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Intelligent Fault Resilient Manufacturing Framework for Variable Pitch Propeller in Turboprop Engines

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Abstract- Engines are the powerhouse of an aircraft as it produces thrust, an opposites force which makes the aircraft to move forward. The most commonly used engine is the gas turbine engine which functions based on the Brayton cycle. It consists of five distinct processes namely Inlet, Compressor, Combustion Chamber, Turbine, and Exhaust. Among these, the turbine blades play a crucial role in thrust generation as it should withstand higher temperature. Hence, they are more susceptible for failures due to assorted reasons like thermal fatigue, crack development, creep deformation, corrosion and other physical damages. The physical examination of these defects is a very tiresome process and shall lead to misleading judgment. To alleviate this issue, Artificial Intelligence (AI) based techniques shall be deployed to detect the presence of defects by exploring the health data obtained from the turbine blades. The proposed research work focuses on designing a comprehensive framework using Deep Convolutional Neural Networks (D-CNN) for detecting the faults in engine blades by learning the intricate patterns and trends in the images. As the D-CNN models can manage extensive amounts of data and can be expanded to inspect numerous turbine blades effectively and also models can be upgraded and retrained to identify new types of flaws to adjust various turbine blade designs.

Keywords: Gas turbine engine, Faculty detection, AI, Corrosion.

1. INTRODUCTION

A propeller is a mechanical device designed to convert the rotational energy into useful thrust. A propeller blade is consisting of a leading edge and a trailing edge, and it is made up of airfoil. The root of the propeller is shaped in such a manner that it blends with the hub. The root is a circular section, sacrificing all the airfoil shapes, to provide good structural strength to the blade. During rotation, the propeller blade is like a cantilever beam. The tip of the propeller is very thin, often may not help to generate the thrust. The Propellers are finally rotating around central shaft, which is the hub of the engine, and this shaft is getting power from the engine as necessitated by the actual propeller rotation. The common feature in airfoils of propellers is that they have flat under surface. There is a rounding around the leading edge of a typical airfoil. The Cambered side is the main lift producing surface of tis propeller. The airfoil always ends with a trailing edge, with a small rounding to reduce various frictional loss.

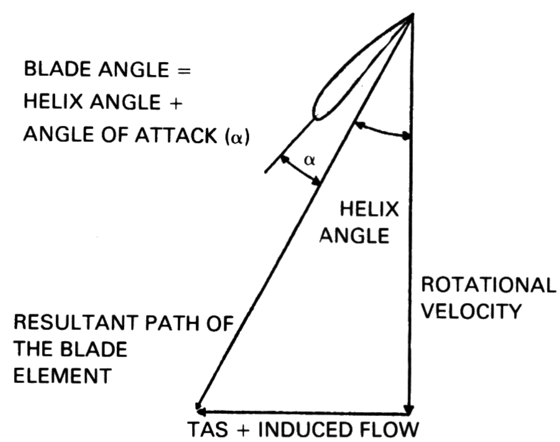
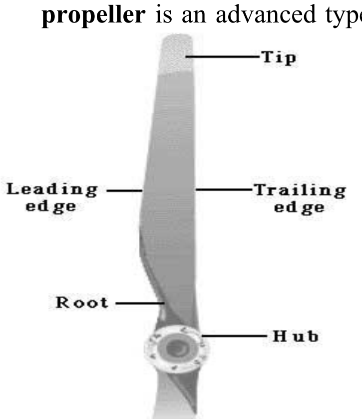


Figure 1.1 Resultant Motion and Angle of Attack

The type of propeller is based on several characteristics such as blade design, number of blades, placement & use and also there are some specialized types of propellers also available. Firstly, in based on design the diverse types of propellers as follows.

1.1. Fixed – Pitch Propeller: In this type of propeller the blade angle is fixed, and it cannot be adjusted during the time of operation. It is lightweight, simple to make and more cost efficient. But the limitation is across varying speed and condition it is less efficient. Fixed – Pitch propellers are widely used in small aircraft's and also in light boats.

1.2. Variable - Pitch Propeller: As the name suggests in the variable pitch propeller the blade angle can be adjusted during the operation to optimize the performance. It has high efficiency, better control and also suitable for varying conditions. But it is much complex to design and expensive. In this chapter we are going to concentrate more about the variable – pitch propeller.
1.3. Controllable – Pitch Propeller: It is a type of propeller where the pitch (angle of the blades) can be adjusted during operation, either manually or automatically, to optimize performance under varying conditions. The pitch can be altered to match speed, load, or environmental conditions. It is Suitable for both forward and reverse thrust by altering the blade angle, eliminating the need for separate reversing mechanisms.
1.4. Constant Speed Propeller: A **constant-speed propeller** is an advanced type of propeller used in many modern aircraft to improve efficiency and performance. Its key feature is the ability to automatically adjust the blade angle (pitch) to maintain a constant engine RPM, regardless of changes in airspeed, altitude, or power settings. This is achieved through a **governor**, which senses changes in engine speed and adjusts the blade pitch accordingly.
1.5. Feathering Propeller: It is a type of adjustable propeller that can change its blade pitch to a position parallel to the airflow, significantly reducing drag. It is primarily used in multi-engine aircraft to improve safety and performance during engine failures. Feathering is usually achieved using hydraulic or electric systems controlled by the pilot or automatically triggered by engine shutdown. A spring or counterweight often assists in moving the blades into the feathered position.



Propeller blad

3-Bladed propeller

4-Bladed propeller

Figure .1.2

2. VARIABLE PITCH PROPELLER

2.1. HISTORY

The concept of a variable-pitch propeller existed as early as the 19th century, inspired by the need for more efficient propulsion in marine vessels. These ideas were later adapted for aviation in the early 1900s, aviation pioneers recognized the inefficiencies of fixed-pitch propellers, particularly during changes in flight conditions. French engineer **Louis Béchereau** developed a manually adjustable propeller in the 1910s, which allowed pilots to adjust blade pitch on the ground. The first practical in-flight adjustable propeller was developed by **Wallace Turn bull**, a Canadian inventor, in 1922. **Reed-controlled propellers**, introduced during this period, allowed limited in-flight adjustments but were not widely adopted. In 1932, **Frank W. Caldwell** of Hamilton Standard (USA) developed the first hydraulic constant-speed propeller. It could automatically adjust pitch to maintain constant engine RPM, revolutionizing flight performance. Caldwell's propeller was first used as the Curtiss AT-5A trainer and later adopted widely in commercial and military aviation. Variable-pitch and constant-speed propellers became standard in military aircraft during World War II.

Modern variable-pitch and constant-speed propellers feature computerized control systems, enhancing precision, reliability, and efficiency. Composite materials have improved the strength-to-weight ratio, while advances in aerodynamics have further optimized performance.

2.2. BASICS OF VARIABLE PITCH PROPELLER:

In the aviation industry, not all aircraft rely on jet engines to produce thrust. Some rely on propellers, with this type of engine also known as turboprops. In turboprops, several types of propellers are used, but one of the most commonly used propellers is the controllable pitch propeller. A controllable pitch propeller is a type of propeller that supports the angle or pitch adjustment in flight. When flying an aircraft with a controllable pitch propeller, the pilot can increase or decrease the pitch of the propeller. The controllable pitch propeller provides better control than its static and fixed counterparts. All propellers have a pitch. It represents the angle between the propeller chord and the rotation of the plane of rotation. Pitch also affects how far a propeller travels per revolution. By adjusting the pitch of an aircraft's propeller, pilots can change the distance the propeller travels per revolution.

2.3. WORKING:

Most pitch-controlled propellers are operated via a joystick. Located in the cockpit, pilots can use this joystick to adjust the pitch of the aircraft's propeller. Altitude control levers usually support multiple settings, such as low pitch and high pitch. A low pitch setting allows the propeller blades to have a low angle. It is commonly used for take-off and climb due to its ability to increase thrust and provide rapid acceleration. On the other hand, a high pitch setting is usually used at cruising altitude. Maximizes fuel efficiency while protecting the aircraft engine from unnecessary wear. Pilots often increase the pitch of the aircraft's propellers when they reach cruising altitude. Some aircraft also support pitch feathers. When this feature is enabled, the propeller blades rotate so that they are parallel to the airflow. The feathers can be useful for maintaining lift in the event of an aircraft engine failure.

