upper surface.

When an axial flow compressor is running at quite a lower speed than the design point, then the result would be such that the axial velocity values would be incorrect and would not contribute to the efficient air flow over the rotor blades and then can cause the blade stalling and in the adverse situation leading to final failure known as compressor surge which would be discussed later in the report.

There are basically 3 distinct types of the stall phenomena occur in the axial flow compressors: -

1. Individual Blade Stall
2. Rotating Stall (Stall Cells Formation)
3. Compressor Surge (Final Failure)

We know that the aerofoil stalls when the pressure distribution is disturbed or on other words, the flow separation occurs on the top surface of the airfoil section. If such thing happens, the pilot will have to apply adequate stick force and pedal force to overcome the turbulence generated.

The compressor stall is more or less the same phenomena. Here, each stage consists of several rotating rotors and stationary stators, and the stalling occurs when the airflow distribution occurs on the suction side of the airfoil and not on the pressure side.

If this stalling occurs in the compressor section, it could disturb the compressor performance and thereby reduce the thrust generated and to control this, various methods are adopted which will be discussed in the text.

### 1.2 Individual Blade Stall

This is the basic stall initiation phenomena. In this the flow separation usually occurs on the single airfoil (rotor) blade of a stage around the compressor annulus area and the stall occurs. The main point to be noted is that the stall propagation phenomena does not occurs at this stage. The situation under which this stall arises will be unknown initially and not observable by the pilots.

We know that the stalling takes place on the upper surface of the airfoil and the stalling occurs when there is some kind of obstruction in the flow and the air gets accelerated towards the leading edge and which on increasing causes a reduction in the pressure gradient.

As the air flows towards the maximum 't/c' ratio of the airfoil, the velocity of the air starts getting reduced and thereby causing the pressure to get increased. This is the positive pressure gradient which starts to increase.

This pressure generated is quite unstable. Now, this unstable pressure generated would lead to flow separation on the suction side and may also cause the reversing of flow on the top surface past the separation point.

Now, as the angle of attack increases, this flow separation will go on increasing and will move forward towards the LE. At a certain angle, there will be a situation where the airflow gets completely separated of the airfoil (rotor), disturbing the actual flow phenomena and this process is known as the stalling of the compressor blades.

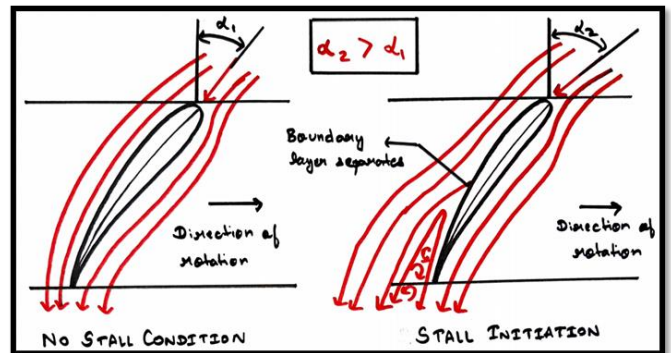


Fig 1 : Stall Initiation in Rotor

### 1.3 Rotating Stall

In the compressors, a single blade stalling can arise due to many potential reasons out of which one is the micro-disturbance going with the airflow in the compressor. This disturbance is usually termed as the 'local phenomena'.

A Rotating Stall is a phenomenon which originates when the airflow forms large stall zones covering several blade passages. This rotating stall is also known as the propagating stall as the stall propagates along the direction of the rotation and also at some considerable airspeed. These stall zones formed can vary at different stages and at each stage stall phenomena would occur.