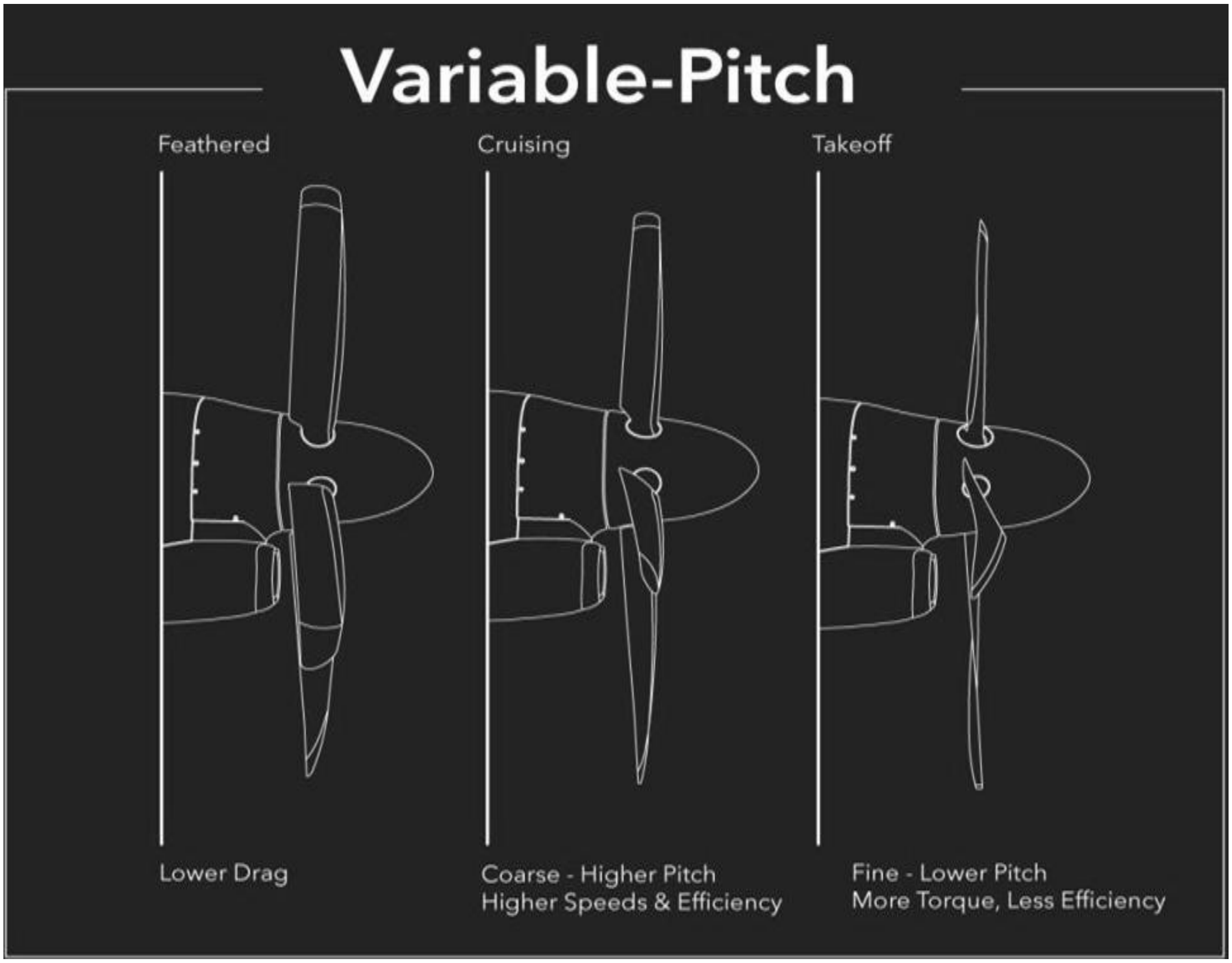


Figure 2.3 Variable Pitch Propeller

According to the blade rotation mechanism, the controllable pitch propeller is classified into two categories, namely:

- Hydraulic Variable pitch propeller
- Electric Variable pitch propeller

2.3.1. HYDRAULIC VARIABLE PITCH PROPELLER:

A hydraulic pitch controllable pitch propeller is a type of propeller system that uses hydraulic pressure to adjust the pitch of the blade, thereby optimizing performance in different flight conditions. A governor senses changes in engine speed and sends pressurized hydraulic fluid to the center of the propeller. The hydraulic fluid moves a piston in the distributor, adjusting the blade angle to maintain the desired RPM.

- ✓ Takeoff/Climb: The blades are set at a fine pitch (low angle) to provide maximum thrust.
- ✓ Cruise: The blades are set at a coarser pitch (high angle) for better efficiency
- ✓ Descent: The pitch can be adjusted as needed to maintain control and reduce drag.

Common on general aviation aircraft, such as Cessna and Piper models. It is widely used in turboprop and commercial aircraft, where efficiency and safety are essential. Essential in multi-engine aircraft to improve performance and safety in the event of engine failure. The hydraulically controllable pitch propeller remains a cornerstone of modern aviation technology, helping to improve efficiency, safety, and performance.

2.3.2. ELECTRIC VARIABLE PITCH PROPELLER:

An electric variable-pitch propeller is a propeller system that uses an electric motor or actuator to adjust the blade angle (pitch). This type of system provides precise control over blade pitch and is increasingly popular in light aircraft, drones, and experimental aviation due to its simplicity and versatility.

An electric motor, typically housed in the propeller hub, drives a mechanism (like a screw jack or gear assembly) to change the blade angle. Power and control signals are supplied via wiring from the aircraft's electrical system. Pilots can manually adjust the pitch through cockpit control. In advanced systems, electronic controllers automatically adjust the pitch based on parameters like engine RPM, air speed, and load.

The electric variable-pitch propeller is a promising technology, particularly for aircraft prioritizing efficiency, simplicity, and compatibility with modern, sustainable propulsion systems.

2.4. APPLICATIONS OF VARIABLE PITCH PROPELLER:

Variable pitch propellers are very versatile and are widely used in various industries to optimize performance, improve efficiency and increase safety in various flight conditions. Here are the main applications:

2.4.1. General Aviation

Purpose: Improve performance during takeoff, climb, cruise, and descent.

Examples: Aircraft like the Cessna 182 and Piper Arrow use constant-speed propellers to enhance fuel efficiency and provide better control across flight phases.

2.4.2. Commercial Aviation

Purpose: Optimize fuel economy, reduce engine wear, and ensure smooth operation.

Examples: Turboprop-powered regional airliners such as the ATR 72 and Bombardier Dash 8 rely on variable-pitch propellers to manage speed and performance efficiently.

2.4.3. Military Aircraft

Purpose: Provide maximum thrust during takeoff, efficient cruising at various speeds, and minimal drag during emergencies.

Examples: Transport aircraft like the Lockheed C-130 Hercules.

Maritime patrol aircraft such as the P-3 Orion, which use feathering propellers for safety during engine failures.

2.4.4. Drones and Unmanned Aerial Vehicles (UAV)

Purpose: Enhance flight efficiency and maneuverability by adjusting pitch to match varying speeds and loads.

Examples: High-performance drones in surveillance, delivery, and research applications use electric variable-pitch propellers.

2.4.5. Turboprop Aircraft

Purpose: Allow reverse thrust for short runway operations and optimize engine RPM for various flight phases.

Examples: Aircraft like the De Havilland Canada DHC-6 Twin Otter, used for short takeoff and landing (STOL) operations.

Business jets like the Pilatus PC-12 for versatility and efficiency.

2.4.6. Electric and Hybrid Aircraft

Purpose: Support sustainable aviation by integrating with modern electric propulsion systems.

Examples: Emerging electric aircraft like those from Joby Aviation and other eVTOL (electric vertical takeoff and landing) designs use variable-pitch technology for efficiency and control.

2.4.7. High-Performance and Experimental Aircraft

Purpose: Enhance speed, climb rate, and versatility in experimental and aerobatic scenarios.

Examples: Home-built and aerobatic aircraft frequently use variable-pitch propellers to maximize performance across a wide range of conditions.

2.4.8. Helicopters (Rotorcraft)

Purpose: Adjust blade pitch to maintain lift and control at varying speeds and altitudes.

Examples: Rotor systems in helicopters operate on the principle of variable pitch.

The variable pitch propeller is a cornerstone technology in aviation, offering adaptability for diverse applications, from light aircraft to commercial airliners and cutting-edge electric aviation. Its ability to optimize performance under varying conditions makes it indispensable in modern and future aerospace designs.

3. TYPES OF PROPELLER DAMAGE

Many types of damage can cause a propeller to fail or become unusable. FAA data on propeller failures shows that most failures occur in the tip area of the blade, usually within a few inches of the tip and often due to a crack initiator such as a pit, notch, or groove. However, blade failure can occur anywhere on the blade, including the mid-blade, stem, and centre, especially when there are cuts, scratches, abrasions, and cracks. The severity of the damage determines the type of repair required.

3.1. Corrosion: One of the main causes of propeller loss of airworthiness is corrosion. External corrosion of blades, hubs and other metal components is a serious problem. Internal corrosion can occur when moisture accumulates in internal cavities such as hubs, blade flanges and pitch control mechanisms. This threatens the structural integrity and performance of the propeller without being noticed. Propeller overhaul periods are established so that the propeller can be disassembled to inspect the internal surfaces. In addition, corrosion acts continuously, regardless of the actual operating time. Corrosion of metallic propeller components can be classified into three distinct types.

3.1.1. Surface corrosion: Loss of surface metal due to chemical or electro chemical action with visible oxidation products that are usually of a color and quality opposite to the base metal. Surface corrosion usually occurs when the corrosion protection of a metal surface is removed by erosion or polishing.

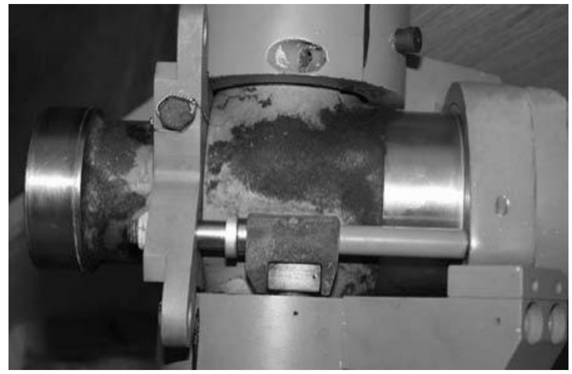


Figure 3.4 Hub Surface Corrosion

3.1.2. Pitting: Pits are visible corrosion cavities that extend from the metal surface. They can grow on the surface, under tiles, or under improperly installed casting boots. Pitting can be small (0.010 inch deep) and still cause major problems, as pitting can be a precursor to cracks.