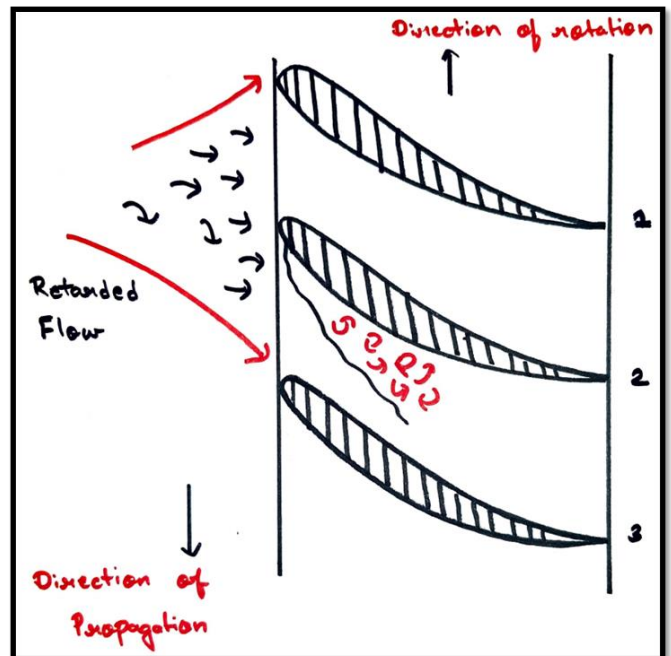


Fig 2 : Propagating Stall in Blade Cascade

Due to the flow perturbation, the air flow separation firstly takes place at the blade number 2 as shown in Fig and it reaches to the stall condition before the other blades due to the flow separation.

This stalling at the blade 2 is not capable to produce sufficient amount of the pressure to maintain a good flow over it, thereby resulting in the blockage of the effective flow and a zone of reduced flow gets developed.

This retarded flow at the blade 2 would tend to affect the flow over the adjacent blades 1 and 3. The deviated or retarded flow over this blade would tend to divert the flow around it leading to increased angle of attack on the blade 3 and reduced angle of attack over the blade 1.

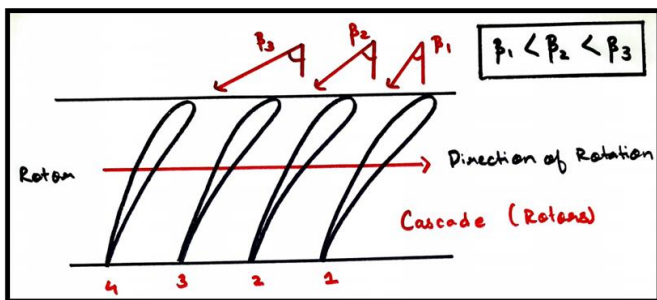


Fig 3 : Rotating Stall

This stall generated at blade 2 propagates downwards as shown and moves at about half of the rotor rotational speed. The distorted flow moves from the pressure side to the suction side in the opposite direction to blade rotation covering several blade passages in the compressor annulus.

The unwanted stalling results in the increase of the boundary layer formation and reduces the effective flow transmission area.

This adverse phenomenon is known as the flow spilling where the incoming air flows just travels randomly due to large boundary layer, and this propagates to other blades also leading to rotating stall in the annulus region.

As discussed above, the increase and decrease in the angle of attacks in the blades adjacent to the blade 2 will result in generation stall first at the blade 3 then at blade 1. This process can continue over a long period and can result in the formation of stalled channel or the stall cells during the rotating stall process and will act in the opposite direction to that of the blade rotation.

The point to be noted is the compressor operating with a rotating stall condition will still be able to generate compressed air to the combustion chamber, but its effectiveness will be reduced.

During the rotating stall, a large number of aerofoils experience flow disturbance and these stalled aerofoils create packets of relatively stagnant air (or stall cells), which starts to rotate around the circumference of the compressor and blocking the flow instead to moving along with the rotor blades.