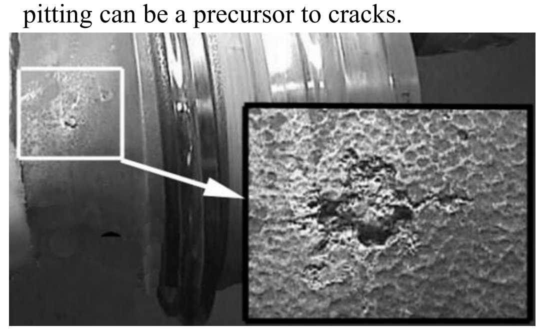


Figure 3.5 Pitting on a Shot Peened Surface

3.1.3. Inter-granular corrosion: Occurs at grain boundaries. The presence of intergranular corrosion can be the result of the continued presence of moisture. Exfoliation is a form of inter granular corrosion that occurs most often in forgings or rolled sheets, and less often in castings. Exfoliation is sometimes visible as the metal slips and cracks on the tip of a blade.

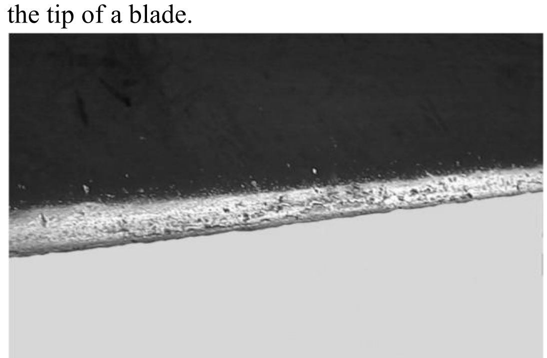


Figure 3.6 Exfoliation on The Blade Leading Edge

3.2. Face, Leading Edge, or Twist Misalignment: When propeller blades are bent, twisted, or tilted, they will not be properly connected during operation. This will cause vibration and may result in loss of thrust. The level of vibration can be significant and, depending on the severity of the distortion, may lead to catastrophic failure.

3.3. Notch: A sharp, chisel-shaped metal movement, usually found on the leading and trailing edges. All cuts are potential sources of cracking.

3.4. Erosion: The loss of material from the blade surface due to the action of small particles such as sand or water, usually present at the leading edge near the tip. This damage destroys the corrosion protection of the blade, which can lead to blade failure.

3.5. Scratches, Cuts, Cuts and Scratches: These terms describe surface damage.

3.6. Cracks: When found anywhere on the propeller, cracks should be removed immediately and inspected in detail. Propeller cracks develop over time, very rapidly, and eventually lead to failure.

Figure 3.7 Hub Crack

3.7. Bumps: Bumps can be dangerous, depending on their size, location, and configuration. The bumps cause an increase in local stress around its perimeter and deep below the surface. Removing the material should repair the scratches. Filling the scratches with a material such as an auto body compound does not correct the added stress and is not recommended. A failure may occur.

3.8. Lightning Strike: A lightning strike on a metal blade may be indicated by a small burned and melted area on the blade, a trail of small holes along the blade, or there may be no indication at all. However, lightning damage can be severe, affecting the strength of the blade material itself, damaging the blade bearings or other internal components. Lightning always creates residual magnetism in the steel parts. Inspection of reported lightning damage may require specialized equipment, such as a Gauss meter, to check the magnetism in the steel components and should be performed by a qualified propeller repair centre.

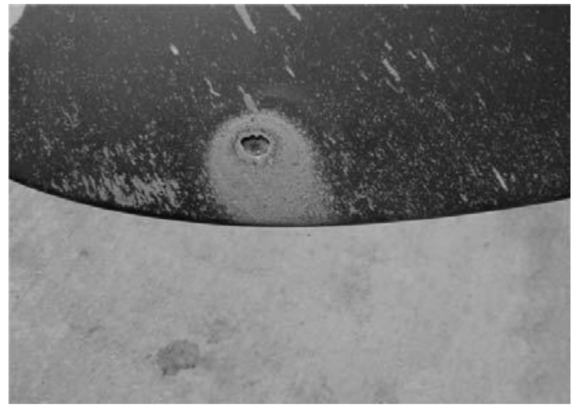


Figure 3.8 Lightning Strike on a Composite Surface

3.9. Over speed: A propeller may have been exposed to an over speed condition and not give any indication of the event. In any case, the event may have severely damaged the propeller due to the dramatic increase in centrifugal loads. If it is suspected that the propeller has been operated under excessive conditions, it should be disassembled and sent to a propeller repair centre for inspection for bolt hole elongation, dimensional changes, or other signs of stress in accordance with the manufacturer's maintenance instructions.

3.10. Foreign Object Strike: The impact of the foreign object can cause a wide spectrum of damage, from invisible damage to a small scratch to a serious impact on the ground. A careful approach to damage assessment is necessary because of the possibility that there may be hidden damage that is not readily apparent during superficial visual inspection.

Figure 3.9 Propeller Blade Struck by a Foreign Object

3.11. Fire or heat damage: In rare cases, the propellers have been exposed to fire or heat, such as in a hangar fire or engine fire. In case of such an incident, an inspection is required before any other flights. These parts are usually discarded. If any parts of an aluminum propeller have been exposed to high temperatures (above 93°C), the parts should be considered unfit for flight unless it can be proven that the incident had no adverse effects. Composite propeller blades may have a lower temperature threshold for potential damage.

4. CAUSES FOR DAMAGE

1. Mechanical Wear: Over time, components of the pitch control mechanism (such as actuators, linkages, and blades) can wear out, affecting the proper operation of the system. This wear can cause incorrect pitch blade settings, resulting in inefficient propeller operation or even a lack of response to commands. Wear on the pitch control actuator or linkage can prevent proper blade angle adjustment, resulting in loss of power or control.
2. Pitch Control System Failure: The variable pitch system relies on hydraulic or electric actuators to adjust the blade angle. Failure of these components can result in the failure to change the pitch of the blade as required in flight. A hydraulic leak or actuator failure can cause the blades to stick at a certain pitch angle, resulting in a loss of aircraft performance.
3. Blade imbalance or damage: If the blades are damaged, such as from excessive shock or vibration, they can become unbalanced. An imbalance results in vibrations that increase stress throughout the propeller system, which can lead to further mechanical problems or complete failure. A cracked or bent blade can cause asymmetric thrust, causing increased vibration and stress, leading to bearing or shaft failure.
4. Control system malfunctions: The control system that adjusts the blade pitch (often integrated into the aircraft's flight control system) can suffer from electrical faults, software problems, or sensor failures. This can cause the blade angles to be adjusted incorrectly, resulting in reduced performance or loss of control. A faulty sensor can send incorrect data to the control system, causing the blades to adjust at an unexpected angle, interrupting thrust generation and efficiency.
5. Corrosion and environmental damage: Aircraft operating in harsh environmental conditions, especially in salty or humid environments (such as over the ocean), are prone to corrosion. Corrosion can affect the mechanical and electronic components of the variable aperture system, leading to failures. And the Corrosion of bearings or control links can increase friction, damaging the step mechanism and causing functional problems such as reduced blade movement or wear of parts.
6. Hydraulic Failures: Many controllable pitch propeller systems rely on hydraulic pressure to adjust the blades. In the event of a hydraulic system failure, such as a leak or pressure drop, the system cannot adjust pitch properly. A hydraulic fluid leak can cause a drop in system pressure, preventing the blades from moving and causing a thrust imbalance.
7. Improper Maintenance or Installation: Improper installation or maintenance practices can cause problems that lead to premature failure. For example, incorrect torque settings on bolts, improper lubrication of components, or failure to replace worn parts can lead to functional failures. A defective propeller hub or an incorrectly installed actuator can cause incorrect blade settings or damage other parts, leading to system failure.

8. Electrical System Failures: In modern aircraft, many pitch-controllable propeller systems use electrical actuators controlled by the aircraft's flight management system. In the event of an electrical failure, such as a loss of actuator power or a short circuit, the propeller system may not be able to adjust the blade pitch properly. A power failure in the electrical system can cause the blades to lock in a pitch, which can reduce thrust and control.
9. Overload or undue stress: If the aircraft is operated under extreme conditions, such as flying at high speeds or exceeding the maximum recommended thrust, this can place undue stress on the controllable pitch propeller system. This can lead to failure of critical components. Overloading the aircraft or operating the propeller at excessively high-power settings for extended periods of time can result in overheating or fatigue failure of critical components of the pitch control mechanism.
10. Incorrect blade angle adjustment: Incorrect blade angle settings or control system malfunctions can prevent the propeller from performing optimally under various flight conditions. This can result in insufficient thrust or excessive drag, thereby reducing fuel efficiency and increasing stress on the aircraft engine and propeller system. A blade set at too steep an angle during cruise flight can create unnecessary drag, reducing speed and fuel efficiency.