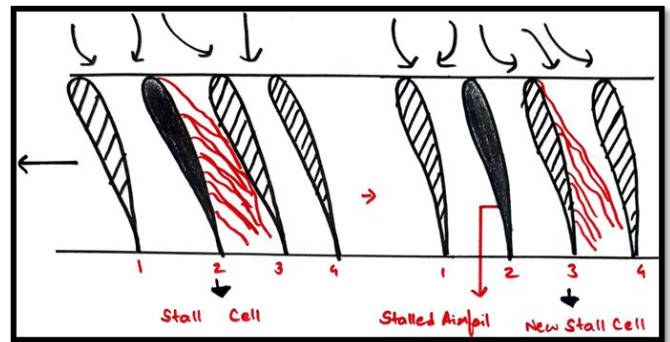


Fig 4 : Stall Cells Formation in Rotating Stall

Most of the researchers and experimentalists have proved from their experiments that pressure fluctuations caused by the rotating stalls were less downstream of the rotor than upstream and the minimum reduction across the rotor was 40% with rotor blades and 75% with stator blades.

It was also clear from the experiments that the stator blades decreased the formation of the stall cells leading to rotating stalls as their function is to guide the air for the next stage.

If the compressor rotating stall is not controlled, it can cover the entire compressor annulus and finally, the efficiency of the compressor would get decreased to generate sufficient amount of the compressed air and can lead to the final failure known as Compressor Surge.

#### 1.4 Factors Which Originate Compressor Stall

1. The main reason of the flow hindrance arises due to the Foreign Object Damage (FOD) including bird strike.
2. The in-flight ice formation is also a major concern leading to the stall formation in the blades.
3. There are certainties where the compressor blade may be left uncleaned during the maintenance, dust may get collected on the blades affecting the streamline design, or the worn out or contaminated compressor blades can lead to abrupt flow distortion during the actual operation.
4. Compressor stall may also occur when the aircraft operates outside the normal operating region provided by the V-n diagram (flight envelope), which is done during extreme flight maneuvers.



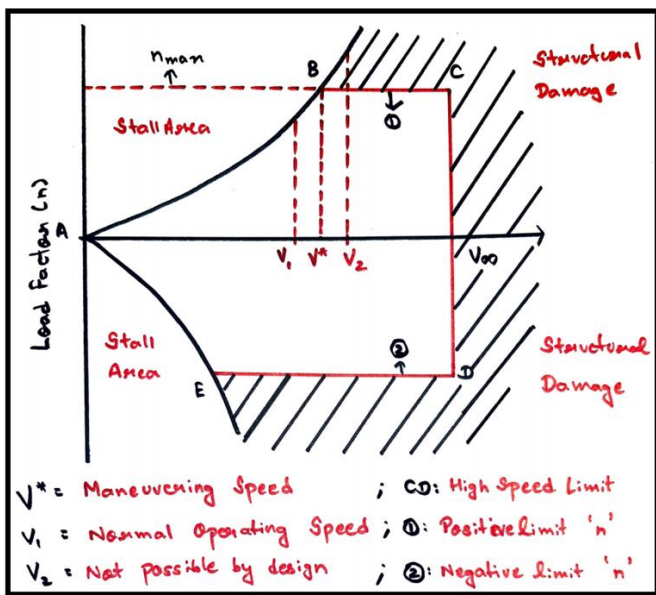


Fig 5 : V-n Diagram

- Improper handling of the engine can also be a reason for the compressor stall.

## 2. Compressor Surge

A compressor surge is defined as the final stage of compressor stall. In other words, it is the 'global stall' and is the rotor phenomena where all the stages consisting of the rotors and stators undergo stalling. It is a very critical situation and is almost uncontrollable by the pilots.

Just as the rotating stall increases and reach to the situation, where the flow completely blocks or chokes, compressor surge occurs where the engine completely fails and can lead to disastrous effects.

During the compressor surge phenomena, the rotor gets completely choked i.e., there will be no effective flow passing uniformly over any compressor rotor blade. Surge of blades becomes more dangerous when the flow gets reversed during the stall.