5. FAULT DETECTION METHODS

Variable pitch propellers (VPP) are crucial components in modern aircraft, allowing for the adjustment of blade angles to optimize performance across a wide range of flight conditions. However, due to their complex mechanical design, VPP can experience faults that compromise their functionality, which may affect aircraft performance, safety, and reliability. Detecting Faults in These Systems Is Essential for Maintaining Operational Efficiency and Preventing Failures. This article explores various methods for detecting faults in variable pitch propellers, emphasizing mechanical, electrical, and sensor-based approaches.

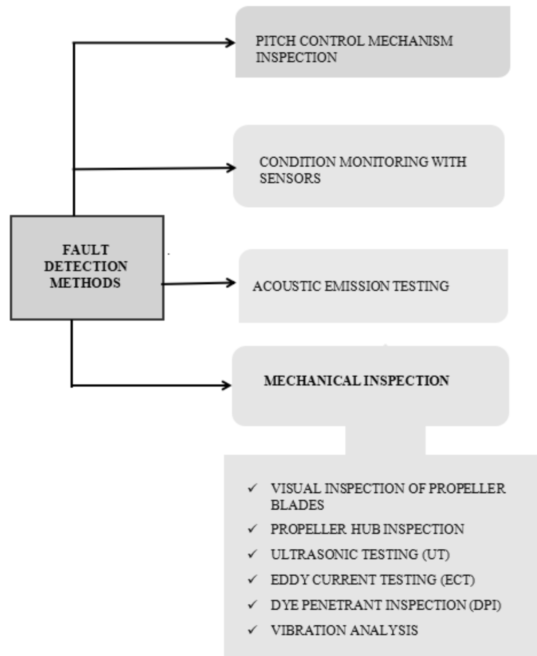


Figure 5.10.Fault Detection Methods

5.1. MECHANICAL INSPECTION**:** It plays a vital role in the maintenance of Variable pitch propellers (VPP) by allowing technicians to identify physical defects that could prevent the system from operating properly. This method involves a thorough examination of the mechanical components of the propeller, focusing on visible damage, wear, distortion, and other potential problems. Given the complexity and dynamic nature of VPP systems, mechanical inspection is typically performed at regular intervals during scheduled maintenance checks.

5.1.1. VISUAL INSPECTION OF PROPELLER BLADES: Propeller blades are the most critical components of a pitch control system, directly affecting the performance of the aircraft. During mechanical inspection, technicians carefully examine blades for signs of physical damage or degradation, including Cracks or breaks Any visible cracks in the blade surface, especially near the root or tip, can significantly affect aerodynamics and structural integrity. Cracks can propagate under stress, leading to catastrophic failure. Corrosion, especially in areas frequently exposed to weather, de-icing chemicals, or sea air, can weaken blades and reduce their ability to withstand stress. Corrosion often appears as surface pitting or rust spots. Erosion Over time, the leading edges of blades can suffer from erosion caused by airborne debris (e.g., sand, ice, or insects), which can damage the aerodynamics of the blades and cause a loss of performance. The Scratches or Grooves Minor impacts or collisions with foreign objects (FOD) can cause scratches or burrs on the blades. These defects can alter the airflow over the blades, reducing efficiency and resulting in unbalanced forces. Bursting Composite blades can develop delamination, where layers of material separate due to impact or fatigue, weakening the blade structure. This phenomenon is often more difficult to detect without more advanced methods, such as ultrasonic testing, but can be observed visually. The Inspection a variety of tools, such as scopes, magnifying glasses, and high-intensity lights, can be used to inspect difficult areas for signs of damage.

5.1.2. PROPELLER HUB INSPECTION : The hub connects the blades to the motor shaft and transmits the rotational energy from the motor to the propeller. The hub is a critical structural component, and any failure here can lead to catastrophic failure. The inspection focuses on Cracks or breaks in the distributor can result from excessive vibration, overload or manufacturing defects. These cracks can spread and cause the blades to lose their bond. The Corrosion around the hub, especially at the blade attachment points or where the part connects to the engine, can weaken the structure. This is especially true in high humidity environments, such as salt water or humid air. The bearings in the hub, which provide smooth rotation and pitch adjustments, are inspected for wear or damage. A faulty bearing can cause abnormal vibrations or difficulty changing pitch. Specialized torque tools, ultrasonic equipment, and magnetizing equipment are used to detect cracks and material integrity.

5.1.3. ULTRASONIC TESTING (UT): A non-destructive ultrasonic testing (NDT) method that uses high-frequency sound waves to inspect materials for internal defects. It is particularly useful for detecting internal defects in the propeller hub that may not be apparent by visual inspection. A transducer sends high-frequency sound waves into the scattering material. The sound waves pass through the centre and are reflected from discontinuities (e.g., cracks, voids, or inclusions). The time it takes for the echo to return helps determine the location and size of the defect. Defects Detected by Ultrasonic Testing Fatigue cracks that develop over time due to repeated stress can be detected deep within the core material. Delamination's and voids: In composite diffusers or layered diffuser materials, ultrasonic waves can reveal delamination's or voids that will reduce structural integrity. UT corrosion can identify internal corrosion in the core material, particularly in areas where external corrosion may not be visible but may have penetrated the material. Limitations of Ultrasonic Testing Access and Surface Preparation UT requires direct access to the surface of the diffuser and the surface must be free of contamination to ensure accurate readings. Operator Skills Correct interpretation of UT results requires an experienced technician, as different types of defects can have similar echo patterns.

5.1.4. EDDY CURRENT TESTING (ECT): Eddy current testing is another commonly used NDT method to detect surface and near-surface defects in conductive materials, such as those found in metal helices. Eddy current probes generate a magnetic field that induces electric currents (eddy currents) in the conductive material of the distributor. Disturbances in these eddy currents caused by material inconsistencies such as cracks, corrosion or wear are detected by the sensor. Defects Detected by Eddy Current Testing Surface Cracks and Corrosion Eddy currents are excellent for detecting surface cracks and corrosion, especially in high stress areas such as hubcaps and not around wheel control mechanisms. Material Defects: ECT can identify hidden defects such as material thinning, porosity or wear on the distributor surface that may not be visible. Limitations of Eddy Current Testing Surface Requirements: Eddy current testing requires the material to be conductive and is limited to detecting surface and near-surface defects. Internal defects more than a few millimetres deep may go unnoticed. Limited to conductive materials: Eddy current testing is only suitable for electrically conductive materials, meaning it cannot be used to inspect composite or non-metallic manifolds.

5.1.5. DYE PENETRANT INSPECTION (DPI): Dye Penetrant Inspection (DPI) is a surface testing technique that uses liquid ink to detect surface defects. It is often used to check the surface integrity of propeller hubs, especially where cracks are suspected.

How it works the surface of the dispenser is cleaned and an ink penetrant is applied to the area being inspected. The ink penetrates any cracks or imperfections in the surface, and, after a waiting period, the excess ink is removed. A developer is then applied, which pulls the ink from any cracks, making them visible. English Under ultraviolet light, a fluorescent paint will glow, highlighting the presence of cracks or defects. A Surface Cracks Penetrant inspection is particularly effective in detecting surface cracks or fissures, which are common in areas of the core exposed to high stress. Porosity and Material Defects: Small surface porosities or defects caused by manufacturing errors can be detected. It cannot detect internal cracks, corrosion, or other defects below the surface. Surface preparation: Proper cleaning of the surface is essential before applying the penetrant. Contaminants such as oil, grease or dirt can interfere with the penetration of the ink, leading to inaccurate results.

5.1.6. VIBRATION ANALYSIS: Vibration analysis is a continuous diagnostic method used to detect problems with the performance and mechanical integrity of the controllable pitch propeller hub. It involves monitoring the vibrations that occur during engine or propeller operation and analyzing these vibrations to detect abnormal patterns. Vibration sensors such as accelerometer are placed in the hub or other critical areas of the propeller. The vibrations produced during operation are analysed to detect any imbalance, distortion, or abnormal movement in the distributor. Defects Detected by Vibration Analysis Disturbances caused by uneven blade wear or improper installation of the propeller hub can cause abnormal vibrations. Misalignment between the hub of the propeller and the engine shaft can also produce unusual vibration patterns. Bearing wear Worn bearings can cause vibrations, indicating that service or replacement is needed. Vibration data analysis requires specialized knowledge and expertise to identify the root cause of abnormal vibrations. External factors Environmental conditions (e.g. wind, engine load) can also influence vibration patterns. It is therefore necessary to carefully consider the operational context.

5.2. PITCH CONTROL MECHANISM INSPECTION**:** The pitch control mechanism is responsible for adjusting the blade angle according to flight conditions. This system consists of mechanical linkages, actuators, and hydraulic or electrical control units. The Actuator Functionality, whether hydraulic or electrical, is examined for leaks, abnormal noise, or restricted movement. If the actuator fails, it can result in incorrect blade pitch or a complete loss of blade angle control. The Connection and Control Systems a mechanical linkage that connect the actuators to the blades are checked to ensure they are aligned, torqued, and worn properly. Loose or improper connections can result in incorrect blade angles, resulting in ineffective propulsion or possible damage to other components. And the lubrication system that maintains the pitch control mechanism is evaluated. Inadequate lubrication can lead to increased friction, wear, and possible failure of the control system. All seals or O-rings that are part of the pitch control system are inspected for wear, cracks, or leaks. A defective seal can cause hydraulic fluid or lubricant to leak, impairing system performance. Tools and Techniques were the Hand tools such as wrenches, screwdrivers, and torque wrenches are commonly used to tighten, adjust, and check the alignment of pitch control components. Additionally, a flow meter or pressure gauge can be used to test hydraulic or pneumatic systems, ensuring proper fluid delivery.