The flow can get reversed due to the to and fro motion of the air in the stall cells, which will completely block the path for the new incoming air, thereby decreasing the compression pressure ratio and eventually it may fail as the efficiency drops below the design operating point. The amount of oxygen would not be sufficient to compress the air and if no adequate high-pressure air is provided to the combustor chamber, it can lead to combustor-induced flame shoot out from the back of the engine and even from the front if the flow gets reversed.

It may be noticed that during the stall condition the average flow may travel until complete choking (blockage) of the flow takes place, but during the compressor surging, the flow rate can abruptly pulse (in order of milliseconds) and can become so violent that it may reverse the flow. This instantaneous

flow reversal may be observed by the pilots as a loud 'bang' from the engine.

If the flame starts coming out from the nozzle or sometimes from the inlet, then the compressor efficiency drops drastically and thrust generated will be reduced. Hence, if thrust gets reduced, the lift on the aircraft will automatically reduce due to disturbance in the pressure distribution and there is a possibility of crash if the situation is not monitored carefully.

This phenomena of burning or release of large flames occurrences is called choking and is highly unstable.



Fig 6 : Su-57 Suffering from a Compressor Stall



Fig 7 : Flame Out Observed from the Cabin Window on Boeing 777

This choking condition becomes more serious when the flow starts to again flow through the compressor itself and then again re-choking occurs simultaneously. This process can occur rapidly within a fraction of seconds, seriously damaging the engine and cause large vibration which can be felt by the pilots and the passengers sitting inside.

Moreover, due to the flame out, the blades of the rotor get damaged and excessive wearing takes place due to surge. The normal circulation of the airflow would stop due to flow blockage and the to and fro motion and causing the flames to go on increasing. The flow reversal is very dangerous as discussed above.

In various contexts, the compressor surge is also known as the 'axi-symmetric stall' or the 'pressure surge' because surge is the disturbance taking place in the axial direction and the pressure distribution over the top surface of the airfoil gets

completely disrupted, there is complete breakdown of the efficient compression phenomena due to the stall cells formation and their propagation.

There is some possibility that the compressor will try to recover itself to the normal flow once the total pressure ratio reach to a desirable stage in the annulus region and the stages can sustain the flow. But the adverse stall and the compressor surge may again arise if any stall cells remain in the region and the stable airflow will again get choked and will result in surging and thereby affection the compression efficiency again.

In the compressor annulus region during the surging stage, the 'self-reproducing' stall is very dangerous leading to 'air locked-in' and will leave the engine to produce very large vibrations causing an engine turbo-wear damage.

Finally, due to the large vibrations, the rotor and the stator blades may get completely damaged if the surging is not controlled and may result in the complete destruction of the engine components due to breaking of the stages blades and then their ingestion into the combustion chamber.

The surging can take place in a fraction of second and is very difficult to control as during surging and flame-released from the nozzle, the ability of engine to generate sufficient amount of thrust will get reduced and there will be not effective thrust generated from that engine. In that situation, the wind with reduced thrust will produce an adverse yawing moment which the pilot has to tackle using the rudder pedals.

If both the engines suffer compressor surge and there is no such possibility of recovery, then the aircraft will sink, and the pilot must do emergency landing on the best medium available.

### 3. Compressor Performance and Surge Cycle

The surging cycle is represented on the typical 'compressor map'.

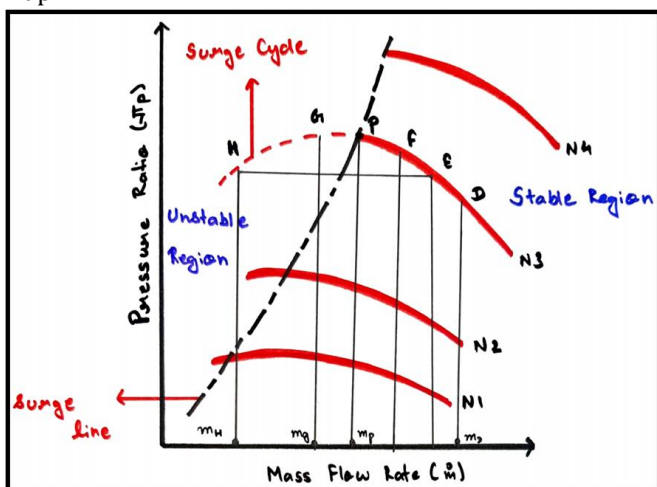


Fig 8 : Compressor Performance Map

The compressor map is the plot between 'total pressure ratio' and the 'mass flow rate' inside the compressor.

Above is the typical plot for an axial-flow compressor performance represented by the compressor map.

In the plot, the surge is the line which is formed by joining the specific points or the surge points calculated at different rpm.

The surge line is basically separation between then stable region and the unstable region.

The design allows the compressors to work most efficiently in the stable region.

In the unstable region, the efficiency drops drastically, leading to adverse phenomena as discussed below.

### 3.1 Surge Cycle

The plot represented in fig 8. represents a line called the surge cycle occurring at N3.

If there exist a situation of the compressor stall, where the compressor may operate in the unstable region where it crosses the surge line, the compressor will still be able to deliver a certain amount of air to the rotors and the stationary stator blades. When the compressor operates in the unstable region then, the higher delivery of pressure will occur at a particular rpm and this adverse pressure increase is undesirable for the compressors and can cause blockage due to the formation of the stall cells. Compressors are itself designed to increase the pressure level but with a significant small increase in the pressure at each stage. But the sudden increase in the pressure will affect the compression efficiency and therefore it is not advisable to operate the engine in the unstable region.

Let us consider that the compressor's initial operating location is defined by D in the fig. at a given rpm N3. On this particular rpm, if the mass flow rate gets decreased then the pressure rise will be very high int eh compressor region. This pressure rise will go on increasing as the stall propagates and will reach the maximum point which is denote by the point P.

This point P is known as the 'Surge Point'. On further moving to the left on the surge cycle, the compressor pressure will then begin to decrease as the mass flow rate decreases as the compressor has entered the surge stage due to large formation of the stall cells.

A situation arises when the flow rate abruptly pulses and due to the rapid 'to and fro' motion the flow will get reversed and completely blocking the normal air flow. The flow will break down and lead to choked flow.

From the above compressor map, it is clear that there is a valve installed to control the mass flow rate at lower value 'G'.

The compressor works in the normal operating region say at point 'E'. Now, if the self-recovery and stalling repeats, so the path 'E-F-P-G-E' will act continuously leading to the breakdown of the flow.

The most crucial situation arises when this mass flow rate further decreased, and the pressure starts to decrease in the compressor annulus say at point 'H'.

The rapid increase and decrease in the pressure will cause flow reversal and completely choke the airflow which completely stops the air circulation. Therefore, the repetition of the cycle 'E-F-P-G-H-E' is known as the 'Surge Cycle'.

This phenomenon of surging will cause large vibrations in the whole engine, affects the compressor performance as it crosses the surge line and lead to the mechanical failure.

Based on the experiments and incidents happened it was concluded that all the above-mentioned cycles occur in the unstable region.

Hence the plot of 'Pressure Ratio vs Mass Flow Rate' is also an important Design Parameter.

Hence, we conclude that surging is a compressor performance reducing factor which can occur either during take-off or during the maneuvering, resulting in excessive flame releasing out of the nozzle due to incomplete combustion at low mass flow rate.

### 3.2 Effects of Surging Phenomena

The efficiency of the compressors drops drastically as no high-pressure air is available to the combustor chamber for the successful ignition of fuel air mixture.

Large vibrations in the compressor annulus due to large stall cells formed. This vibration can damage critical components of the aircraft.

If the frequency magnitude of these large vibrations match with the actual natural frequency of the rotor blades, resonance would take place and will damage the blade leading to failure.

### 3.3 Unstable Combustion resulting in Flame Out and Flame Release

For a stable combustion phenomenon, a certain amount of the pressurized air is mixed with the fuel and ignited to an exceedingly high temperature where the volume increases, and the pressure remains constant.