5.3. CONDITION MONITORING WITH SENSORS: Advanced sensor technologies are increasingly being used to detect defects in controllable pitch propellers by continuously monitoring critical parameters such as pressure, temperature, and rotational speed. These sensors can provide real-time data for anomaly detection, such as: Torque Sensors, Strain Gauges, Accelerometer, Temperature Sensors, these sensors measure the torque applied to the propeller shaft. Abnormal torque readings can indicate problems such as incorrect blade pitch angles or malfunctions in the pitch control mechanism. The Strain gauges can detect changes in mechanical stress on the propeller, signalling potential problems such as blade bending or deformation. The Accelerometer sensors measure the acceleration and vibrations experienced by the propeller. Any abnormal readings may indicate a problem with the propeller and trim or pitch control system. The Temperature sensors Overheating of the actuator or bearings due to lubrication failure or internal friction can be detected through temperature changes. The disadvantages Sensor-based systems may require constant monitoring and regular calibration. Additionally, false positives or errors in sensor readings can lead to unnecessary maintenance procedures.

5.4. ACOUSTIC EMISSION TESTING: Acoustic emission (AE) testing is a powerful, non-destructive testing (NDT) technique that is widely used to detect and monitor defects in various engineering systems, including aircraft components such as variable pitch propellers in turboprop engines. AE testing involves the detection of high-frequency stress waves, which are generated by the release of energy from localized sources in materials or components under stress. In the case of VPP, AE testing can identify early signs of damage, wear, and malfunction of critical components, ensuring the safe and efficient operation of the aircraft. For detection Using piezoelectric or other types of AE sensors to detect these stress waves as they propagate through the material. Signal analysis the detected signals are analysed for specific characteristics such as the frequency, amplitude, and duration of the emissions. These characteristics can provide insight into the nature and severity of the defect. How Acoustic Emission Testing Works in VPP Flaw Detection Sensor Deployment AE sensors are typically placed on critical propeller control components, including propeller blades, to monitor for damage, cracks, or other signs of fatigue. Pitch Control Mechanism To detect malfunctions or degradation of pitch control actuators and linkages. Bearings To detect wear, corrosion, or other failures in bearings that support the rotating propeller assembly. Signal Detection When a stress or deformation occurs in a component, such as the onset of a crack, friction, or wear, the component emits acoustic emissions. These emissions are picked up by AE sensors mounted on the structure. The sensors convert the acoustic waves into electrical signals, which are then transmitted to a central data acquisition system for processing and analysis. Signal Analysis After AE signals are captured, they are analysed to identify specific characteristics such as amplitude, frequency, and duration. The intensity or magnitude of the transmitted signal. Larger amplitudes generally correspond to larger defects such as crack propagation or sudden energy release.

6. AI -BASED FAULT DETECTION METHODS

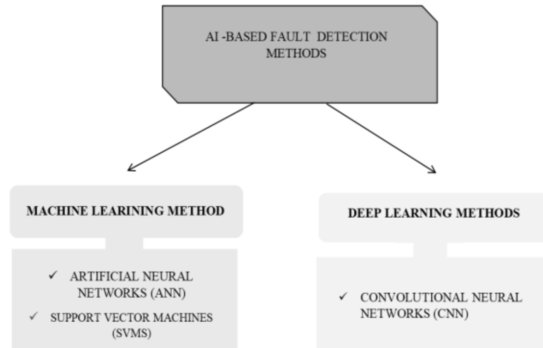


Figure 6.11. AI – Based Methods

6.1. MACHINE LEARINING METHOD:

6.1.1. ARTIFICIAL NEURAL NETWORKS (ANN): An artificial neural network (ANN) can be used to detect and diagnose faults in a controllable pitch propeller (CPP) system in an aircraft. ANNs can be trained to recognize patterns in vibration data, temperature sensors, and other relevant data to detect faults. The goal is to leverage the ANN's ability to learn from complex patterns in the data to identify faults or abnormal conditions in the propeller system that may not be readily apparent using traditional methods. Below is a detailed explanation of how ANNs can be applied to fault detection in controllable pitch propellers, including specific fault types and how the network works. A controllable pitch propeller in an aircraft is designed to adjust the angle of its blades to optimize performance under various flight conditions (e.g., take off, cruise, and landing). The pitch control system adjusts the propeller blade angle based on flight parameters such as speed, power settings, and load. Common components of a VPP system include: The pitch actuator controls the blade angle in the VPP system can result in sub optimal performance, higher fuel consumption, reduced control authority, or even catastrophic failure. Therefore, early detection of faults is essential.

FAULT DETECTION: Real-time Monitoring: The trained artificial neural network takes real-time sensor data as input and generates a prediction about the state of the VPP system. If the system is classified as faulty, an alert is raised, and corrective action can be taken. Fault Classification: The artificial neural network can classify different types of faults (e.g., pitch control failure, imbalance, or sensor malfunction) based on patterns in the sensor data, helping operators understand the exact problem.

a) Artificial Neural Network (ANN) in Fault Detection

- ✓ ANNs are a class of machine learning algorithms inspired by the structure of the human brain. They consist of interconnected layers of nodes (neurons), which process data in a way that mimics human learning and decision-making. ANNs are well-suited for fault detection because they can model complex relationships between different input functions and predict output. In the context of VPP systems, an ANN can be trained to: Classify the status of the propeller system as normal or faulty. Identify specific faults based on sensor readings, such as vibration, temperature, and pitch angles. Predict future faults by analyzing trends in sensor data. Steps in using ANNs for fault detection in VPP data collection, data preprocessing, using neural networks
- ✓ Data Collection: Sensor Data Collects historical and real-time data from VPP system sensors, such as blade pitch angle, RPM (revolutions per minute), temperature, vibration signals, and hydraulic tire pressure readings. Error Data To train the neural network, historical data that includes both normal and error conditions is required. This data can come from past failures, simulated fault conditions, or operational data marked with known fault occurrences. Neural Network Training:

1. Supervised Learning: A neural network is typically trained using a supervised learning approach, where the model is fed labelled data containing inputs (sensor readings) and corresponding outputs (error or no error).
2. Network Architecture: A neural network consists of an input layer (representing the sensor data), one or more hidden layers (processing the data), and an output layer (classifying the fault condition or predicting failure). The architecture can be a fully connected network or a more complex convolutional neural network (CNN), depending on the nature of the data.
3. Back propagation and training: During the training process, the network adjusts its internal weights using back propagation, a method to minimize the error between the predicted and actual results. This process helps the neural network learn to distinguish between normal operation and various fault conditions. Collect real-time and historical data from the VPP system's sensors, such as blade pitch angle, RPM (rotations per minute), temperature, vibration signals, and pressure readings from the hydraulic system. The Fault Data To train the neural network, historical data that includes both normal and faulty conditions are required. This data can come from past failures, simulated fault conditions, or operational data tagged with known fault occurrences.

- ✓ Data Preprocessing: Data Normalization Collected data often needs to be normalized to ensure consistency across different sensor types (e.g., scaling vibration readings or pitch angles to a standard range). Feature Engineering Important features (such as vibration frequency components or pitch angle changes over time) are extracted from the raw data using techniques such as Fourier transform, or wavelet transform. This helps capture key patterns that indicate defects. Data must be labelled as "normal" or "faulty" with specific fault types, based on past failures or expert diagnosis collected data often needs to be normalized to ensure consistency across different types of sensors (e.g., scaling vibration readings or pitch angles to a standard range Feature Engineering Important features (such as vibration frequency components or changes in pitch angle over time) are extracted from raw data using techniques like Fourier Transform or Wavelet Transform. This helps capture key patterns indicative of faults. Data Labelling: Data should be labelled as "normal" or "faulty" with specific fault types, based on past failures or expert diagnosis.

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6.1.2 SUPPORT VECTOR MACHINES (SVMS): SVM can be used to classify defects based on features extracted from vibration data, pressure sensors, and other relevant data. SVM is a supervised machine learning model commonly used for classification and regression tasks. It is particularly effective in cases where the data is not linearly separable, which is often the case in complex systems such as aircraft diagnostics.

REAL-TIME DEVELOPMENT AND MONITORING:

Once the model is trained and evaluated, it can be deployed in real time to monitor the propeller system during flights. Real-time defect detection as new sensor data is received, the trained SVM model classifies it and can trigger alarms or automatic systems to alert maintenance teams to potential problems. This allows defects to be detected early, reducing the risk of catastrophic failures in flight

SVM CAN BE APPLIED FOR AIRCRAFT PROPELLER FAULT DETECTION:

1. DATA COLLECTION:

- ✓ Sensors and Measurements: Sensors and Measurements: To detect faults in the propeller pitch control system, it is necessary to collect relevant data from sensors.
- ✓ Blade Angle Data: the actual blade angle.
- ✓ Hydraulic Pressure Data: to monitor the operation of the hydraulic system used to adjust the blade Data on engine speed and the resulting thrust from the propeller.
- ✓ Vibration Data: Vibration data that can indicate a mechanical failure.
- ✓ Temperature Data: The temperature of the propeller and hydraulic system can indicate overheating or failure

2. DATA PRE-PROCESSING: Feature Selection Identify the most important features from the collected data that can help detect faults. Characteristics may include the rate of change of pitch angle, fluctuations in hydraulic pressure, or sudden changes in vibration. Label the data appropriately. For example, a "1" may represent a bug (e.g., a blocked pitch command), while a "0" may represent normal conditions. Can be used to classify faults based on features extracted from vibration data, pressure sensors, and other relevant data. SVM is a supervised machine learning model commonly used for classification and regression tasks. It is particularly effective in cases where data is not linearly separable, which is often the case in complex systems like aircraft diagnostics.