**Fig 9 : C-17A Suffering from Compressor Surge**

A Flame out in the combustion chamber generally occurs when the air inside the combustor chamber gets extinguished.

The main cause of the extinction of the air is the Compressor Stall. This stalling of the compressors leads to the fuel starvation for the incoming compressed air. This generally occurs at a high angle of attack of the rotor blades. The compressor surge or the complete disruption of the airflow over the blade surface can critically cause sudden flame out.

Another reason for the flame out is the ingestion of some FOD's such as birds, heavy rain causing ice formation, dust accumulation leading to choked flow, and the hot gases from the firing armaments. For e.g. The A-10 Warthog suffered from the flame out due to hot fumes ingestion while firing leading to compressor surge.

In the modern jet engines, these flame out can be prevented by continuously providing ignition with the spark plug. This method can restart the combustion process if the compressor is not completely stalled or reached surge stage.

## 4. Control and Preventive Measures

### Bleed Air Valves

Bleed air is basically the compressed air which is generally taken out at one stage from the compressor upstream of the fuel-burning area i.e. combustor chamber. The bleed air has a temperature range of about 200°C to 250°C and the pressure of the compressed air is around 40 PSI.

However, this bleed air is not suitable for the compressor if it is not removed from the compressor chamber. This bleed air can reduce the air velocity of the incoming flow and thereby lead to the stalling at the first stage of the rotor. If the stalling occurs at the first stage, then it will go on propagating as the engine speeds up and can lead to stalling of all the blades.



The bleed air removal valves are employed at a specific stage in the gas turbine engines.

The main function of the bleed valves is to relieve the compressor from excessive pressure during starting of the engine and during take-off operation in order to prevent from the compressor surge. If the compressor stalling and surging is prevented at the initial stages, then there will no effect on the engine performance or damage to the components when surge occurs.

The bleed air removal will result in reducing the flow incidence angle in the front stages of the rotor blades and would unstage the blade.

### Inlet Guide Vanes

The inlet guide vanes are used by the compressors to guide the airflow to the first stage in the multistage compressor. These inlet guide vanes are designed such that they transport the air to the first rotor stage at a proper incidence angle so that most efficient compression can be achieved.

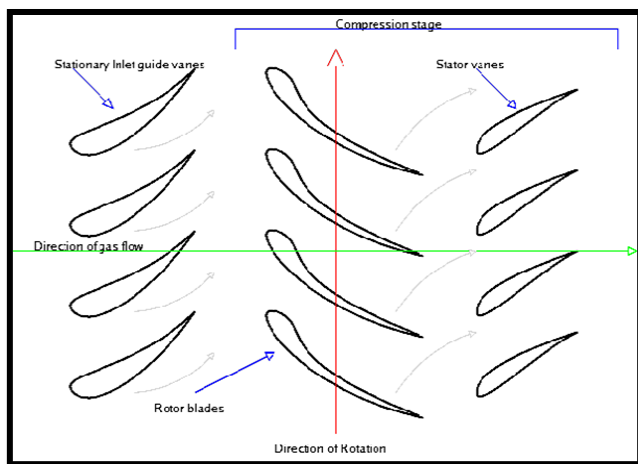


Fig 10 : Inlet Guide Vanes

The stalling at the front rotors takes place when the inlet air flow gets disturbed, and the adverse pressure gradient is generated. The IGV's are basically the stationary stator vanes that are located upstream of the first stage and guide the inlet air at a correct angle so that stalling does not take place at the initial stages.

Most of the jet engines have now dispersed with the use of the IGV's because the IGV's permit the flow angle to get adjusted with the rotational speed of the rotors and therefore increases the off-design performance.

These inlet guide vanes also help the compressor to achieve the maximum possible mass flow per unit area with a minimum increase in the engine weight. These IGV's also provides some additional benefits like reduction of the engine noise as the airflow is streamlined initially for the

rotors and they also help in the anti-icing phenomena. These IGV's must be created from the high-quality material. Stainless is a preferred choice because it offers high strength.

### Variable Inlet Guide Vanes (VGV's)

The variable inlet guide vanes are more enhanced form of the conventional guide vanes. These guide vanes can adjust their exit flow angle (absolute flow angle) to allow a proper flow incidence on the rotors of the first stage in the axial flow compressors.

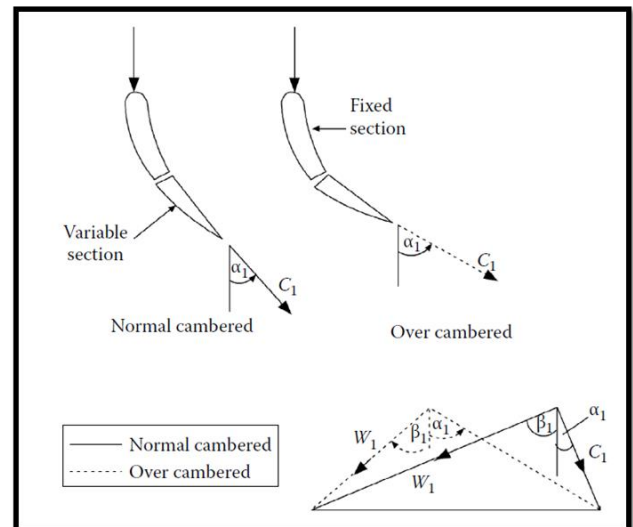


Fig 11 : Variable Stator Vanes

The variable inlet guide vanes are basically the variable stator vanes. These vanes can more efficiently guide the air at desired angle of attack to the initial rotor blades.

There are two main purposed served by these VIGV's due to which their usage has been advanced by many gas turbine engines today: -

1. Regulation of the amount of the ambient air by varying the stator exit air angle. The stator vanes can be adjusted by the controls in the cockpit.
2. Helps in minimizing the compressor stall by keeping the flow attached to the upper surface of the rotor blades. Hence, the turbulent boundary layer is not formed due to which flow separation does not occur and the compressor can efficiently produce desirable pressure for the entry to the combustor.
3. VIGV's allow the compressor to operate at part load, which means a partial throttle will give the same output as the full throttle at the full load.

Since, the stalling is troublesome at the front or the rear stages of the compressors, so these vanes are generally confined in this region only. The variable stators perform their action to unstage the stages which suffer from the compressor rotating stall.

However, the mach at the rear stages is low so stalling in the rear stages is not severe. So, these variable vanes are located

generally to the initial stages and their work is to provide a reasonable low speed starting acceleration to the engine.

Positive stall i.e. stalling on the suction side of the rotor blades is increased when the inlet angle of attack is increased and due this the relative flow angle ( $\beta_1$ ) also gets increased.

There are two methods in which these variable stator vanes operate.

From the fig. 11, it can be observed that for the normal cambered stator vanes, the absolute flow angle is low, and the relative flow angle is high.

The first method is to adjust the stator vanes away from the flow axial direction in order to achieve the correct flow angle the rotor stage. Here, there would be an increase in the absolute flow angle ( $\alpha_1$ ) so the corresponding relative flow angle i.e. ' $\beta_1$ ' would get reduced.

The other method is to deploy the rear part of the stator vanes and they are extended so that the value of the absolute flow angle i.e. ' $\alpha_1$ ' is increased. As the camber of the stator vanes is increased by lowering the trailing edge downwards, ' $\alpha_1$ ' is increased, the flow over the first stage of the rotor blade is maintained as stator vanes lowers the relative flow angle i.e.  $\beta_1$  gets reduced.

From the velocity triangles depicted in fig.11, it is clear that how these VGV's operate to adjust the flow angle for the rotor stage so that the stall blade gets recovered and the airflow over the rotor blades again become streamlined without any flow distortion.