FAULT CLASSIFICATION:

- ✓ USING THE SVM MODEL: Once the Model Is Trained, It Can Classify New Data into Two Categories: Faulty or Normal. When New Sensor Data Is Fed into The Model, The SVM Indicates Whether the Propeller System Is Operating Normally or Has Had a Fault Detected.
- ✓ DECISION BOUNDARY: SVM Draws a Hyperplane (Decision Boundary) To Separate the Faulty Data from The Normal Data. When New Data Is Introduced, It Is Classified on Which Side of The Boundary It Lies.

EXAMPLE FAULT SCENARIOS AND SVM APPLICATION

ERROR 1: Pitch mechanism stuck

SYMPTOMS: The blade angle cannot change or is stuck at a certain value.

SVM APPLICATION: The model will report unusual or static blade angle data over time and potentially abnormal changes in vibration or thrust Error

ERROR 2: Hydraulic system failure
SYMPTOMS: Slow or no response when adjusting volume
SVM APPLICATION: The model can detect abnormal hydraulic pressure or delayed reactions to elevation changes, thus identifying a possible hydraulic failure.

ERROR 3: Sensor Failure
SYMPTOMS: Incorrect or fluctuating pitch angle readings.
SVM APPLICATION: The model can detect abnormal patterns in sensor data, reporting any discrepancies between expected and actual readings.

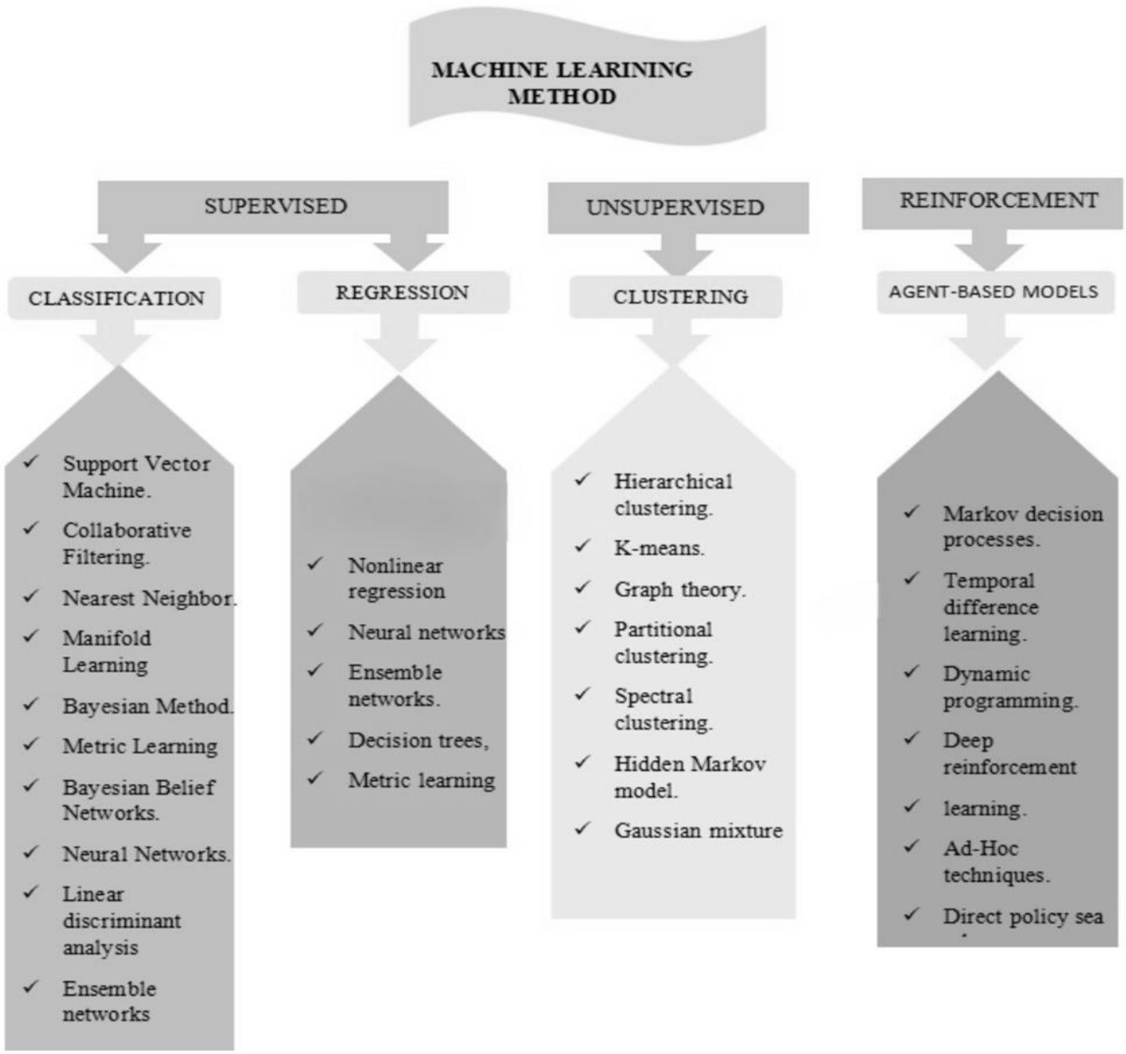


Figure 6.12 Machine Learning Categories and Algorithms

6.2. DEEP LEARNING METHODS

6.2.1. CONVOLUTIONAL NEURAL NETWORKS (CNN):

Convolutional neural networks (CNNs) are a class of deep learning algorithms that have been widely applied in various fields, including image and signal processing. In the context of controllable pitch aircraft propeller defect detection, CNNs can play a key role in identifying and diagnosing problems that can affect propeller performance.

CNNs can be used in several ways:

a) Vibration analysis: Operating propellers generate vibrations, which are often detected using sensors such as accelerometer strain gauges. CNNs can be applied to time series data from vibration sensors, where they can learn to recognize patterns that indicate defects such as imbalances or mechanical failures. CNNs can analyze vibration signals in the frequency domain, where specific frequencies can be associated with specific defects.

b) Image-based inspection (using visual data): In some cases, visual inspection of propeller blades or components may be possible with cameras, in situ or via drones. CNNs can be trained to detect visible defects such as cracks, abrasions or distortions from images of the propeller. Techniques such as image classification and segmentation can help identify specific areas of concern on propeller blades, allowing for faster diagnosis.

c) Acoustic signal processing: The propeller system can also produce characteristic acoustic signals during normal and abnormal operation. CNNs can be applied to audio analysis, where they process acoustic signals to identify faults by recognizing abnormal patterns in audio data.

d) Sensor fusion and multi modal analysis: In modern aircraft, multiple sensors can provide data on vibration, temperature, acoustic emissions, and even visual data. CNNs can combine data from these different modalities to provide a comprehensive analysis, thereby improving the robustness of fault detection. For example, a CNN can combine vibration signals with thermal data to detect overheating problems in a propeller mechanism.

FAULT DETECTION: Once trained, the CNN can be used to analyse real-time data from the propeller system to identify faults. The model generates predictions about the presence and type of failures, which can be used for maintenance decisions. Interpretation and action If a failure is detected, the system notifies the maintenance teams, who can inspect and solve the problem before it affects the operation of the aircraft.

CNNs WORK ON FAULT DETECTION FOR PITCH VARIABLE PROPELLERS:

- ✓ Data Collection: Data is collected from various sensors of the aircraft, such as vibration sensors, temperature sensors and cameras. These data can be time series (e.g. vibration signals) or images (e.g. visual inspection of propeller blades).
- ✓ Data Preprocessing: The data is pre-processed to make it suitable for CNN analysis. This may include normalizing signals, resizing images, or converting raw sensor data into spectrograms for vibration or acoustic analysis.
- ✓ CNN Training: The CNN model is trained on labelled data, where defects are already known (e.g., defective blades, vibration issues, or pitch distortion). The CNN learns to recognize patterns in the data that correspond to specific defects.

BENEFITS OF USING CNN FOR PROPELLER DEFECT DETECTION:

- ✓ Automation: CNN's can automate the defect detection process, reducing the need for manual inspections.
- ✓ Accuracy: With sufficient training data, CNN's can identify complex patterns in the data, leading to high accuracy in defect detection.
- ✓ Real-time analysis: Once trained, CNN's can process incoming sensor data in real time, providing immediate feedback to the aircraft maintenance team.
- ✓ Scalability: CNNs can handle large data sets and scale with additional sensors or data sources, improving over time with more data.

FIGURE 6.13 Variable Pitch Propeller Design Made in Solid Works Software

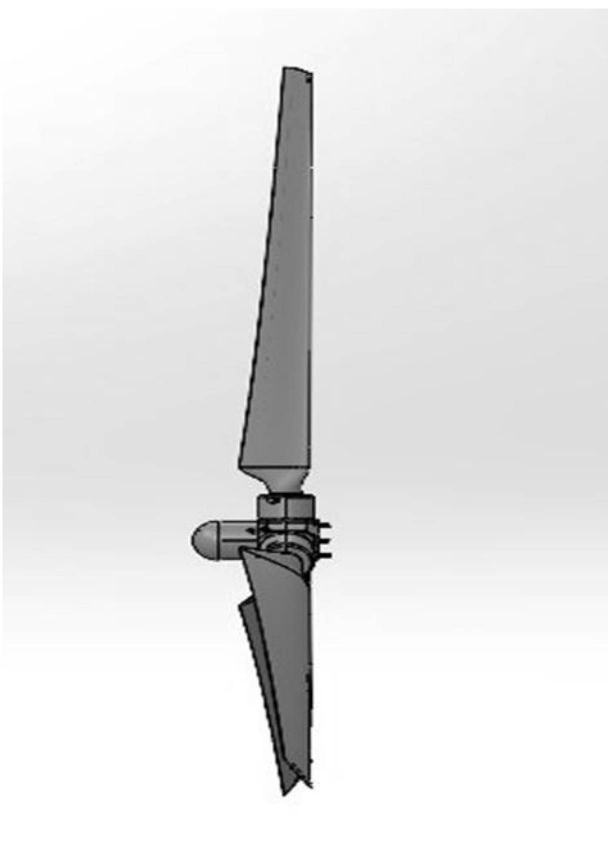


FIGURE 6.14

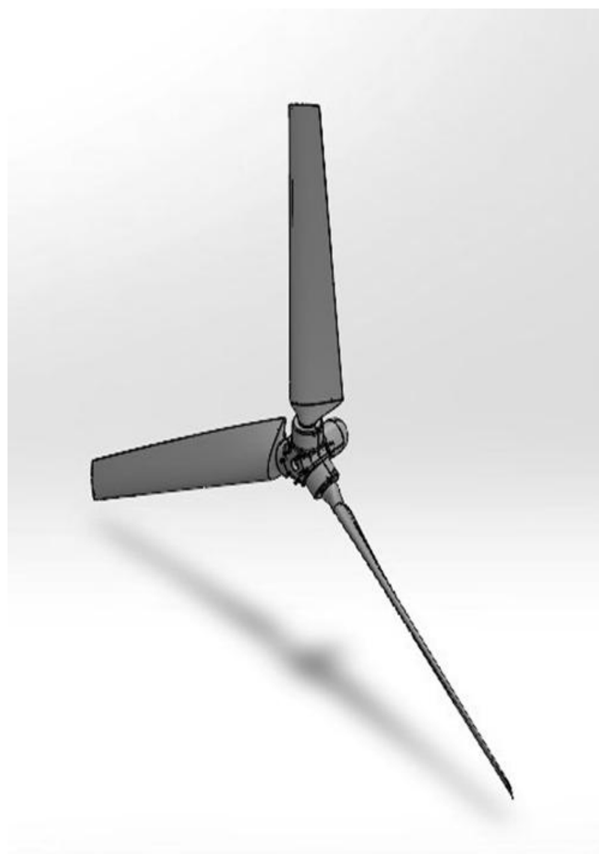
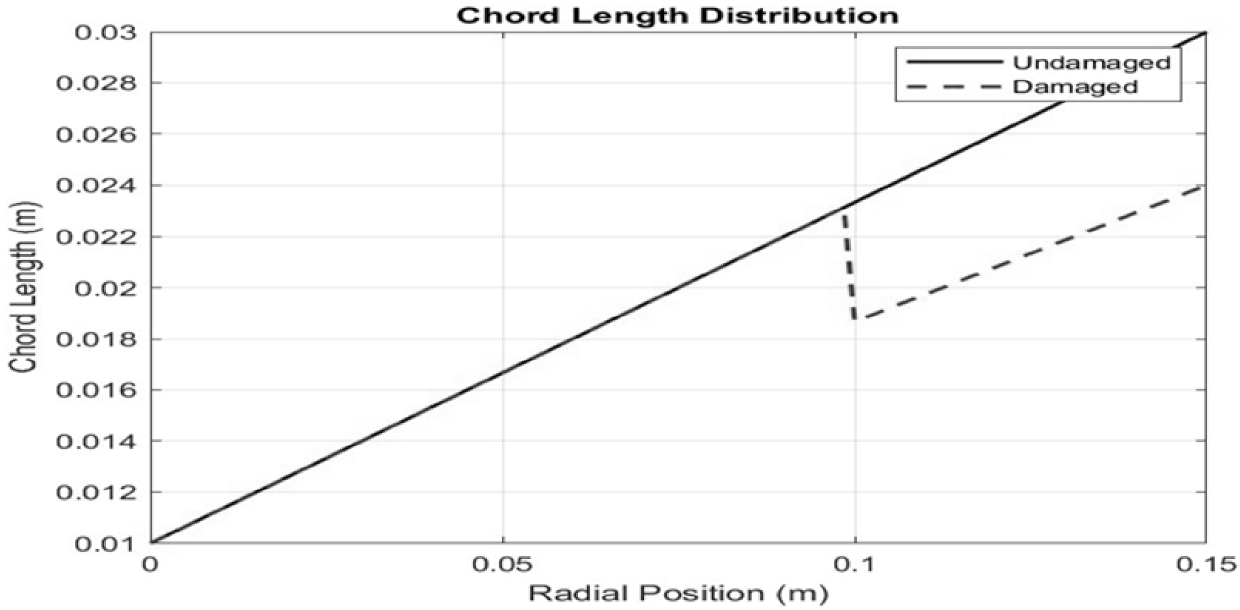
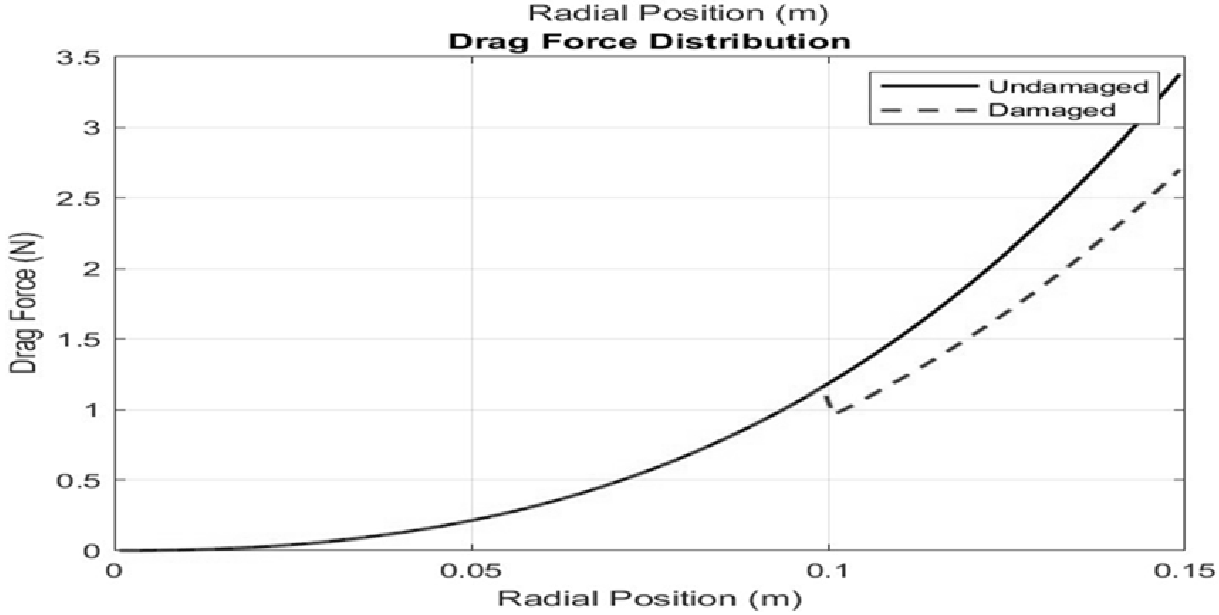
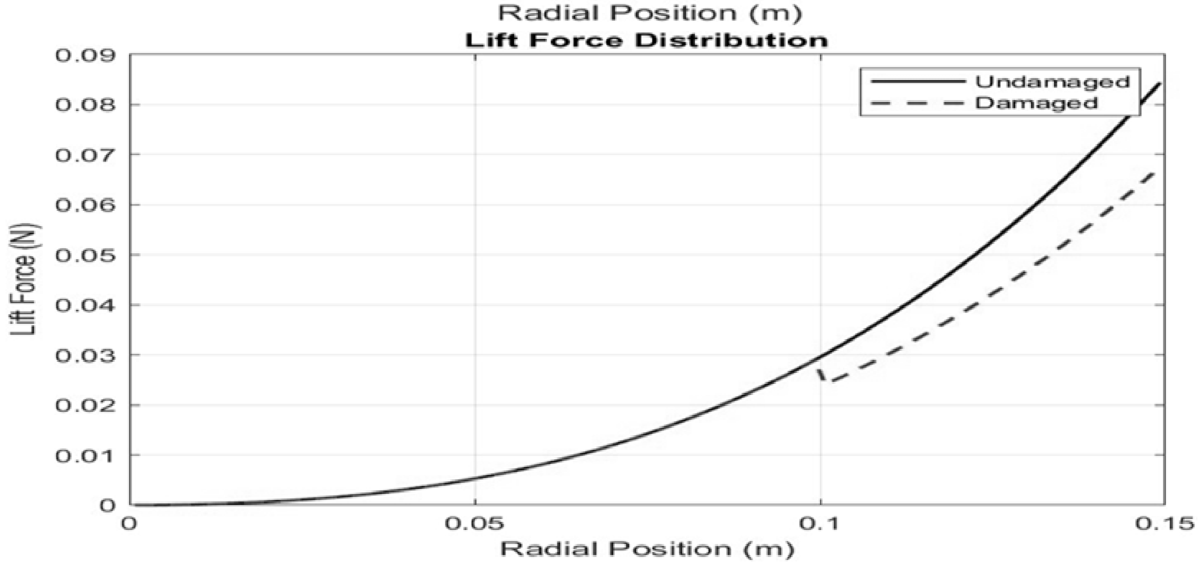