Hence, both the techniques work to obtain the same result i.e. reduce the value of the relative inlet angle of attack ( $\beta_1$ ) so that the stalled blades do not propagate further, and the compressor remains in the stable region.

## 5. CONCLUSIONS

The entire research study included the theoretical research on the axial flow compressors performance characteristics and the phenomena of stalling and surging. The research work highlighted on the study of stalling and surging and the use of the performance parameters of the axial-flow compressors i.e., pressure ratio and mass flow rate, in non-dimensional form for plotting the compressor performance maps.

The main approach of all the researchers was based on the effects on the performance characteristics due to the stalling of the axial flow compressor. All the experiments and researches shows that the stalling of the compressor starts from the stalling of a single rotor blade, due to foreign object ingestion like bord strike, ingestion of sand, dust, in-flight ice formation and due to domestic object damage (DOD).

The single blade stalling does not affect the compressor performance as the other blades compresses the incoming air efficiently. However, when the foreign objects disturb the air flow at a large scale, then the air gets separated from the leading edge of the blades causing the tip flow separation.

This condition is extremely critical as the separated flow disturbs the flow over adjacent blades, leading to stalling of many blades of the rotor stages. The situation becomes more adverse when the stalled blades propagate in the opposite direction of the blade rotation. This phenomenon results in the rotating stall formation where the stall cells are formed in large quantity, and they cover the entire compressor annulus. This results in the choking of the flow and if not controlled with appropriate stall control techniques, then can lead to compressor surge.

Compressor surge is the phenomenon where all the rotor stages get completely stalled and there is a small possibility of recovery. Surging can severely affect the compressor performance as there will be no air available of efficient compression process. During surging, a loud bang can be heard along with the violent vibrations due to the flow reversal in the compressor chamber. The choking occurs due to the to and fro motion of the stagnant air in the stall cells. The compressor performance maps depict the variation of the pressure ratio with the change in the air mass flow rate. The pressure ratio first increases, reaches to maximum point on surge line and then it decreases as the mass flow rate decreases. All the research papers describe the adverse effects on the compressor performance and its operation in the unstable region. The combustion chamber also starves for the compressed air, due to which flame is released with a loud bang. The flame gets released due to uneven combustion of the air. The process of flame release can repeatedly occur for several seconds if the compressor is unable to recover from surging. The project also discusses about various successful stall control techniques like IGV's, bleed air removal, variable stator vanes and multi-spool compressors. Further, discussion has been made on the material selection to prevent the compressor rotor blade damage during compressor surge. Cleaning process also plays an important role in maintaining the compressor life by frequent cleaning of compressor blades.

**Recommendations:** The accidents occurred due to compressor stall and surge shows that the aircraft's needs to be equipped with more advanced sensor system which can detect the stalling of the blades at the early stages. Utilization of high strength-to-weight ratio material like Titanium alloys and stainless steel is very essential for the manufacturing of inlet guide vanes, rotor blades and the inlet fan. Although titanium is expensive, but it is the best material and is most reliable which can protect from the mechanical damages and can easily withstand bird strikes or other FOD ingestion. For high performance aircrafts, the bleed air removal must be performed during engine start up and take-off to avoid the possibility of stalling. The multi-spool compressors provide a better performance and quick recovery from stall over the single spool compressor, but they are expensive. Installation of the variable inlet guide vanes can effectively prevent the stall formation in the single spool axial flow compressors as they are equipped with hinged mechanisms to vary exit flow



angle. Future research work could include design of more enhanced stall control techniques in addition to the bleed air removal. The work can be done to design the first rotor stage in such a way, that flow separation does not occur from the initial stages.

The stall and surging are the critical phenomenon's which can drastically reduce the engine performance during the flight and can lead to fatal accidents. However, by the application of proper stall control techniques, these adverse situations can be minimized and controlled. The engines must be tested for their design limit operation using rig testing and the manufacturing team must focus on the selection of most appropriate material to prevent blade damage. A detailed information about compressor stall, surge and control techniques were highlighted in the project.

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