FIGURE 6.15


Chord Length Distribution
Undamaged
Damaged
Chord Length (m)
Radial Position (m)
0.03
0.028
0.026
0.024
0.022
0.02
0.018
0.016
0.014
0.012
0.01
0
0.05
0.1
0.15


Drag Force Distribution
Undamaged
Damaged
Drag Force (N)
Radial Position (m)
3.5
3
2.5
2
1.5
1
0.5
0
0
0.05
0.1
0.15


Lift Force Distribution
Undamaged
Damaged
Lift Force (N)
Radial Position (m)
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
0.05
0.1
0.15

7. INTELLIGENT FAULT RESILIENT MANUFACTURING FRAMEWORK FOR VARIABLE PITCH PROPELLER IN TURBOPROP ENGINES

The proposed framework is aimed towards predicting the blade faults in the turboprop engines. The input to the proposed framework is the high-quality blade images collected during the manufacturing of the turboprop engines. As the images are collected from the real time environment, they are subjected to different kinds of noise and other perturbations. Hence, the proposed intelligent fault resilient framework is constructed by creating an ensemble of three homogeneous deep convolutional neural network (D-CNN). The base learners are constructed using multiple D-CNN blocks, which comprises of a convolution layer, Max pooling layer followed by drop out layer. The proposed ensemble model is constructed by layering the D-CNN blocks. Fig 6.6 Show the block structure of the D-CNN. Unlike the other ensemble models, the proposed architecture is more resilient to faults, as the same image is being explored and transformed by 3 D-CNNS. In contrast to the other deep ensemble model, which uses majority voting technique or meta learner as the final classifier, the proposed architecture

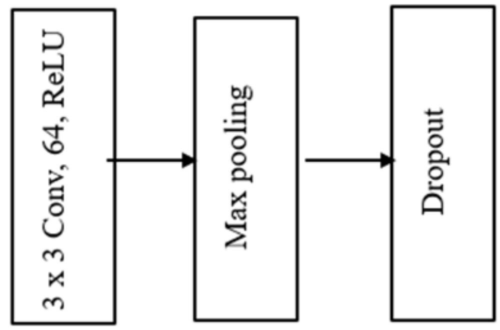


Fig 6.16 D-CNN block of the proposed framework

extracts the probability of individual class from the SoftMax output. These probabilities are then averaged and argmax function is applied to get the final output. This framework considers the predictions of all the 3 individual D-CNN learners, without loss of generality. Fig 6.7 shows the complete comprehensive architecture of the fault resilient framework for detecting the presence of blade faults in turboprop engines using deep learning.

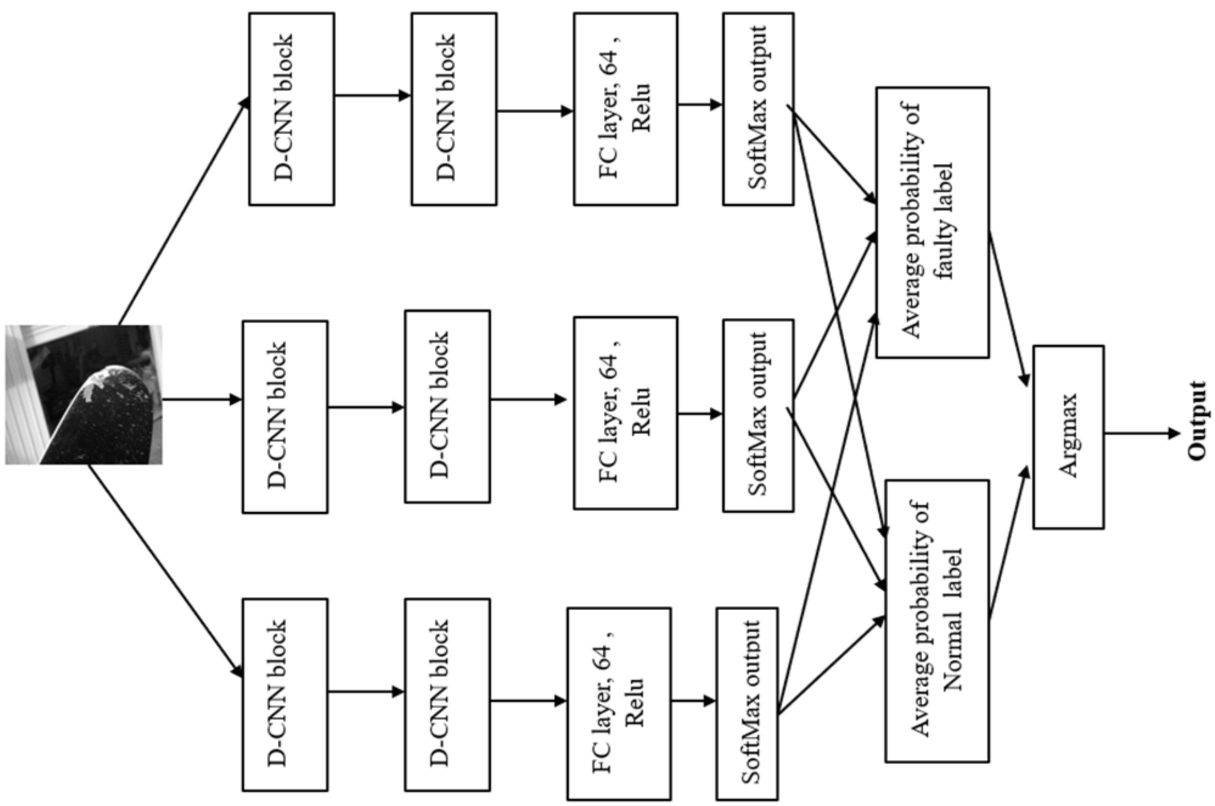


Fig 6.17 Proposed fault resilient framework for defect detection in blades

8. CASE STUDY

A COMPREHENSIVE REVIEW ON CORROSION DETECTION METHODS FOR AIRCRAFT: MOVING FROM OFFLINE METHODOLOGIES TO REAL-TIME MONITORING COMBINED WITH DIGITAL TWIN TECHNOLOGY

The case study presents a comprehensive review of corrosion detection techniques in aircraft, focusing on the shift from traditional non-destructive inspection (NDI) methods to real-time monitoring and digital twin technology. Corrosion poses significant threats to aircraft integrity, safety, and maintenance costs. The study discusses various detection techniques, including conventional NDI methods, real-time sensors, AI-based approaches, and digital twins for predictive maintenance. Key topics include Types of corrosion, such as uniform, pitting, and stress corrosion, along with their causes, The economic and safety impacts of corrosion, underlining its burden on aviation budgets and referring to historical accidents. And Corrosion detection techniques, detailing the strengths and limitations of various NDI methods and real-time sensors, including advanced technologies like AI and machine learning for automated detection. The Challenges such as the need for aircraft grounding with NDI techniques, maintenance of real-time sensors, and data requirements for AI models. Digital twin technology, which allows for the creation of a virtual replica of an aircraft to integrate data from various sources for predictive maintenance, ultimately reducing costs and enhancing safety. In conclusion, the paper advocates for the integration of advanced detection techniques and technologies within a digital twin framework to improve predictive maintenance, reduce downtime, and enhance aviation safety.

9. CONCLUSION

The exploration and analysis presented in this chapter emphasizes the critical importance of variable-pitch propeller systems in optimizing aircraft performance and safety. By integrating advanced detection and monitoring techniques, such as artificial intelligence, non-destructive testing, and data-driven machine learning models, the proposed framework effectively addresses common challenges in identifying and mitigating faults. These advancements enhance the operational reliability of variable-pitch propellers, ensuring efficiency across diverse flight conditions while reducing risks associated with mechanical wear, environmental factors, and improper maintenance. The proposed fault resilient framework can detect the faults in the engine blades during their manufacturing by examining the intricate features through ensemble of D-CNN architecture. The model uses 3 homogeneous D-CNN models, whose results are integrated by finding the mean probability of each class. In this way, the proposed architecture is capable of detecting the false in blades of turboprop engines by extensively analysing its images.

Future developments in variable-pitch propeller technology are expected to leverage innovations in sensor systems, hybrid propulsion mechanisms, and enhanced material science to further improve resilience and sustainability. This research lays a strong foundation for adopting AI-driven fault detection and predictive maintenance strategies in turboprop engines, which can significantly extend component lifespans and optimize fuel efficiency. As aerospace engineering continues to evolve, the integration of these technologies will be pivotal in supporting the global shift towards greener, more dependable, and safer aviation solutions.

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